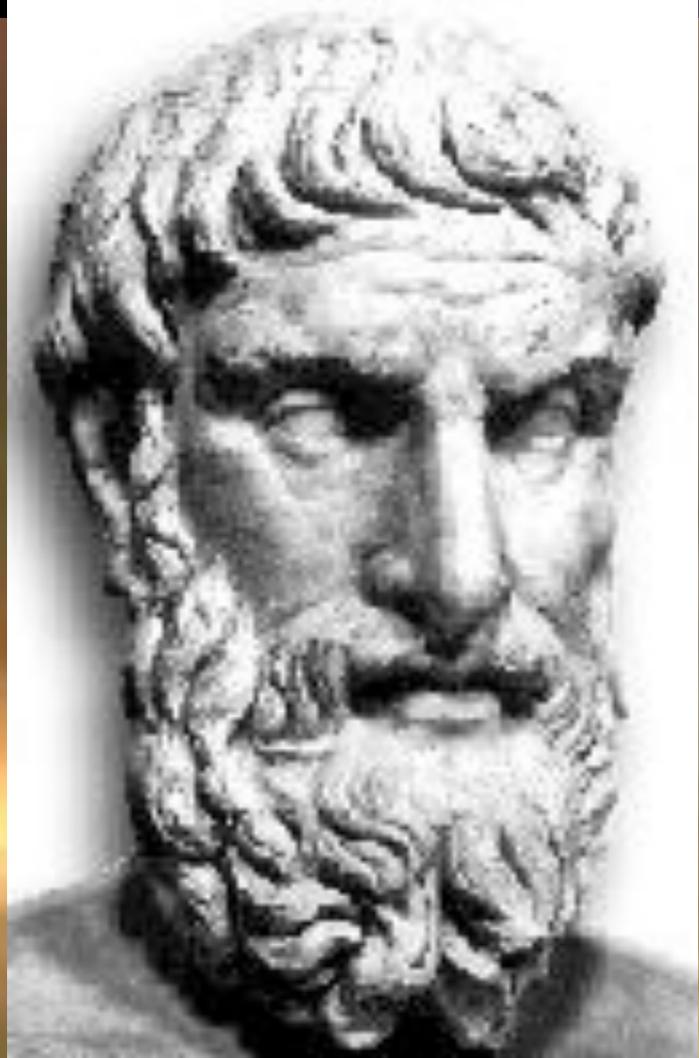


*D'autres Mondes dans le Cosmos ?
La Recherche de Planètes semblables à
notre Terre et ...peut-être abritant de la Vie !*

Michel Mayor
Université de Genève



Une question ancienne!

Epicurus 341 - 270 AC

Les Mondes sont en nombre infini, certains similaires au nôtre, d'autres étant différents...

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

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

Circa 1200-1280: Saint Albert le Grand:

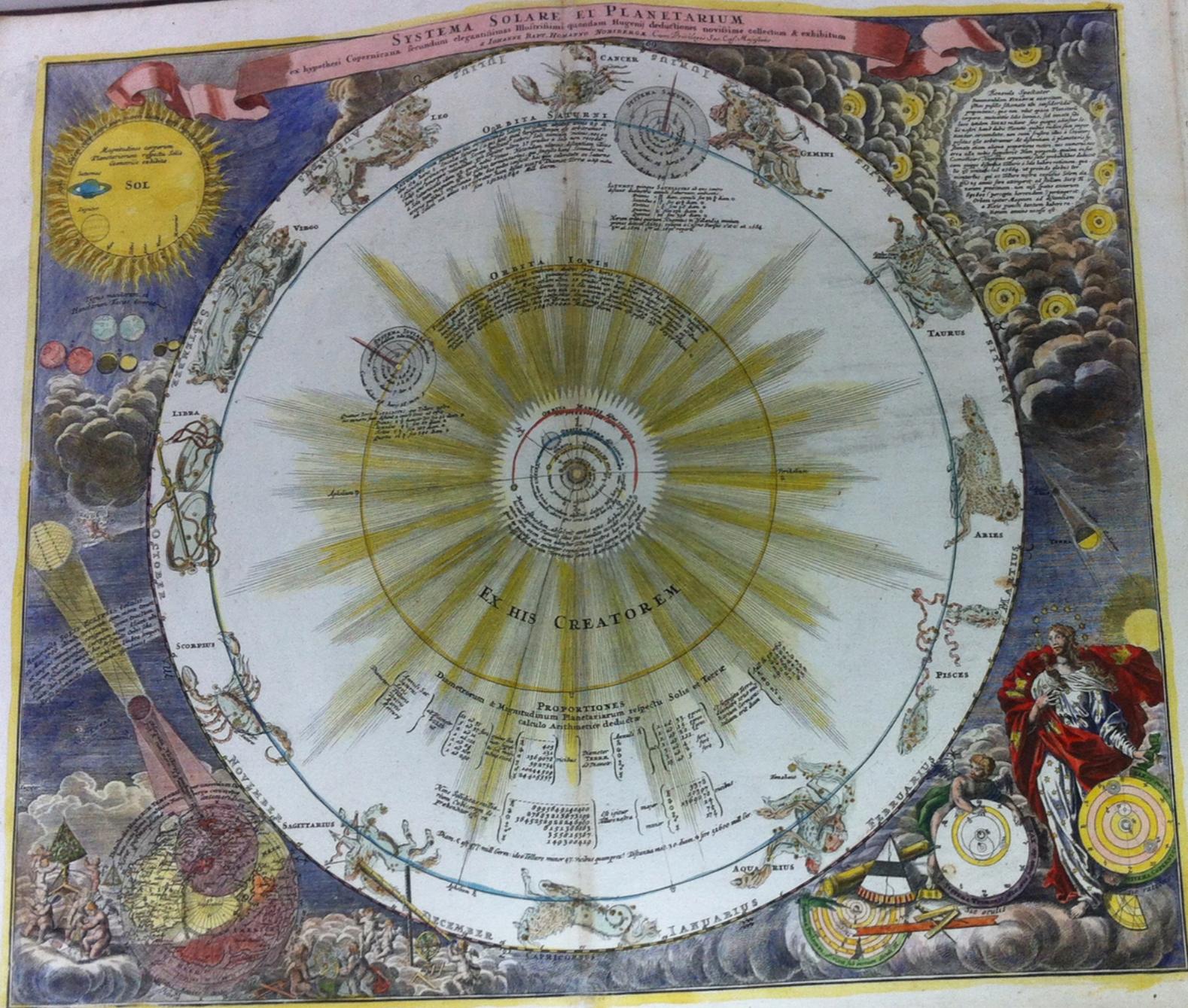
« Existe-t-il plusieurs Mondes, ou n'y en existe-il qu'un ? C'est une des plus noble et exaltante question dans l'étude de la Nature. »

1277 : Etienne Tempier (Evêque of Paris, avec l'accord du Pape Jean XX1) demande que la question de la pluralité des Mondes soit enseignée à la Sorbonne.

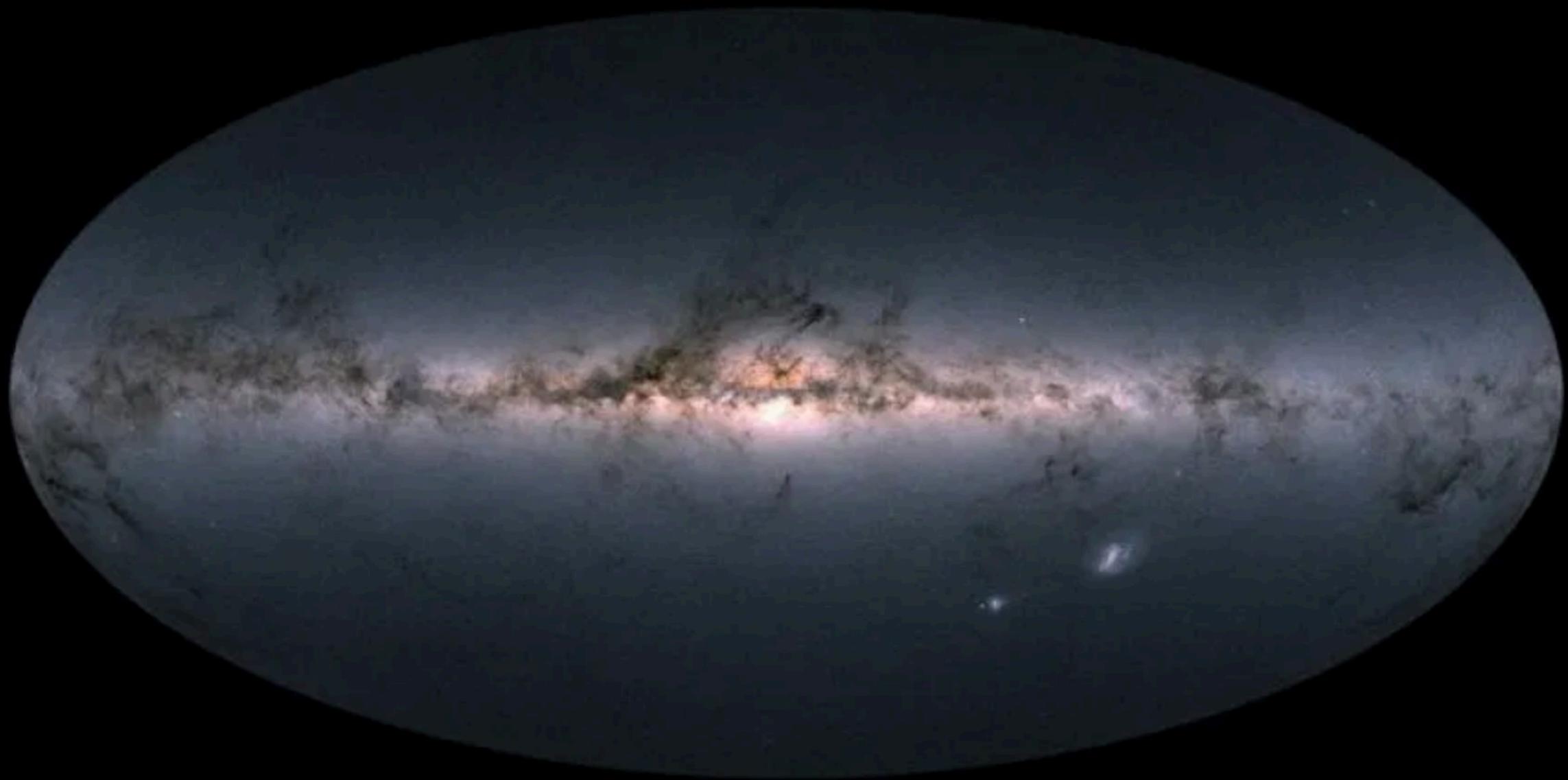
1600+ Giordano Bruno: « De l'infinito , universo e Mundi »

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

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



- LA voie Lactée. ... notre galaxie
- 200 milliards d'étoiles : Combien de « Terres » ?
- La lumière a besoin de 100'000 ans pour traverser .

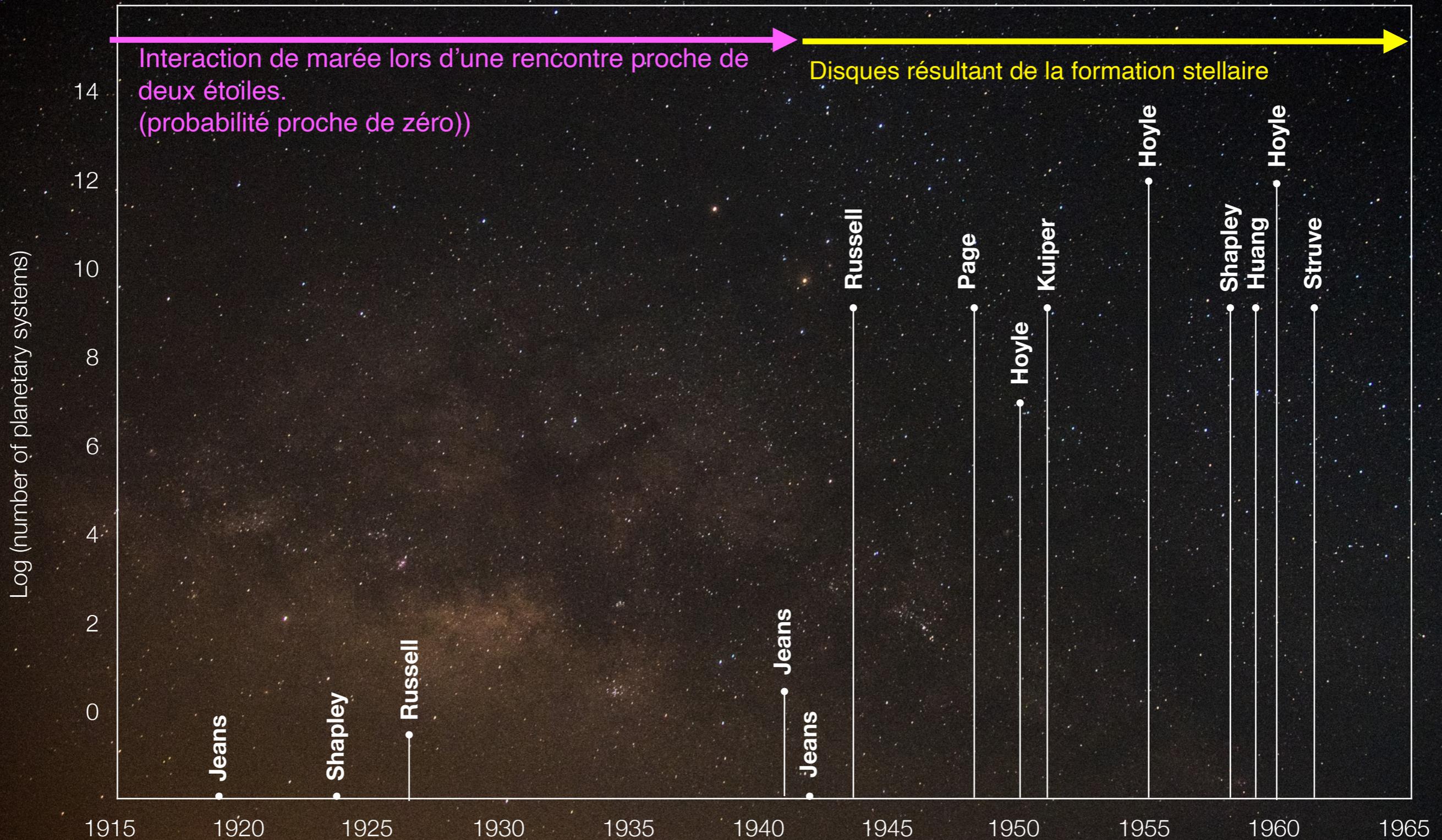


Combien des
systèmes
planétaires dans
la Voie Lactée ?



Nombre estimé de systèmes planétaires dans la Galaxie

dans la Galaxie



PROPOSAL FOR A PROJECT OF HIGH-PRECISION STELLAR
RADIAL VELOCITY WORK

By Otto Struve

"I have suggested elsewhere that the lack of rapid axial rotation of normal solar-type stars ... suggests that these stars have converted their angular momentum from axial rotation to angular momentum from the orbital motion of the planets. Therefore there can be many planet-like objects in the galaxy. "

Disques protoplanétaires observés avec le HST



**Protoplanetary Disks
Orion Nebula**

HST · WFPC2

PRC95-45b · ST ScI OPO · November 20, 1995

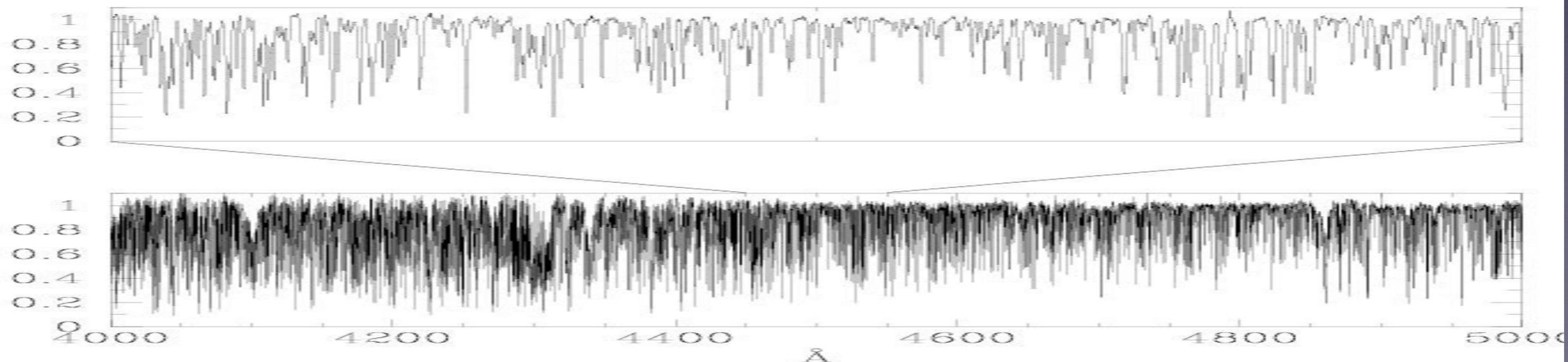
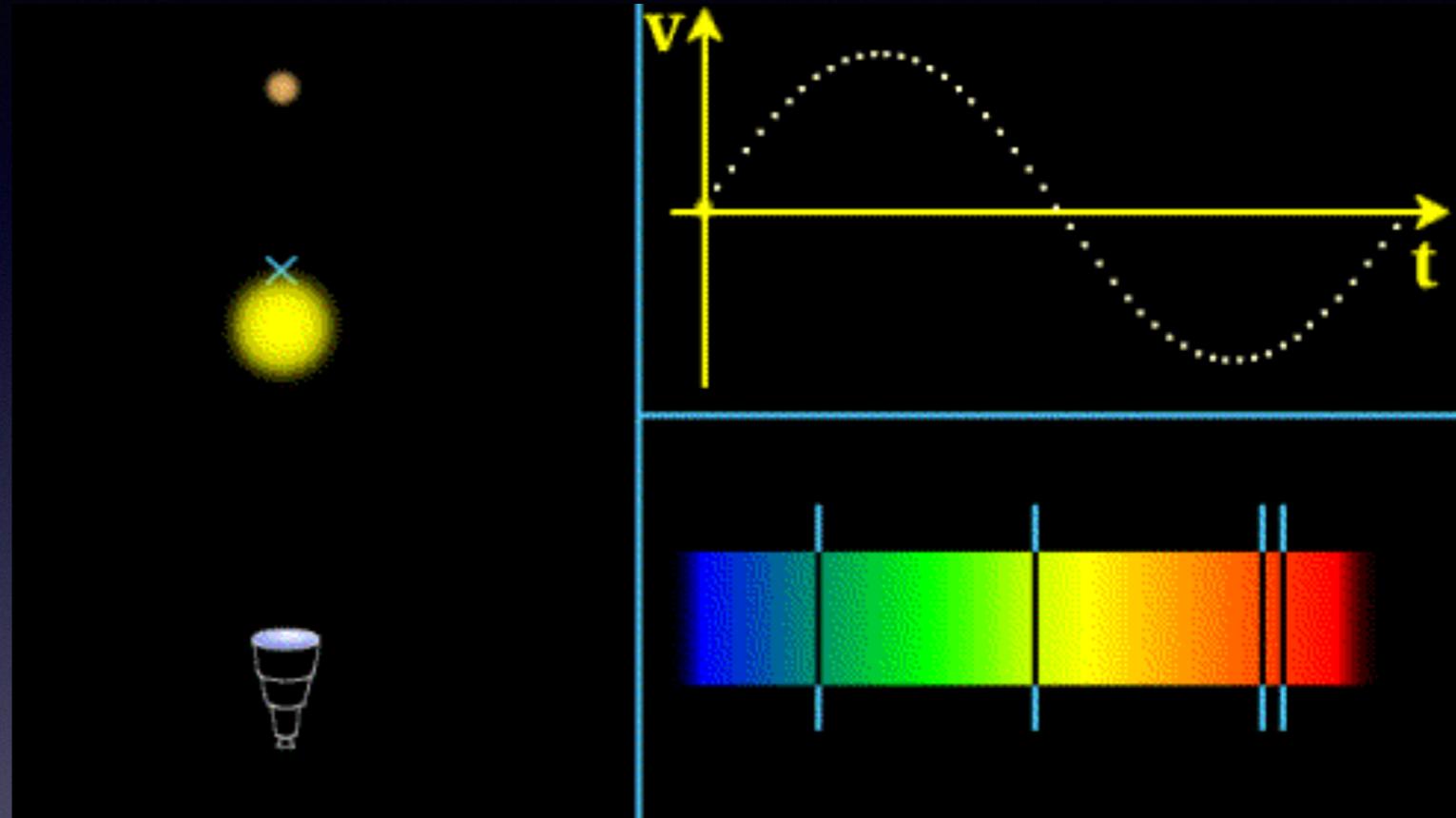
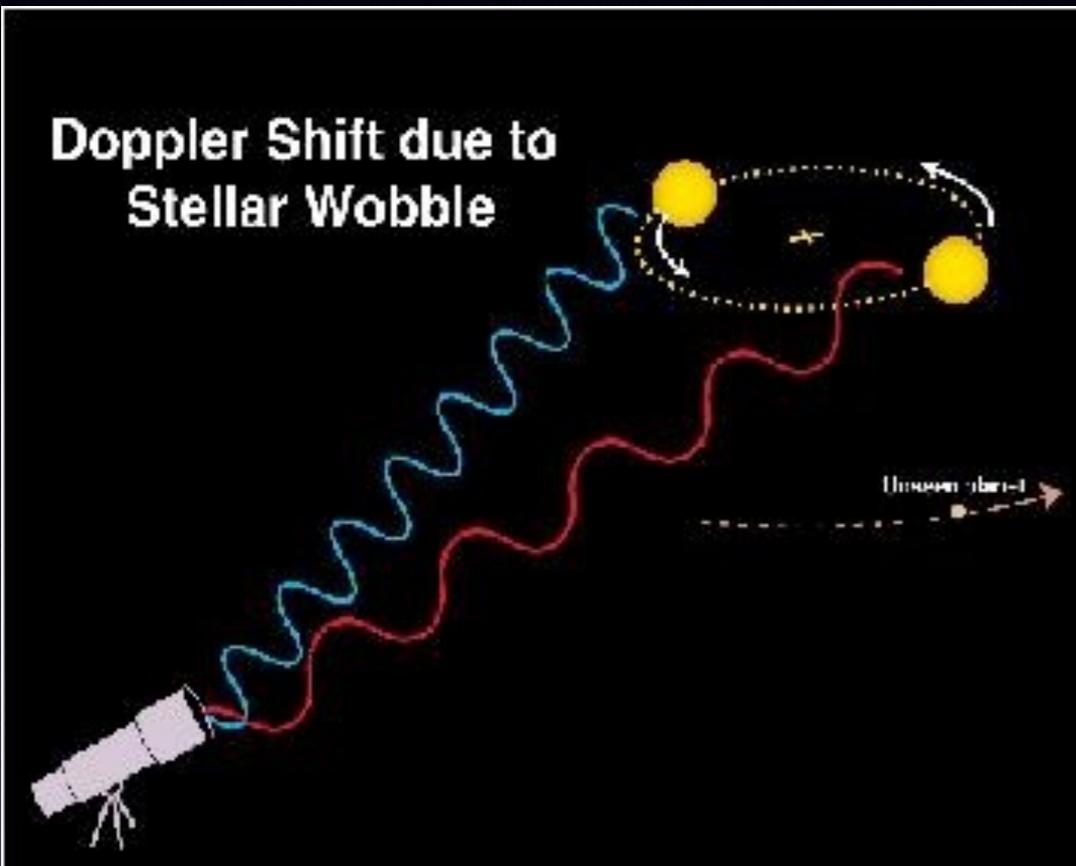
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

Comment détecter les planètes ?



Effet Doppler

Doppler Shift due to Stellar Wobble



*Une planète en orbite autour d'une étoile
similaire à notre Soleil :*

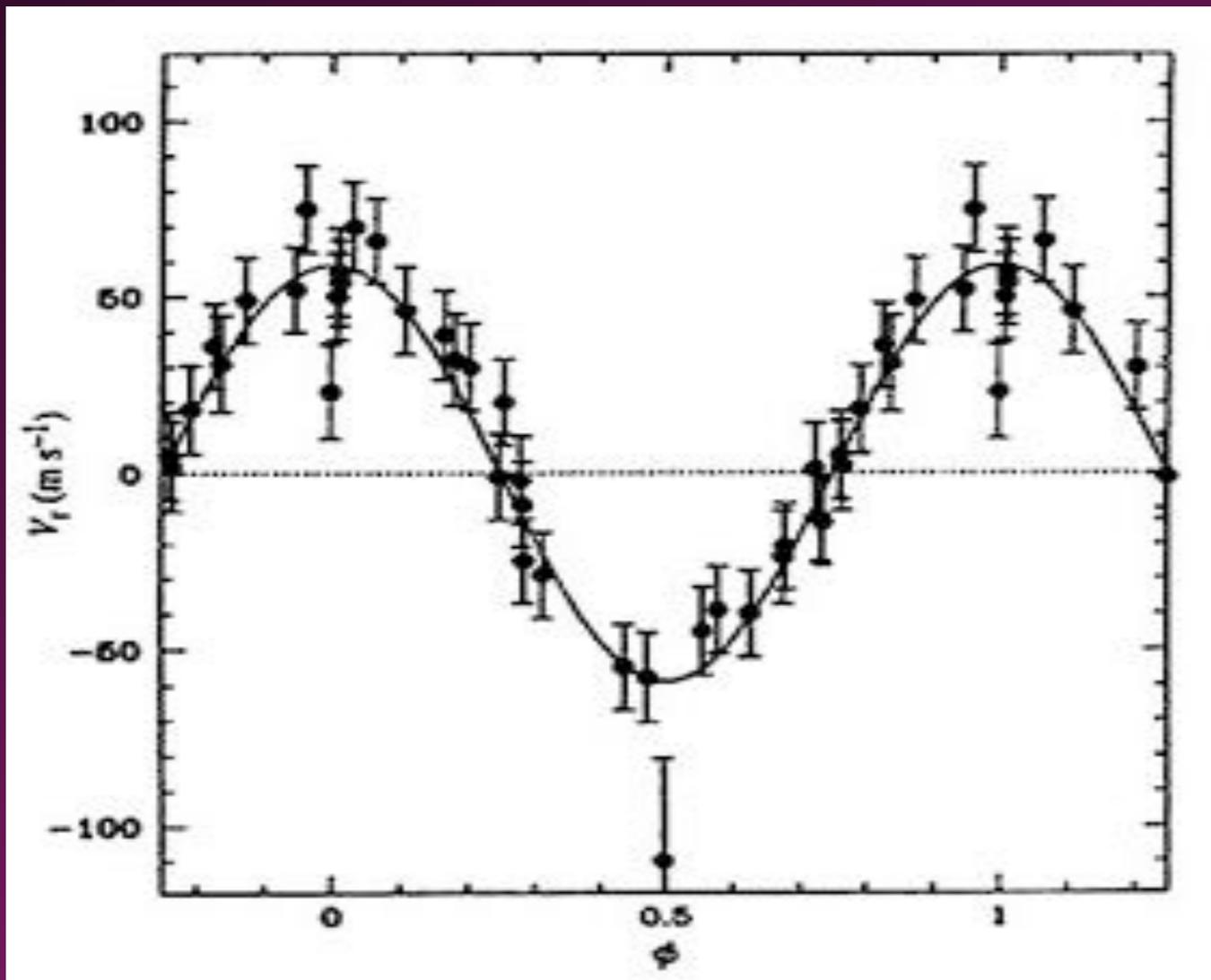
51 Pegasi b

$$M_{\text{pl}} = 0.5 M_{\text{Jup}}$$

$$P = 4.2 \text{ jours} \llllll!!!!$$

$$a = 0.04 \text{ AU}$$

Précision: 13 m/s



*Observatoire de
Haute-Provence
193 cm*

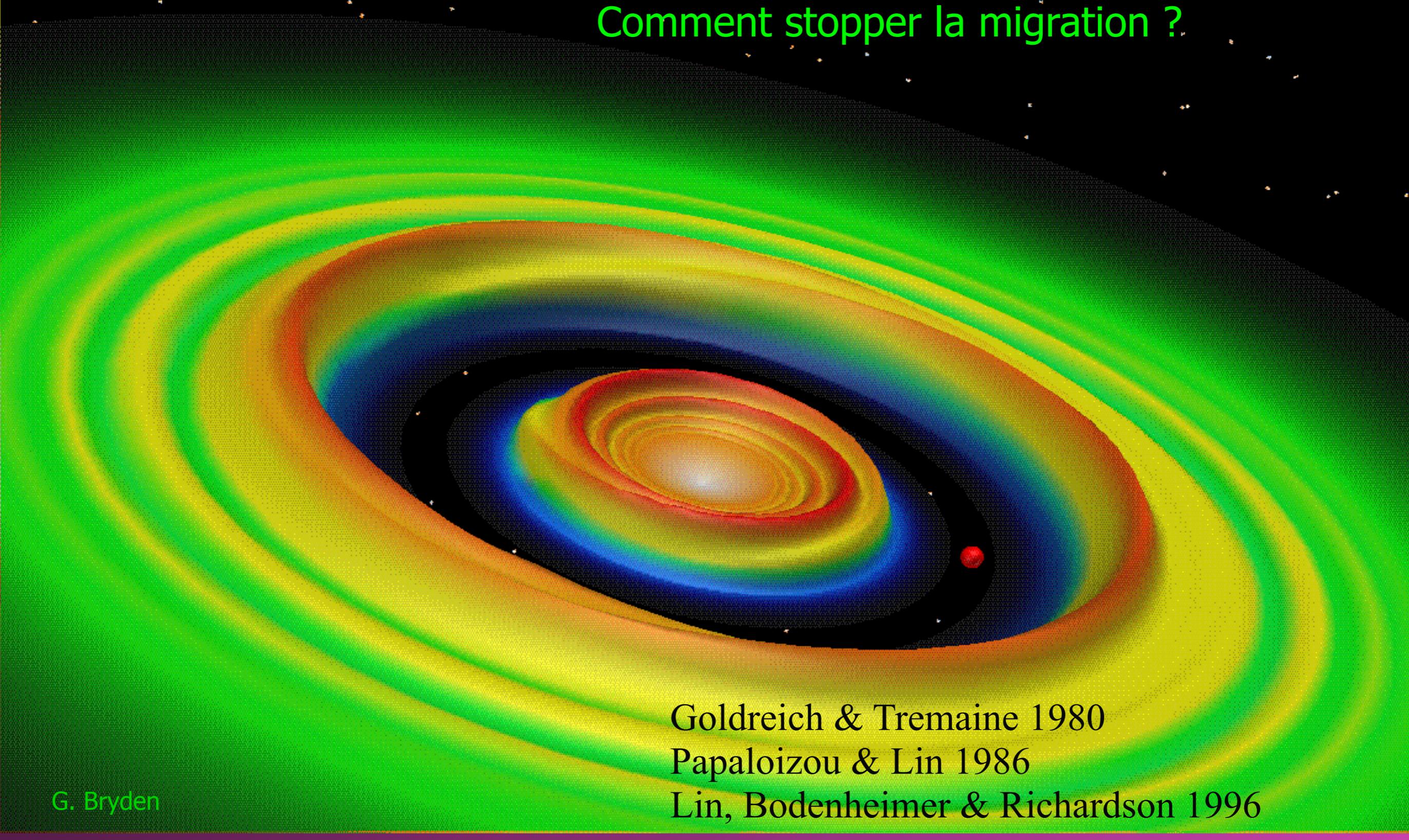
Mayor & Queloz , Nature Nov.1995

Formation de planètes proches de leur étoile:

interaction disque-planète

Formation au-delà de la "ligne des glaces" -> migration -> centre

Comment stopper la migration ?



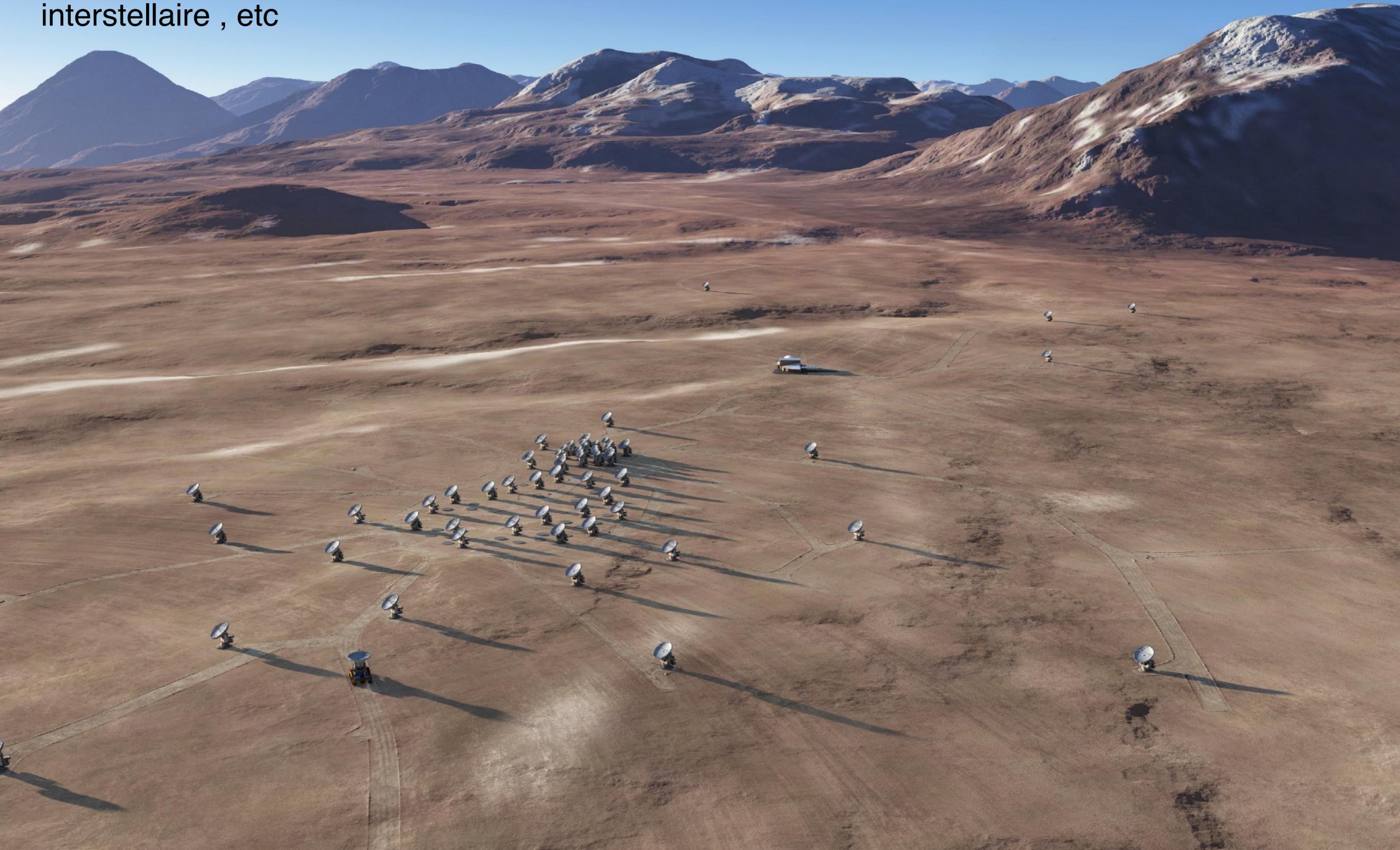
Goldreich & Tremaine 1980

Papaloizou & Lin 1986

Lin, Bodenheimer & Richardson 1996

ALMA: Un interféromètre submillimétrique à une altitude de 5000 mètres dans les Andes chiliennes pour étudier le gaz froid dans l'Univers (ESO,US,Japan)

Formation des galaxies, étoiles , planètes , la matière interstellaire , etc

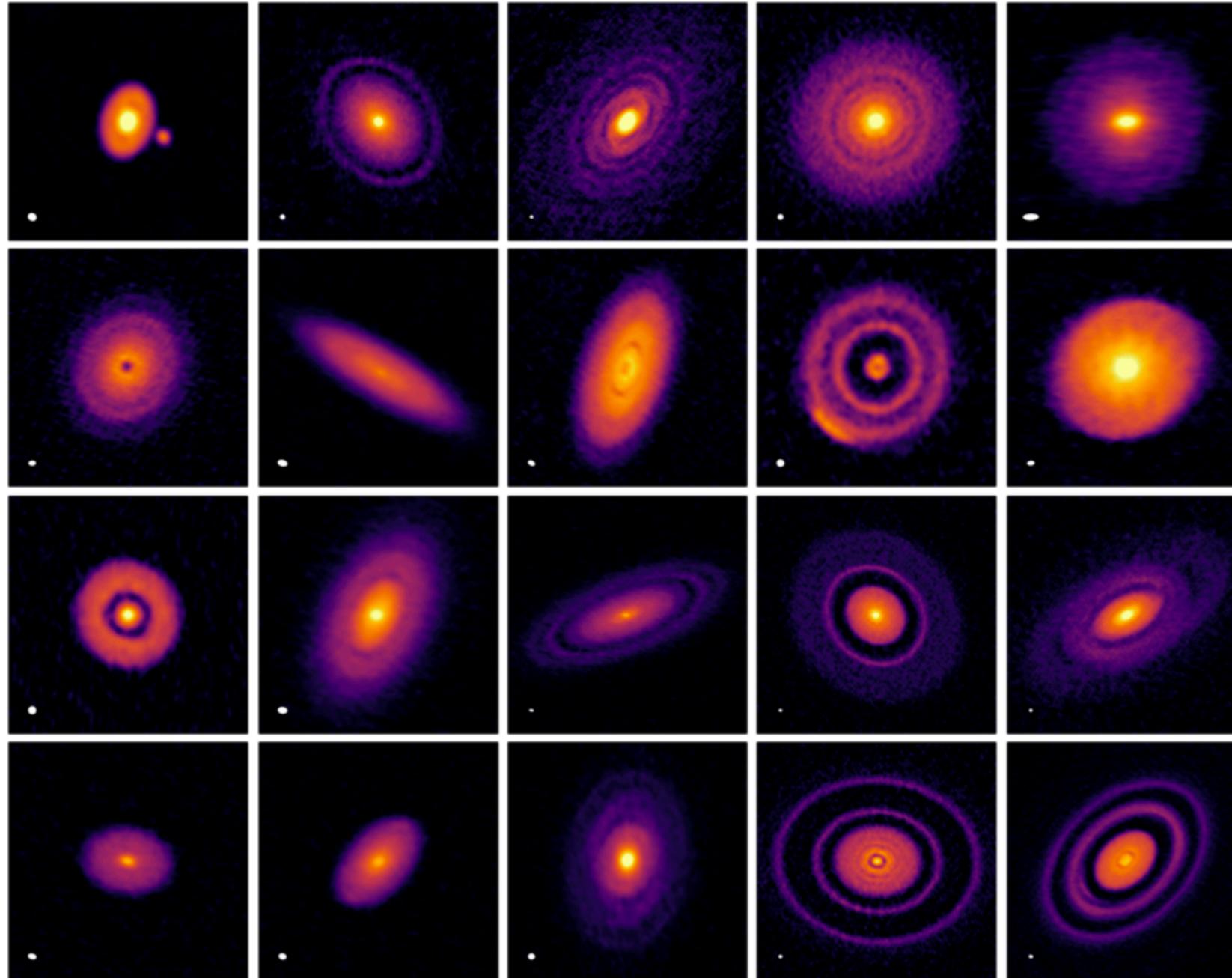








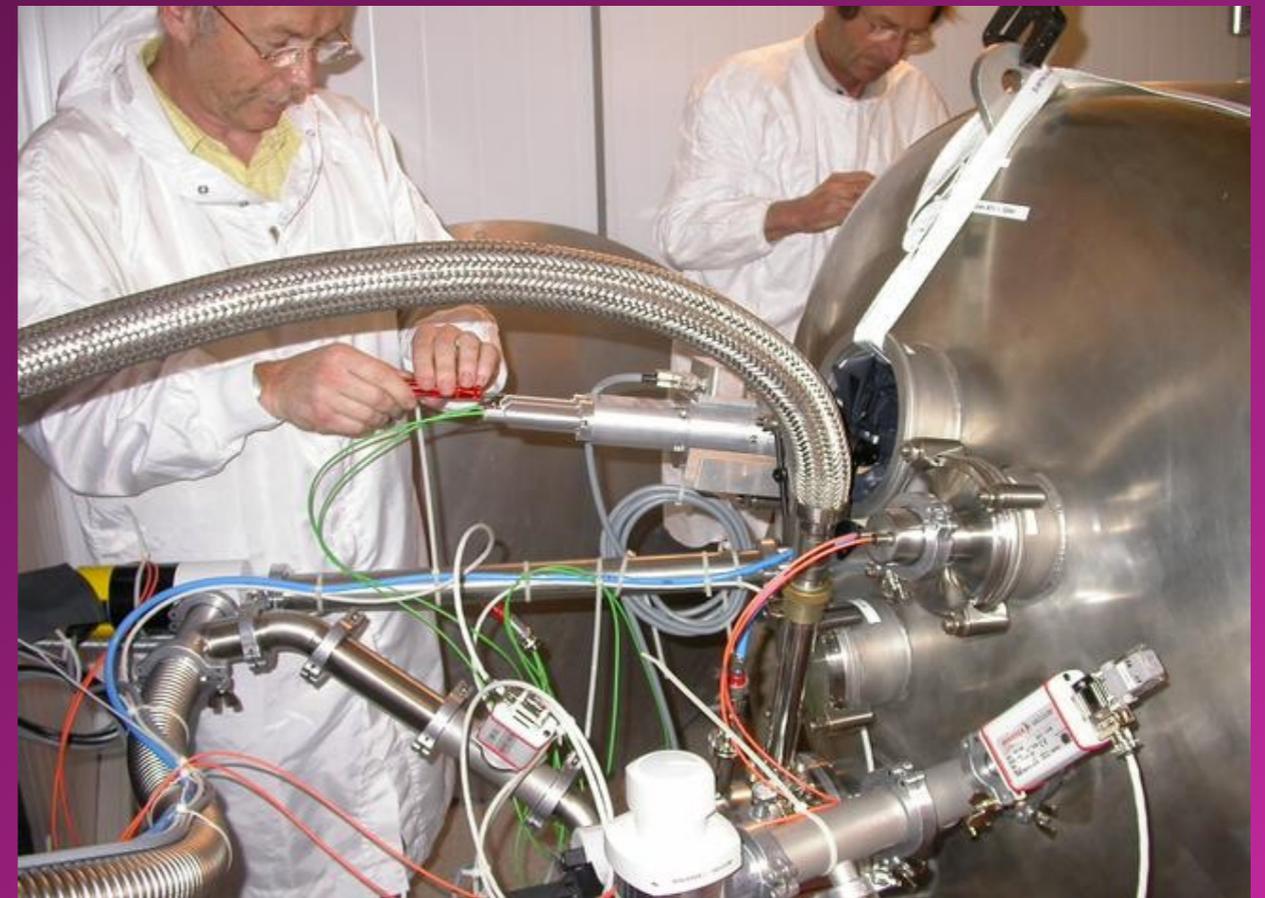
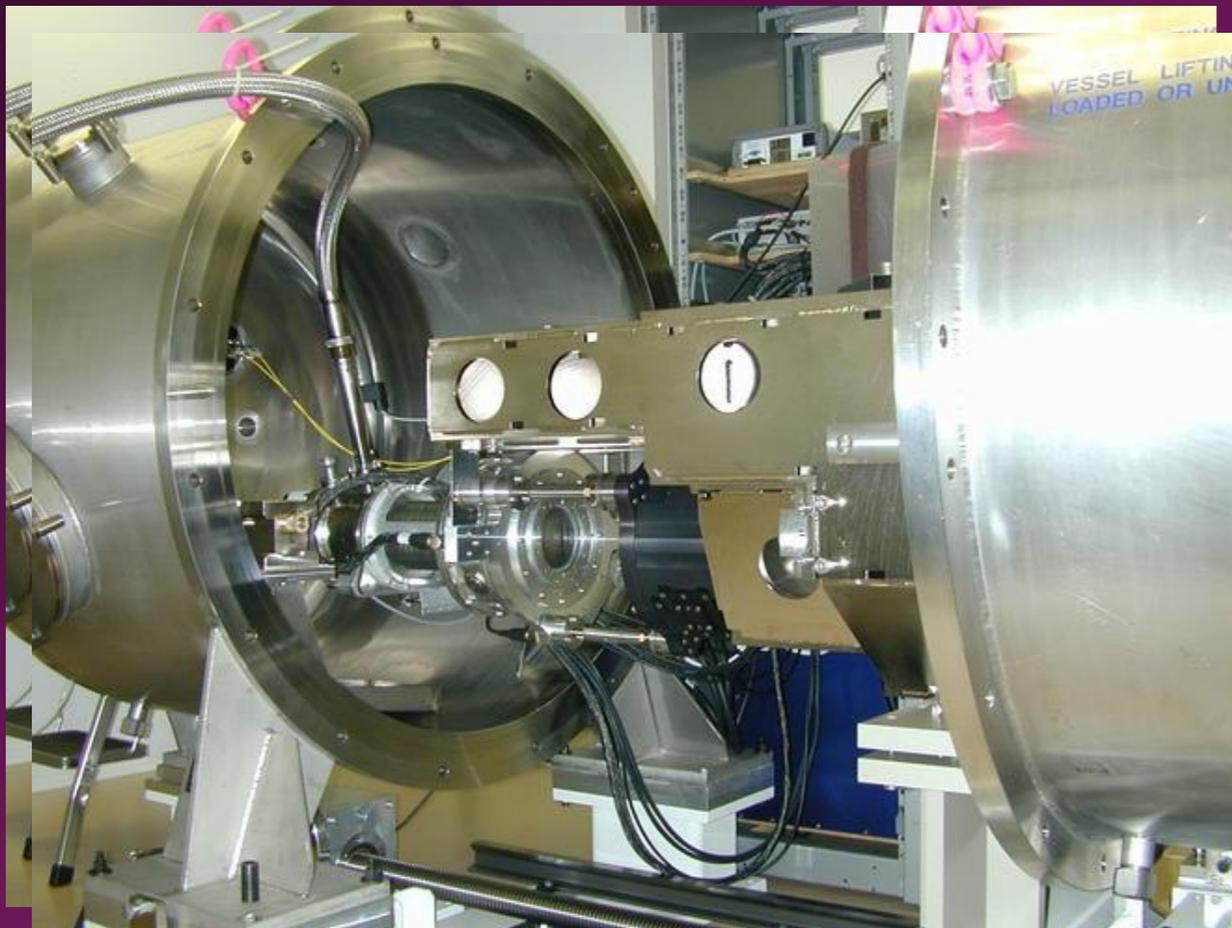
Disk Substructures at High Angular Resolution Project (DSHARP)



This is the official Data Release webpage for the ALMA Cycle 4 Large Program *Disk Substructures at High Angular Resolution Project (DSHARP)*. DSHARP is a deep, high resolution (35 mas, or 5 au) survey of the 240 GHz (1.25 mm) continuum and $^{12}\text{CO } J=2-1$ line emission from 20 nearby, bright, and large protoplanetary disks, designed to assess the prevalence, forms, locations, sizes, and amplitudes of small-scale substructures in the distributions of the disk material and how they might be related to the planet formation process.

HARPS (Observatoire de La Silla, ESO) 2003

Mayor, Pepe, Queloz et al. 2003, Msngr. 114,20



Increasing the precision

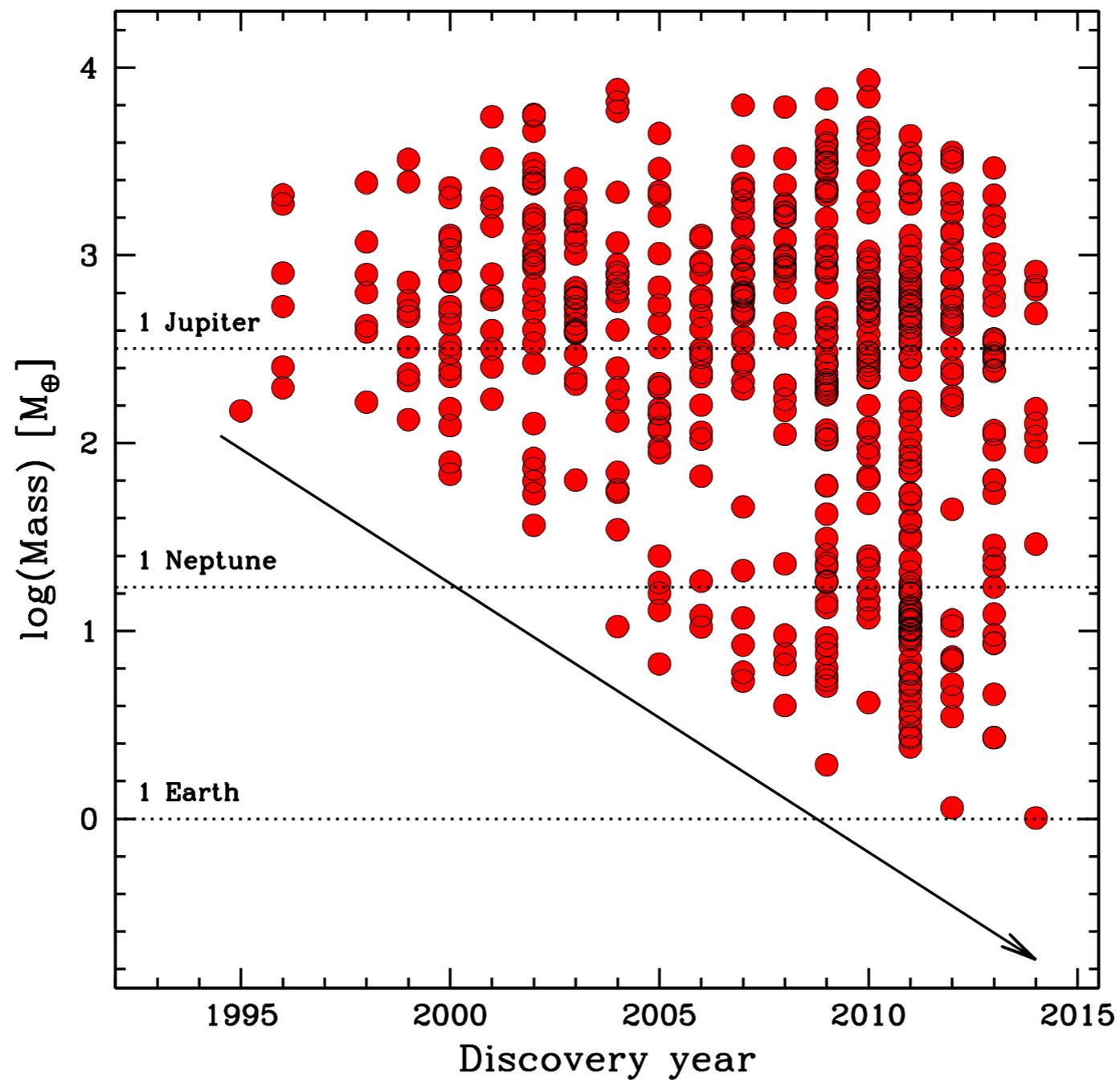
Radial velocity via cross-correlation spectroscopy:
A path to the detection of Earth-type planets

SPECTRO	year	precision	Telescope	
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	IAC La Palma
ESPRESSO	2018	0.1 m/s	8.2 m (x4)	ESO Chile



An increase of the sensibility by a factor 3000 during the last 40 years

Depuis 1995 : Un grand nombre de nouvelles découvertes et une amélioration de l'instrumentation astronomique.



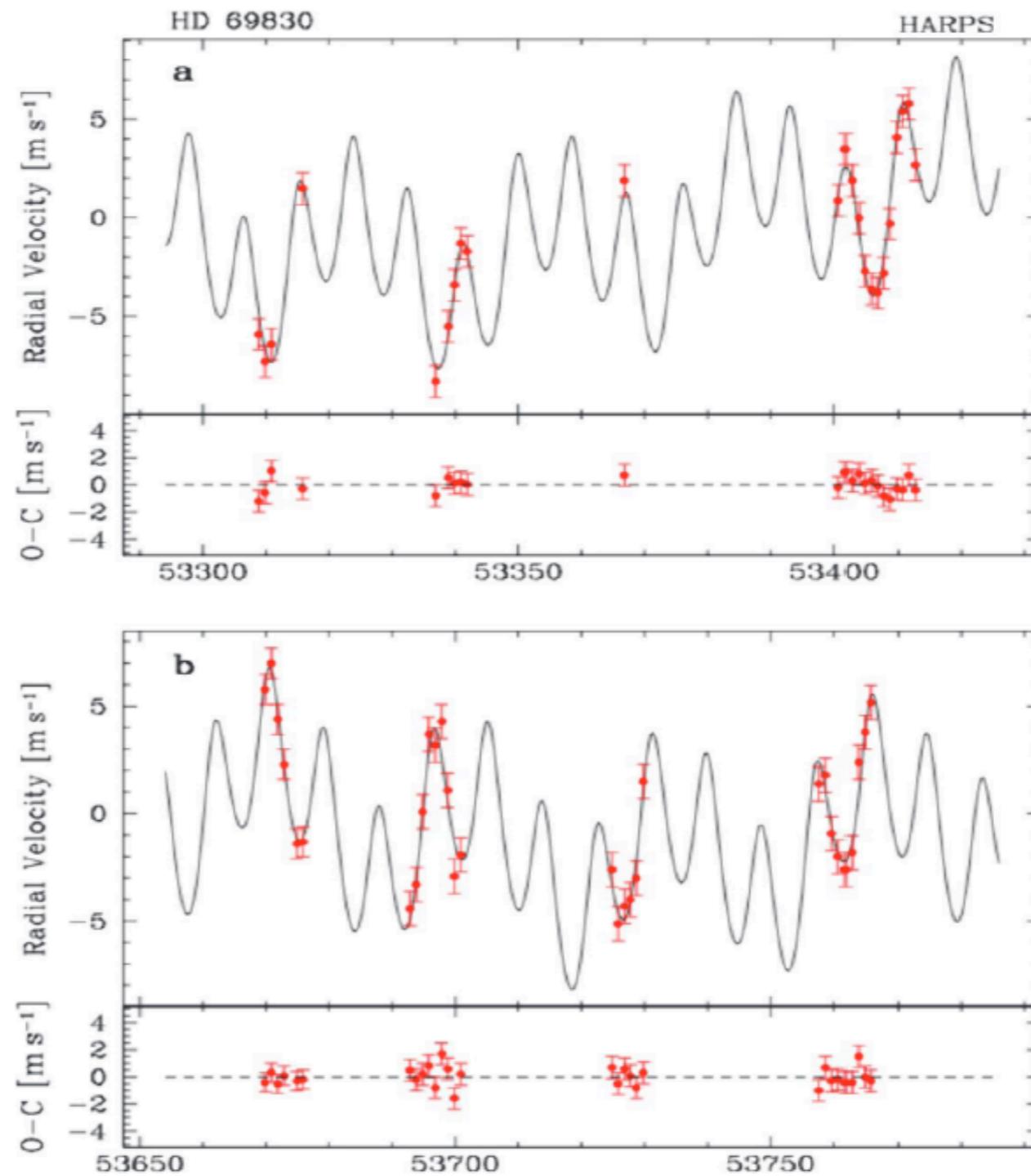


Fig. 4. A limited range of the velocity variation of HD 69830 giving an example of the complex curve resulting from the stellar reflex motion due to three planets (Lovis *et al.* 2006, *Nature* 441, 305).

Diversité observée des systèmes exoplanétaires

Périodes allant de quelques heures à plusieurs dizaines d'années

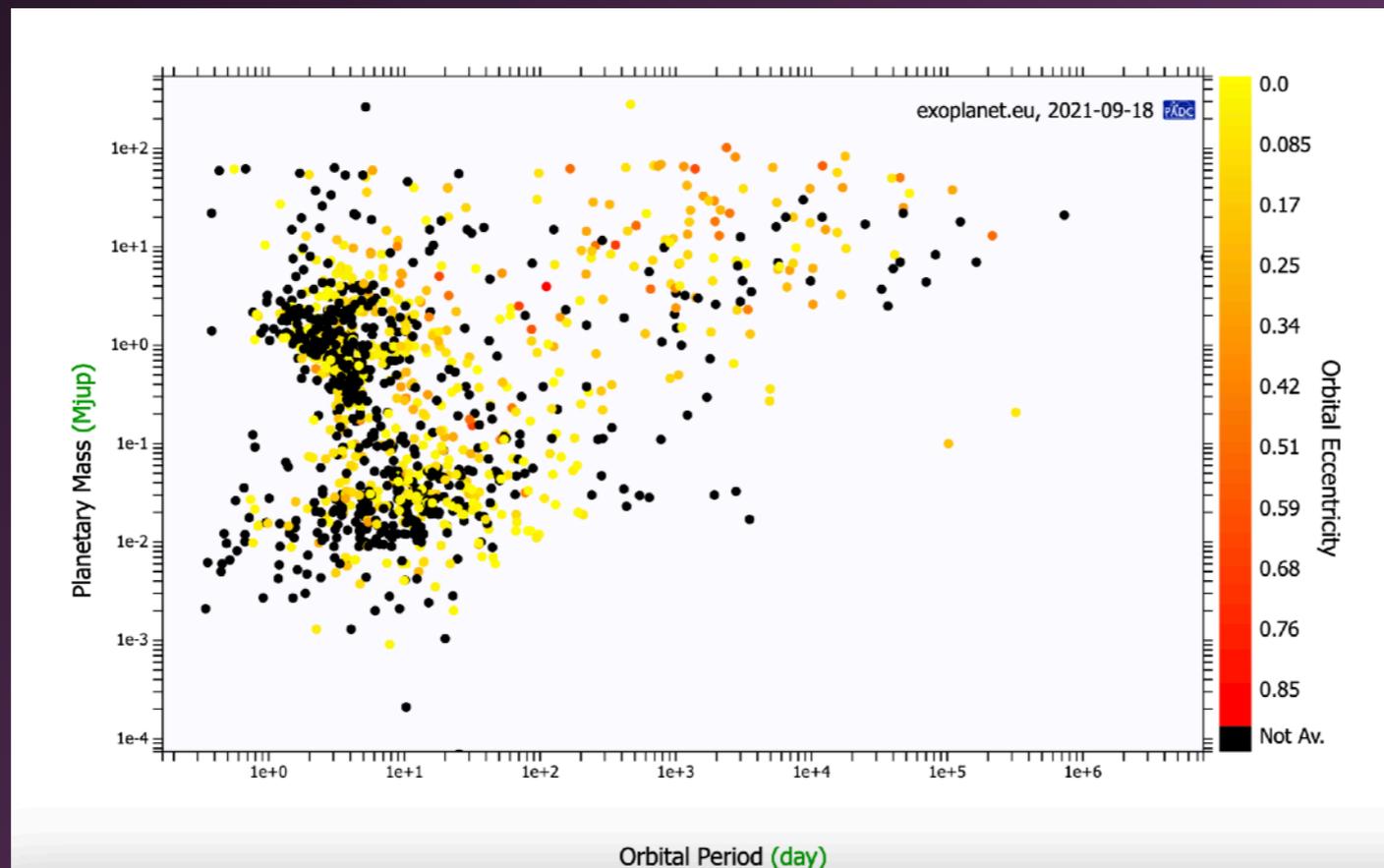
Masses allant d'une fraction de la masse terrestre à plus de 10 fois la masse de Jupiter.

Excentricité orbitale jusqu'à 0.93

Multiplicité extrêmement fréquente, jusqu'à 8 planètes.

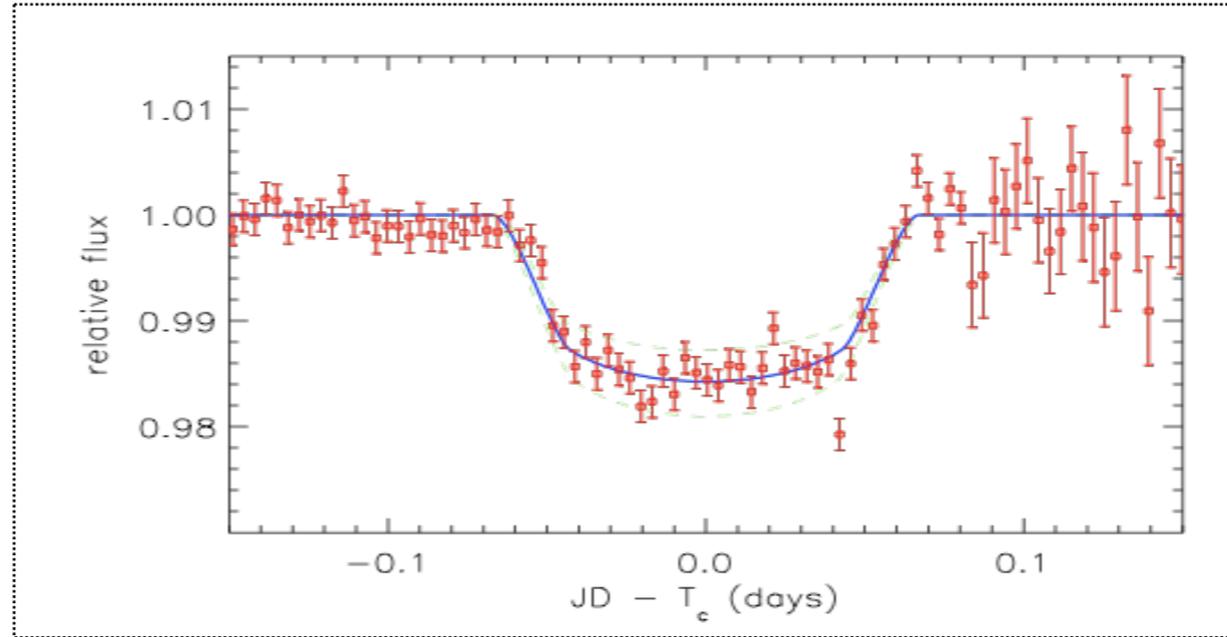
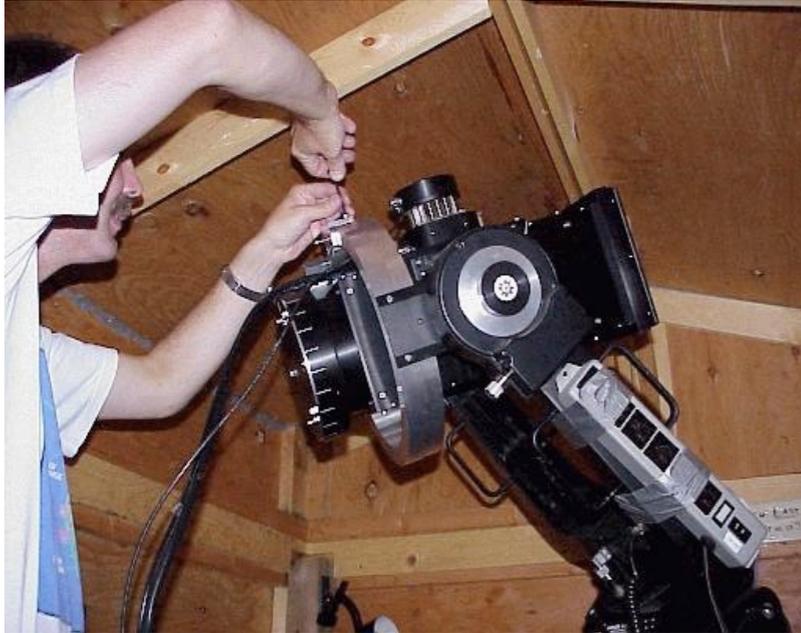
Inclinaison orbitale (par rapport à l'axe de rotation stellaire) ... parfois orbite rétrograde.

Diversité de la structure interne des planètes

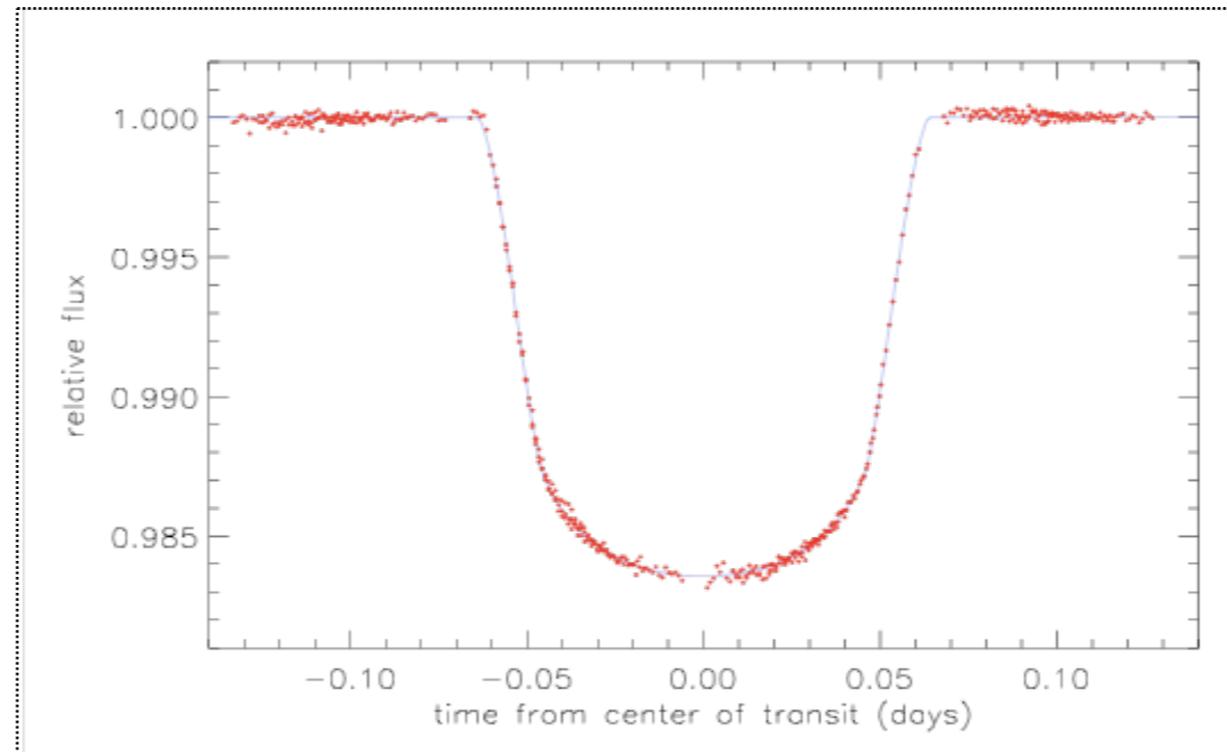


>>>> Complexité des mécanismes de la formation planétaire
accrétion, migration orbitale, interactions, effet Kozai.... 24

9 et 16 Sept 1999: Un premier transit planétaire



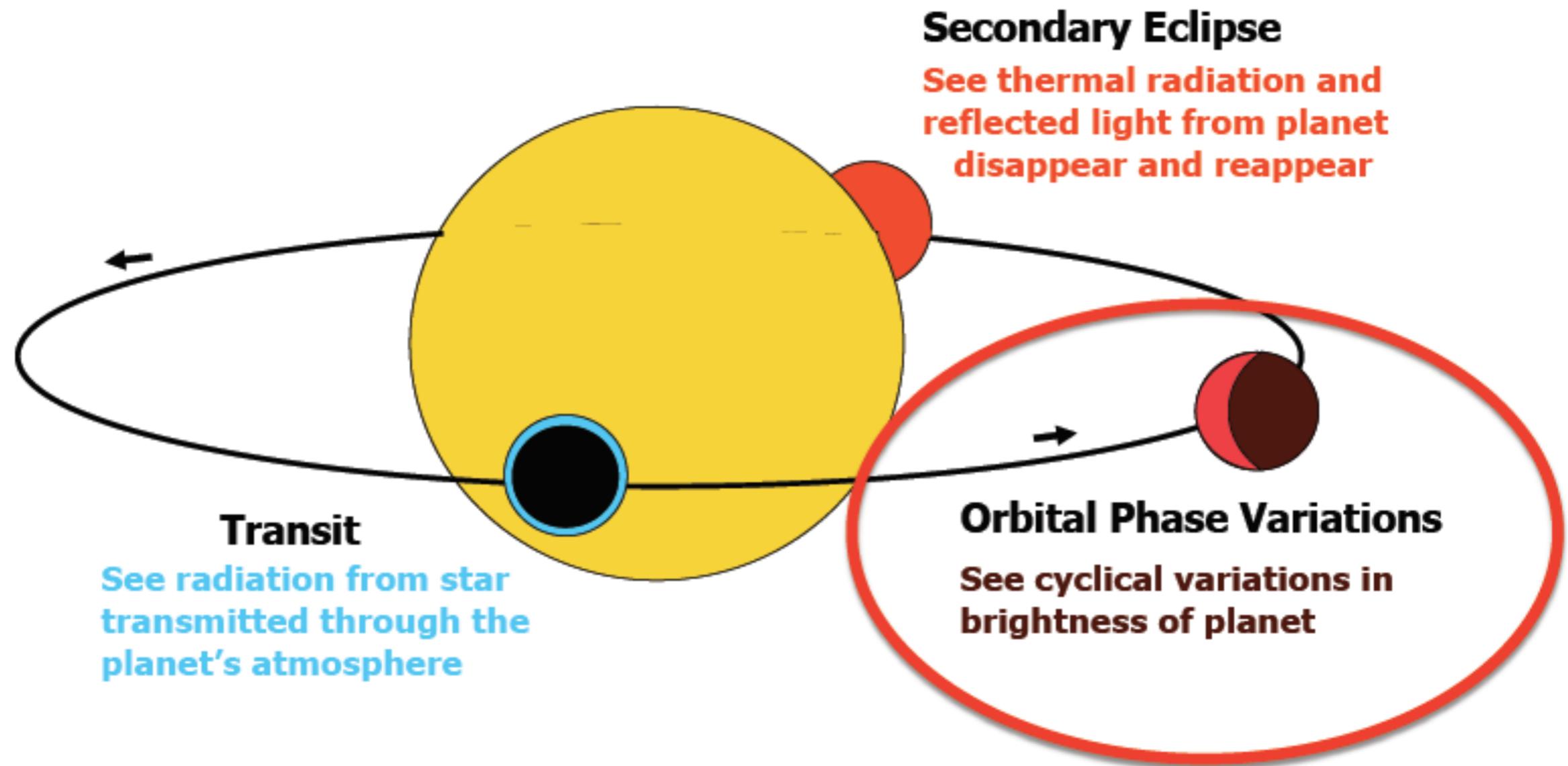
Charbonneau,
Brown, Latham,
Mayor 2000, ApJ, 529



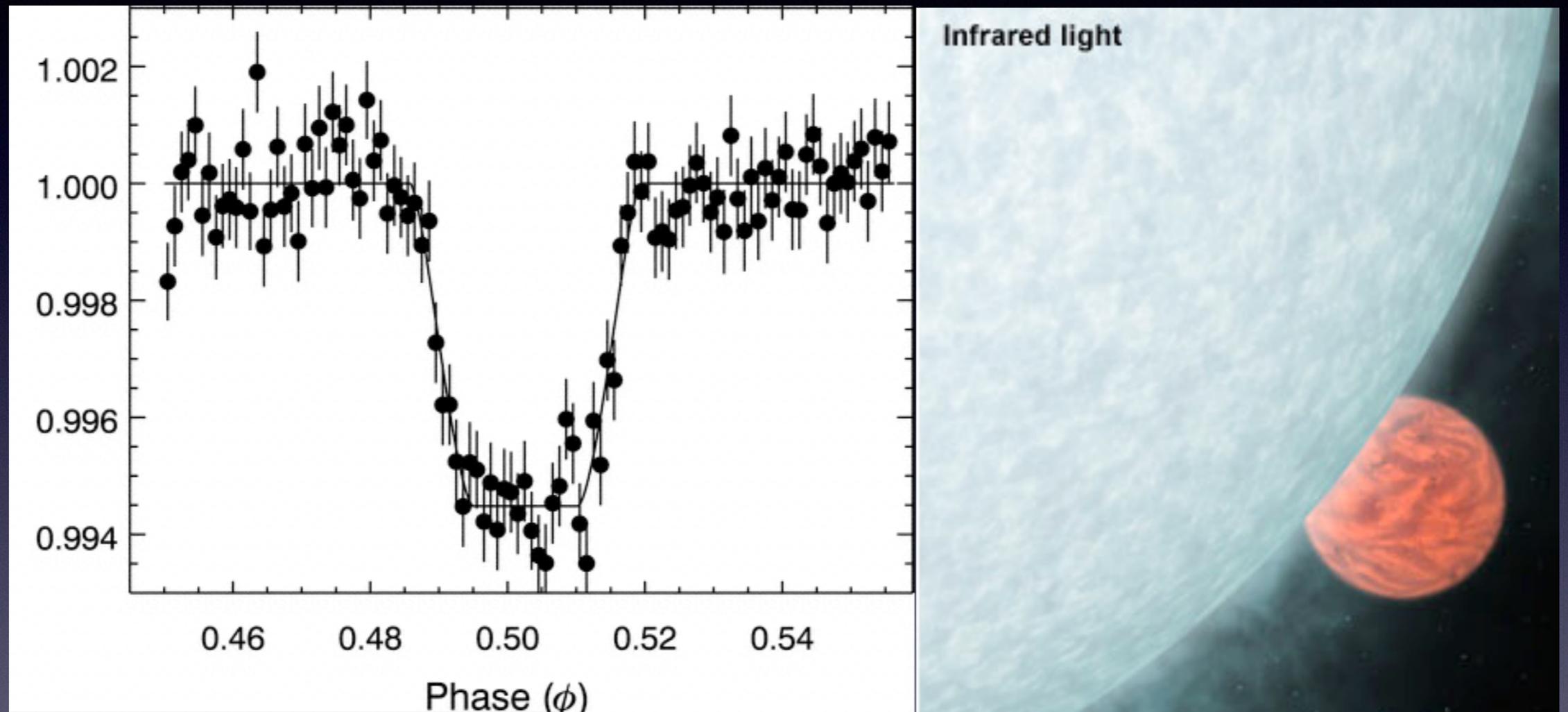
Brown, Charbonneau,
Gilliland, Noyes,
Burrows
2001, ApJ, 552, 699

HOT JUPITERS are gaseous giant planets : density = 0.3 g/cm^3

Transiting Planets as a Tool for Studying Exoplanetary Atmospheres



Détection des éclipses secondaires de HD 189733

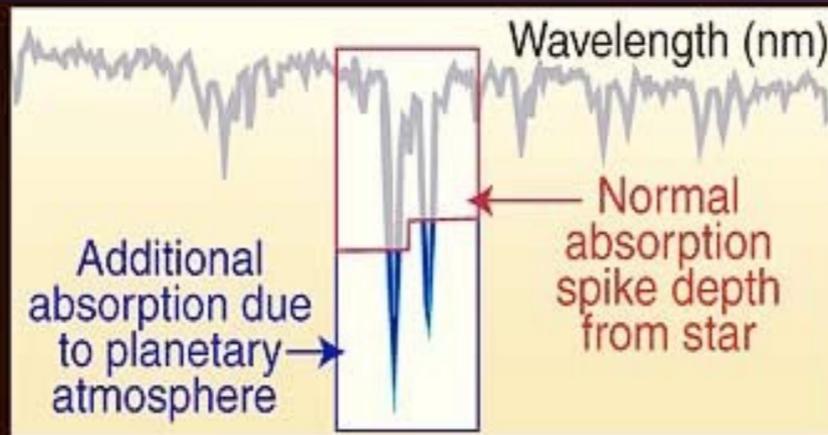


Deming et al. 2006 (Spitzer, 16 micron)

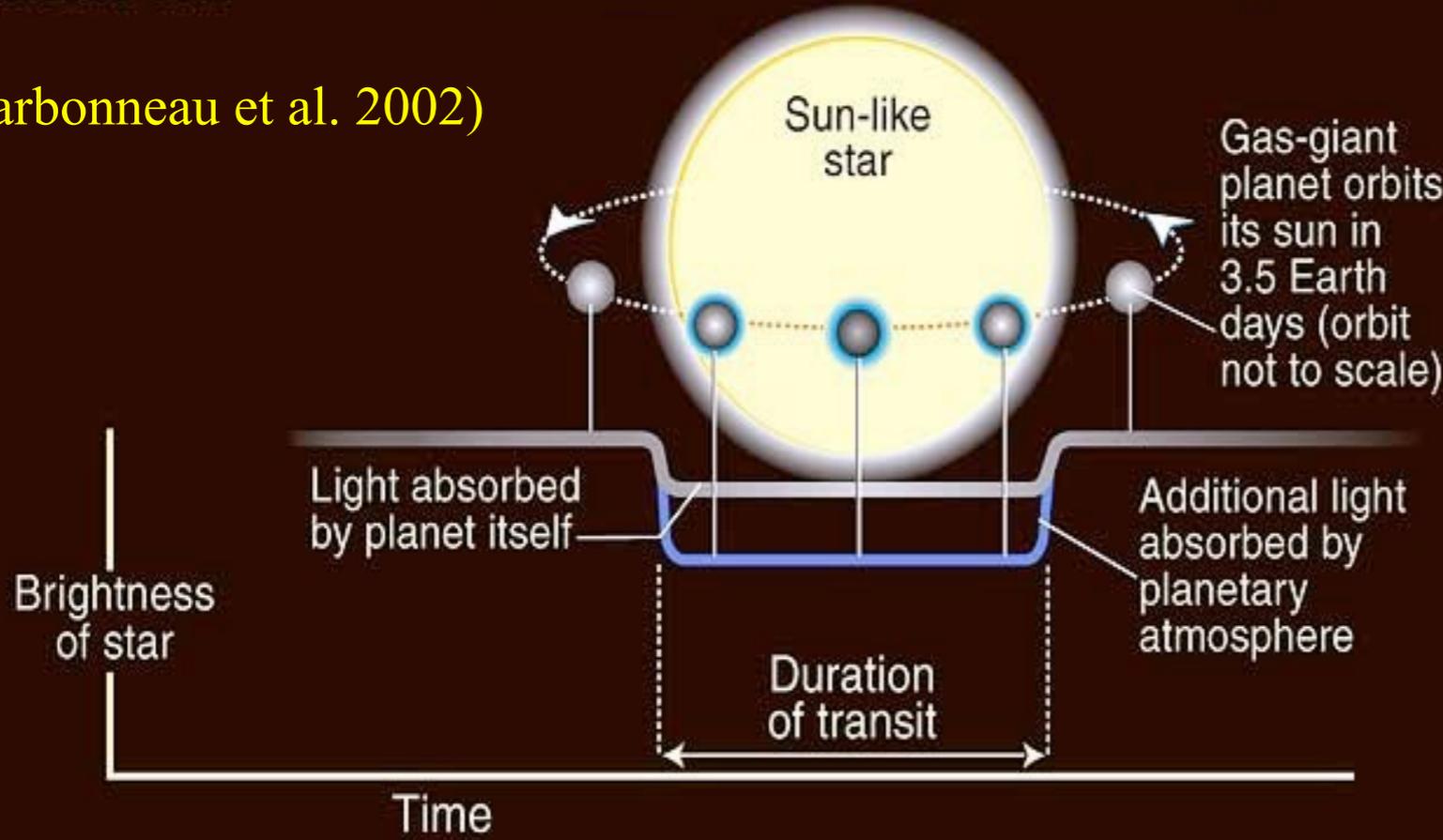
Spectroscopie par transmission

Identification d'atomes et de molécules

HST detects additional sodium absorption due to light passing through planetary atmosphere as planet transits across star



(Charbonneau et al. 2002)



- Na (Charbonneau et al. 2002)

- H₂, H₂O

(Grillmaire et al. 2008,
Swain et al. 2008, 2009)

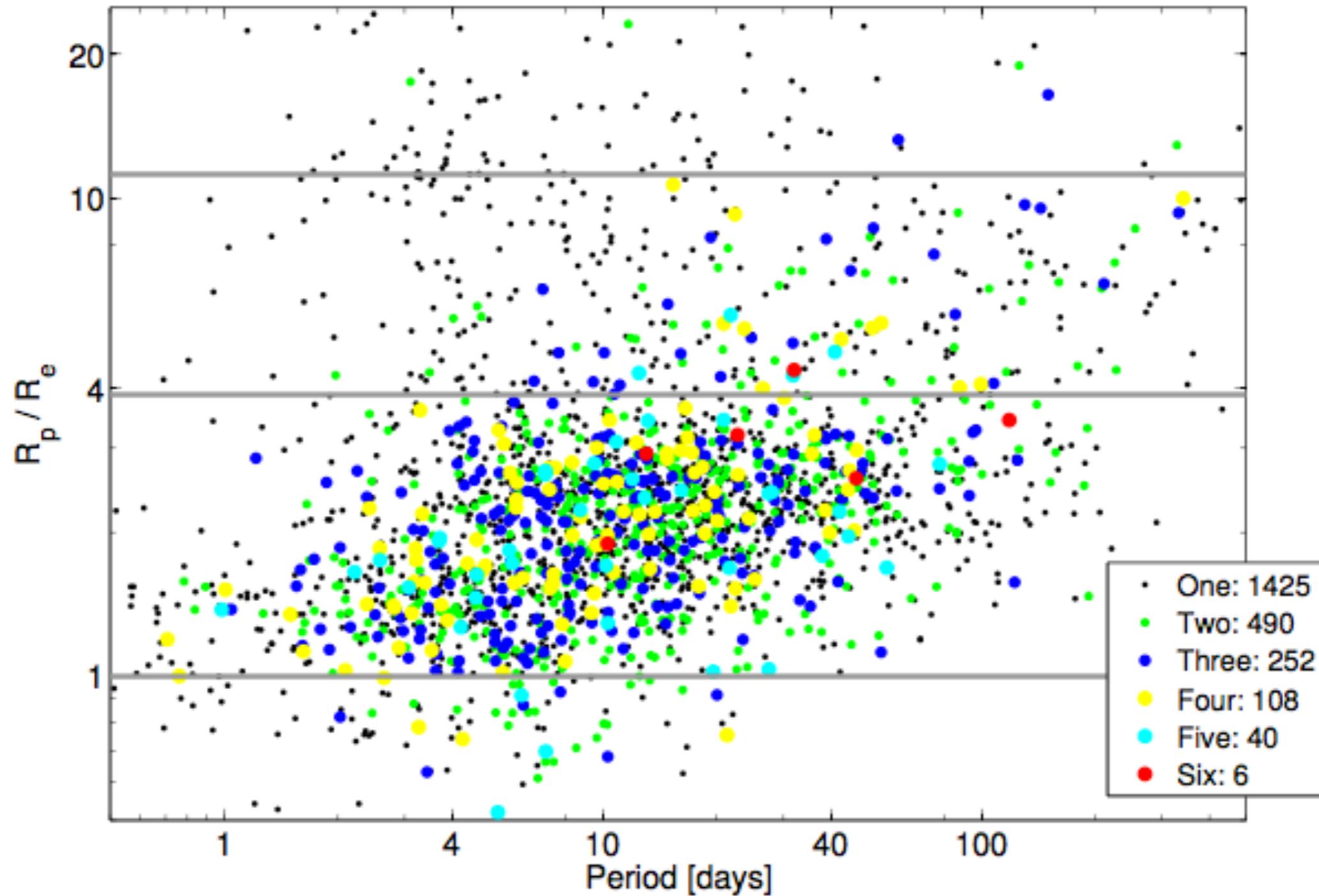
- CO, CO₂ (Swain et al. 2009ab,
Madhusudhan & Seager 2009)

- CH₄ (Swain et al. 2008)

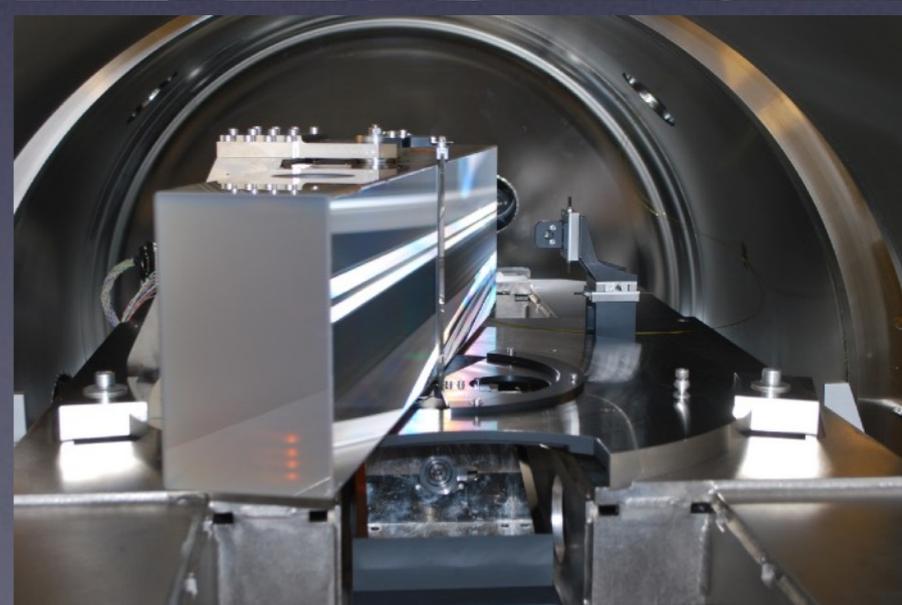
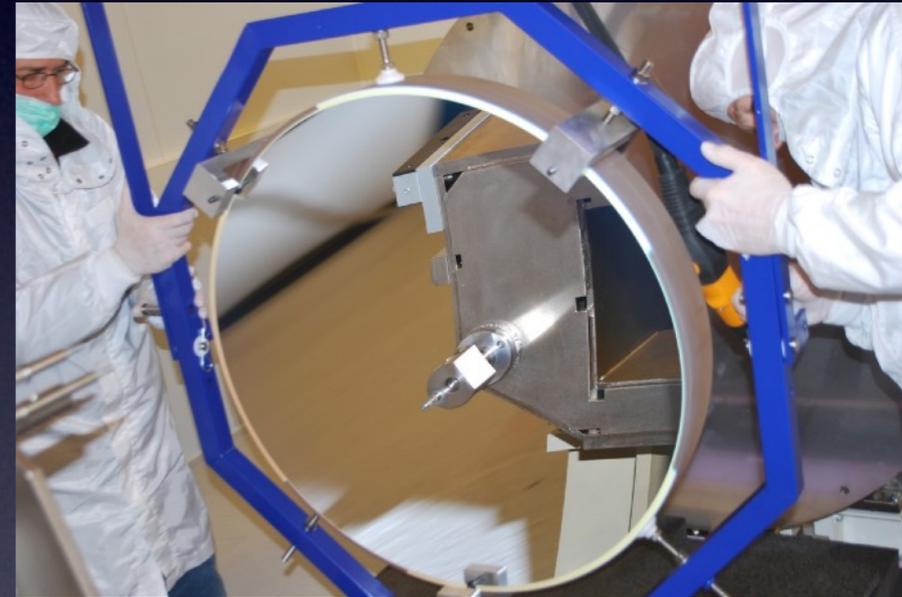
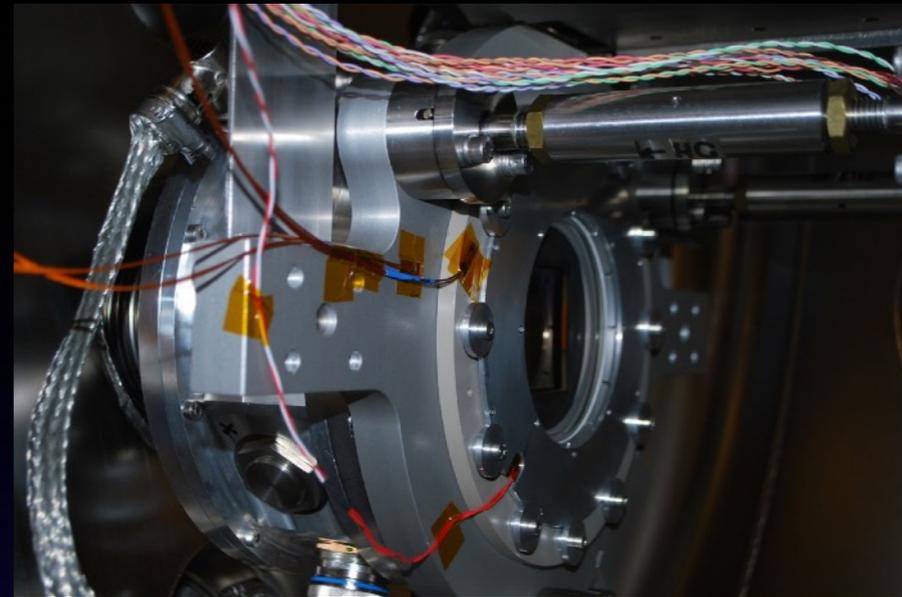
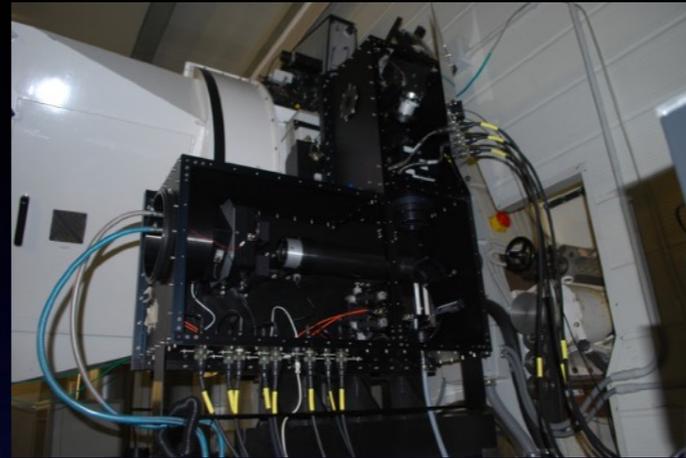
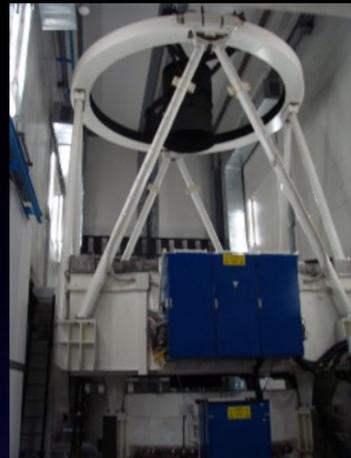
- Fe, Fe⁺, Ti⁺ (Hoejmakers et al, 2018)

Exemple: Le diamètre de la Terre vue à 9.7 microns est environ 0.5% plus grand qu'en lumière visible .

L'énorme « moisson » de la mission spatiale Kepler :



HARPS-N @ Galileo telescope at La Palma Observatory



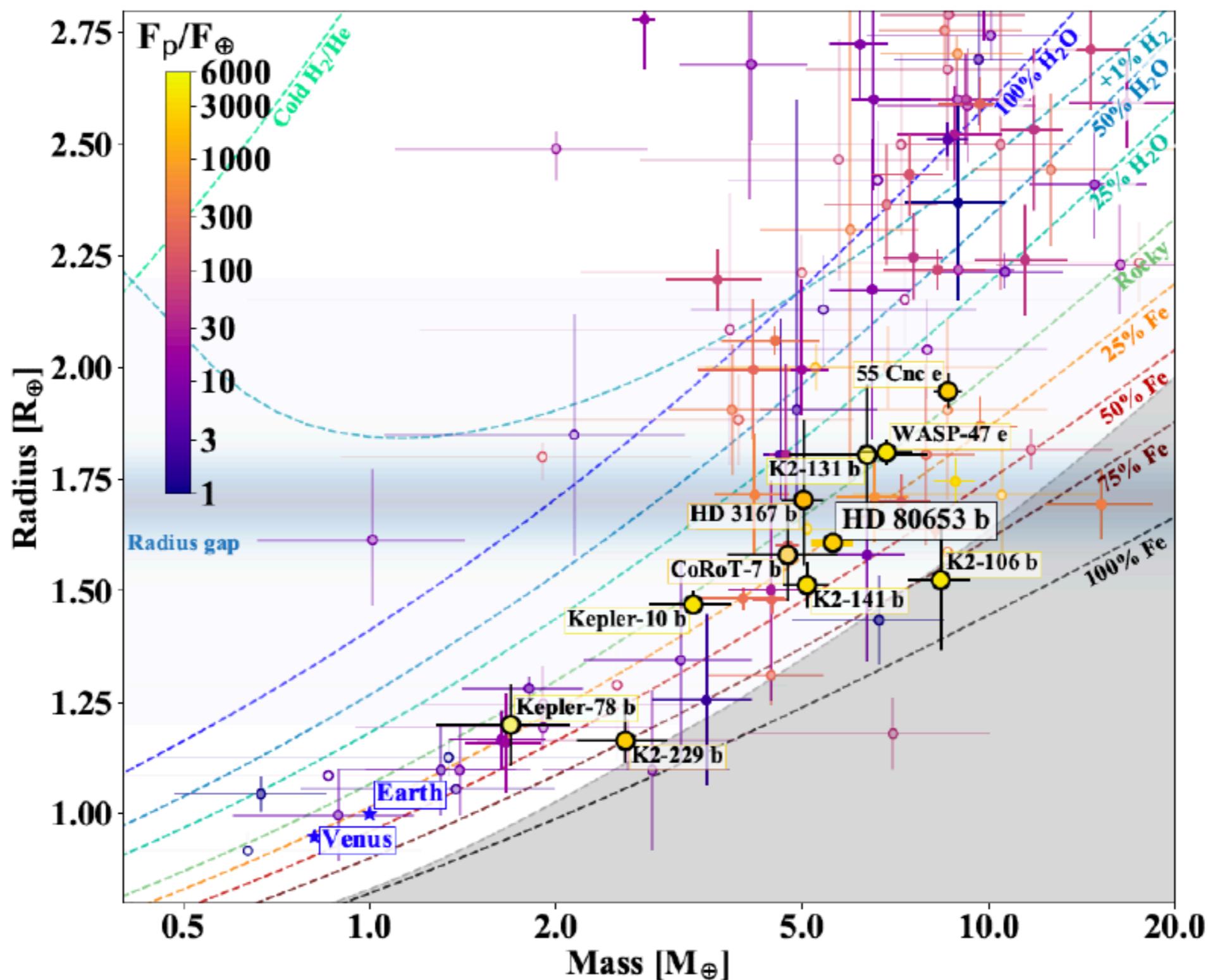


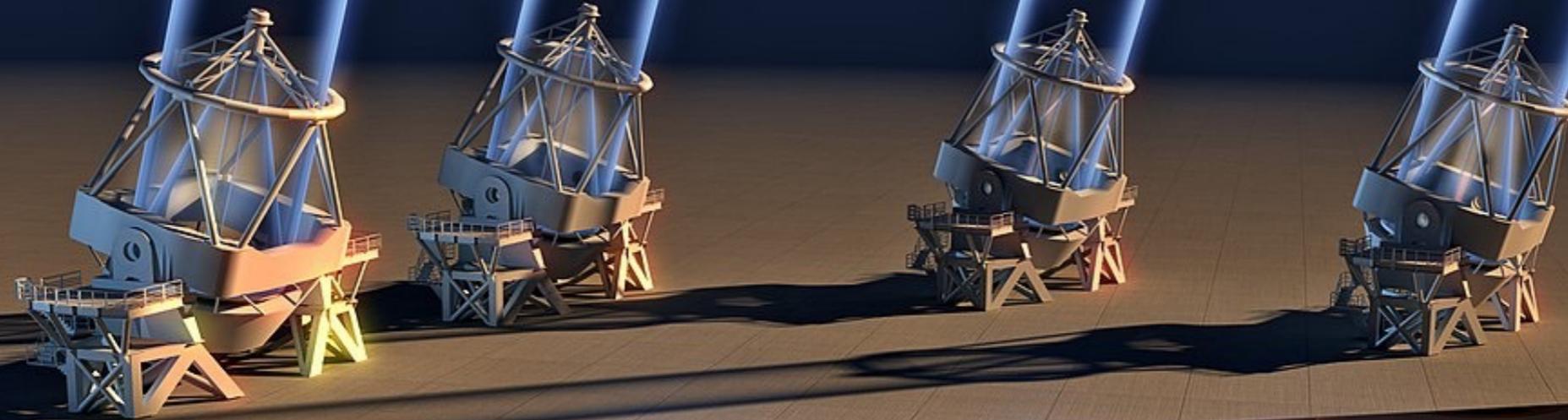
Fig. 11. Mass-radius diagram of planets smaller than $\sim 2.8 R_{\oplus}$. The data points are shaded according to the precision on the mass, with a full color indicating a value better than 20%. Earth and Venus are shown for comparison. The dashed lines show planetary interior models for different compositions as labelled (Zeng et al. 2019). Planets are color-coded according to the incident flux F_p , relative to the solar constant F_{\odot} . The horizontal light-blue shade centered on $R \sim 1.70 R_{\oplus}$ shows the radius Gap. The shaded gray region marks the maximum value of iron content predicted by



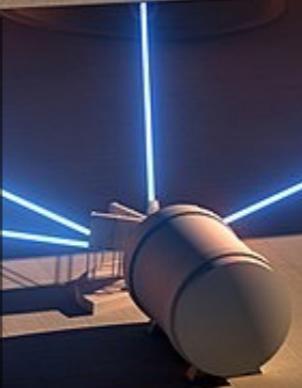
ESPRESSO : Un spectrographe pour la recherche des planètes similaires à notre Terre , ...sur un télescope de 16 mètres.,
P.I Prof.Francesco Pepe



Four 8-meter Unit Telescopes Very Large Telescope Paranal, Chile



Precision :
10 cm/s
Towards characterization of
Earth-type planets



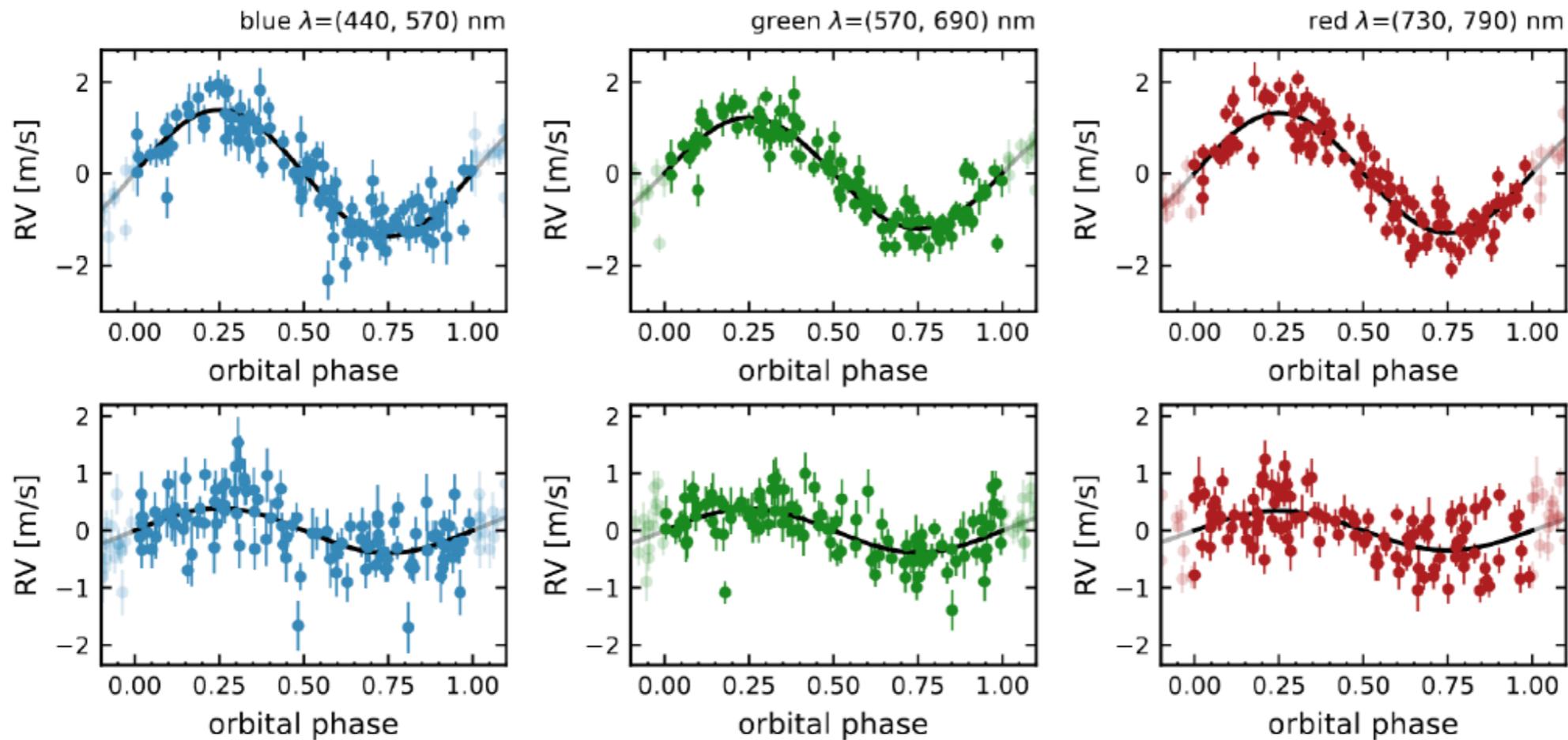
ESPRESSO
@Combined Coudé lab
380–780 nm
 $\lambda/\Delta\lambda=134,000$

A 3D rendering of the ESPRESSO spectrograph, a cylindrical instrument mounted on a base. It is illuminated by a blue beam of light from the left, which is reflected off its top surface. The spectrograph is positioned in the foreground, to the right of the text block.

Proxima Centauri , **ESPRESSO** measurements of the 2 inner planets,

Proxima b $P = 11$ d Anglada-Escudé et al. 2016

Proxima d $P = 5.12$ d Faria et al. 2022 Mass = 0.26 Earth.mass



A composite image featuring a bright, orange-hued star in the upper left quadrant and a detailed view of the Earth from space in the lower right quadrant. The Earth shows green continents, blue oceans, and white clouds. The background is a dark field of stars.

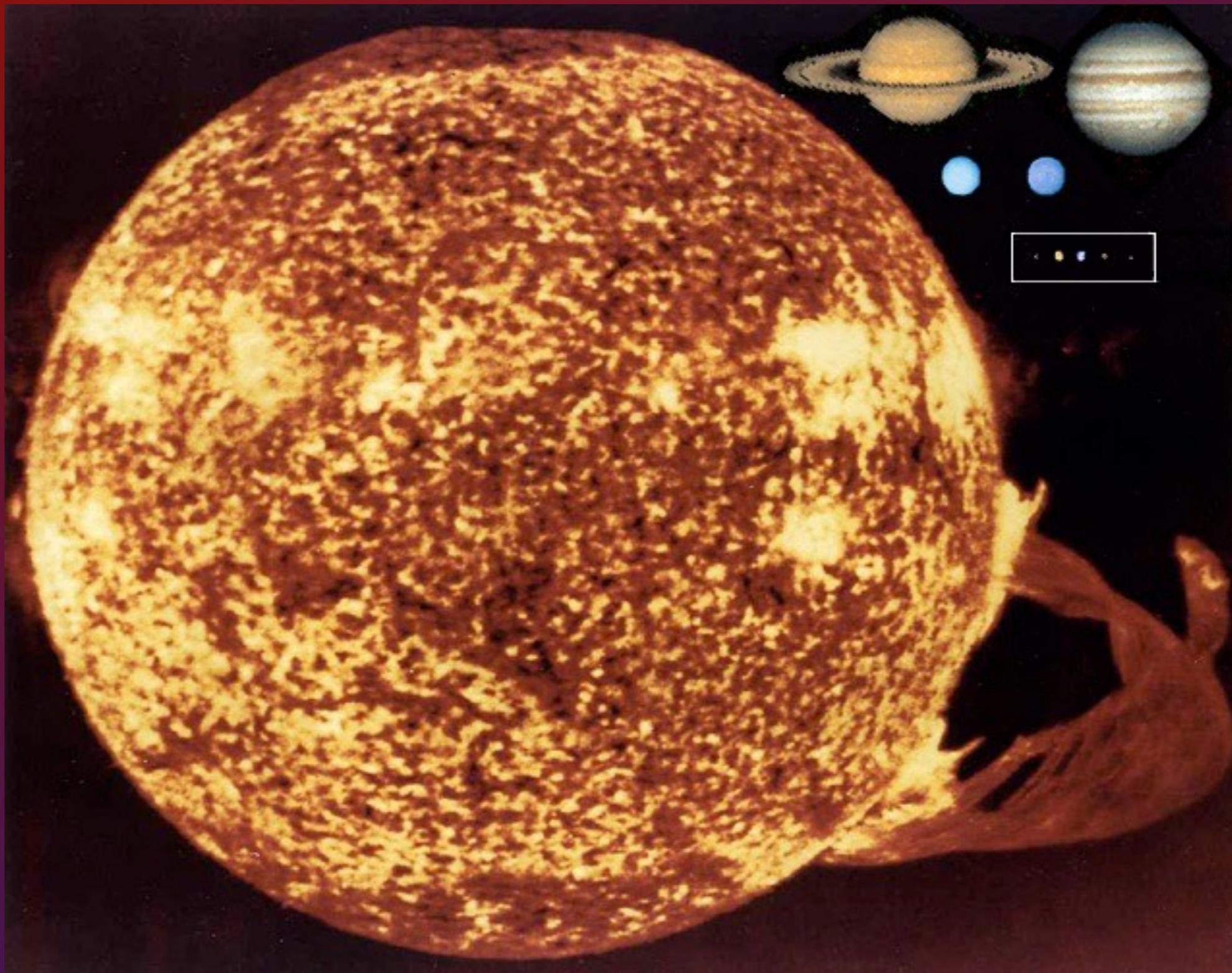
Des analogues de la Terre ?

De la vie ?



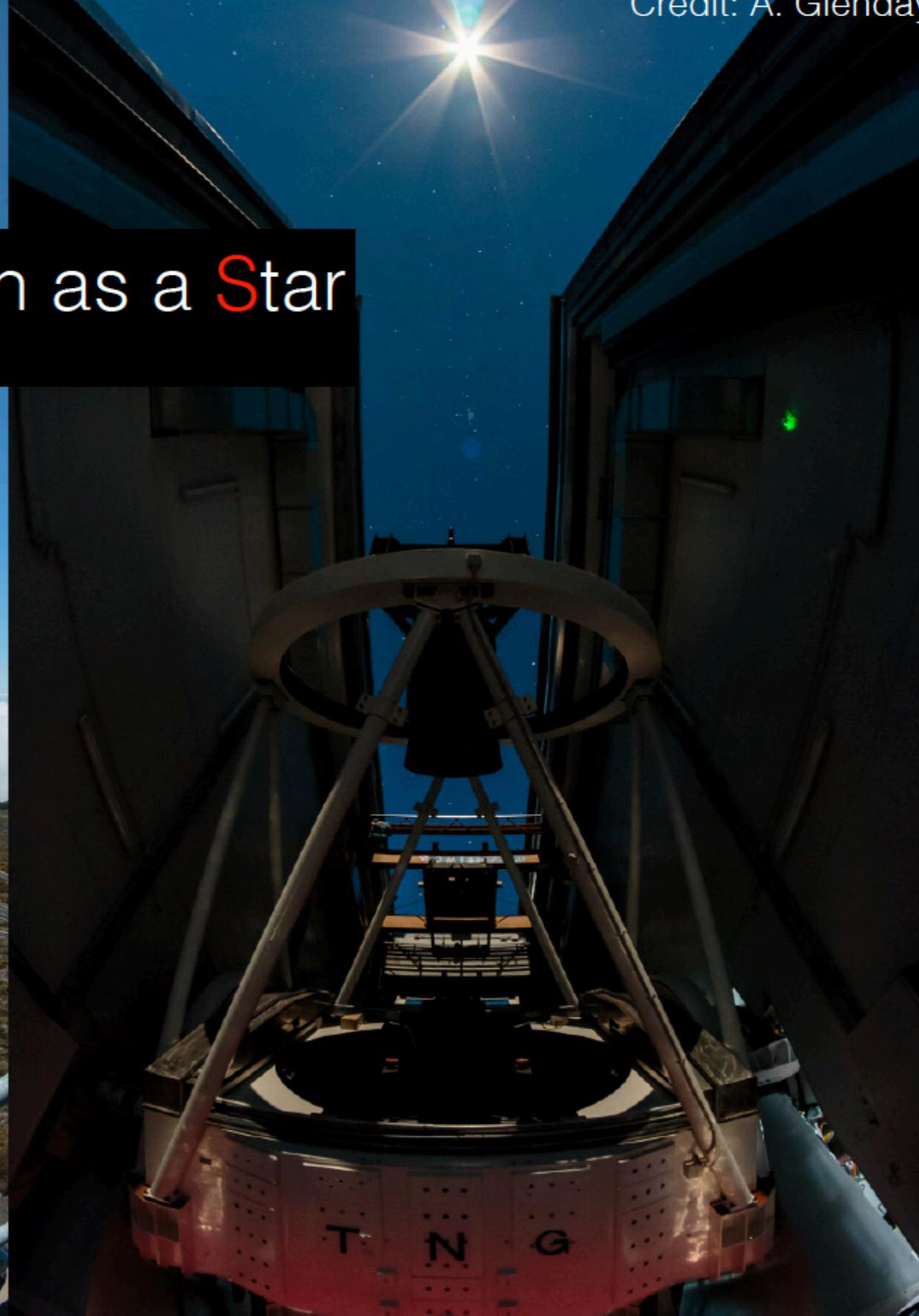
*En route pour la prochaine
« révolution copernicienne »*

*La vie est-elle un « impératif
cosmique » ?*

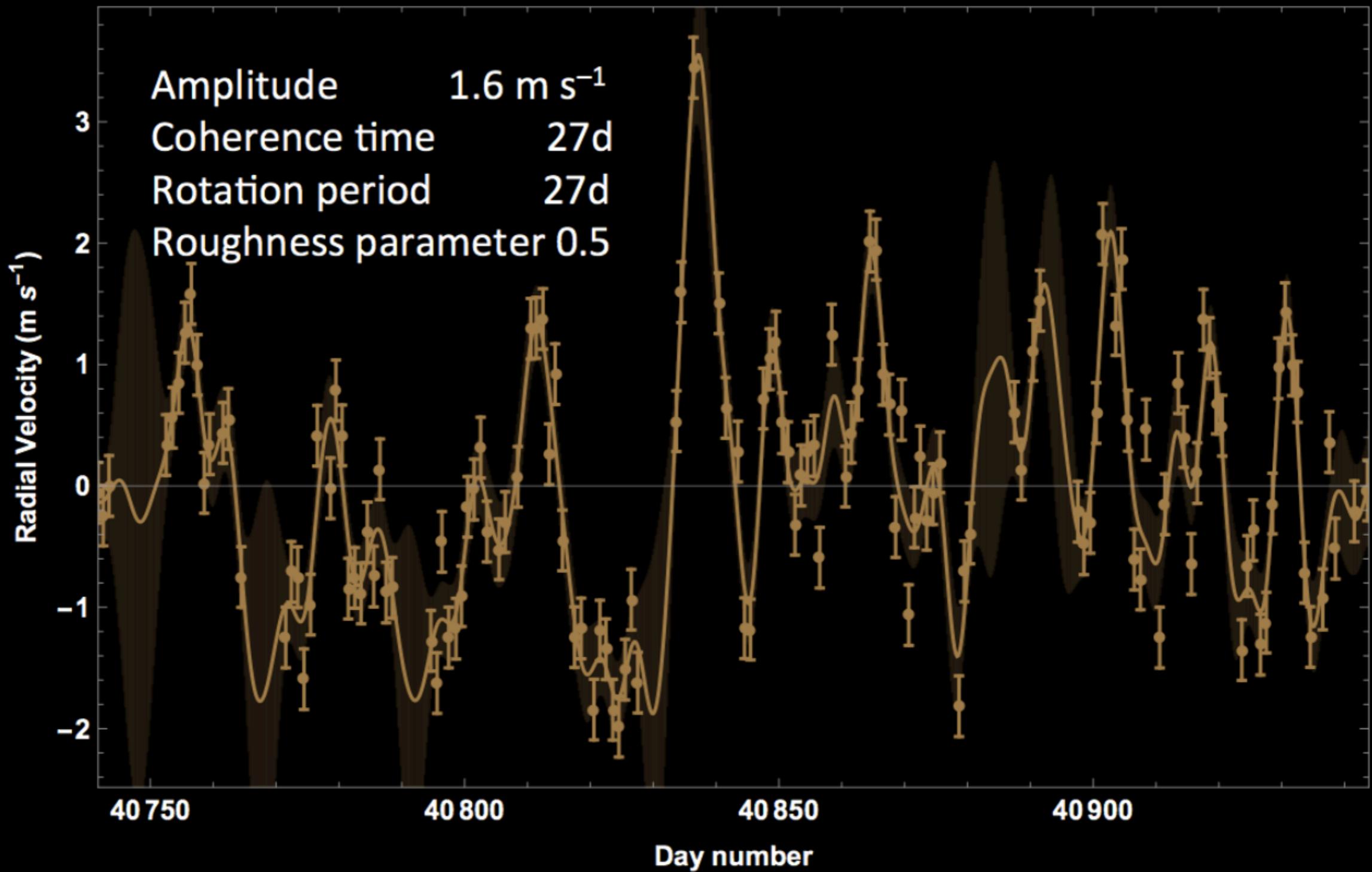


HARPS-N Observes the Sun as a Star

X. Dumusque et al. 2017

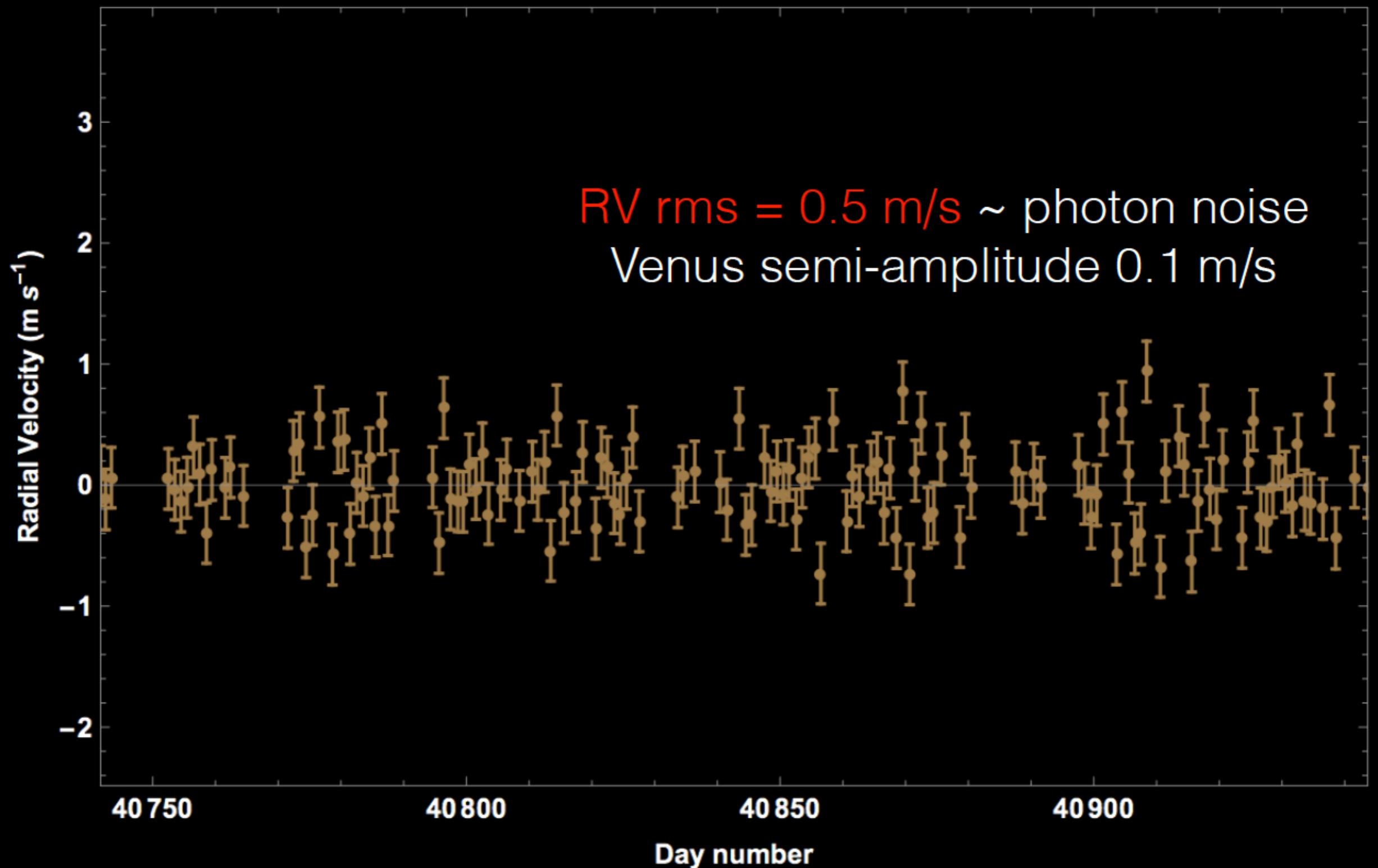


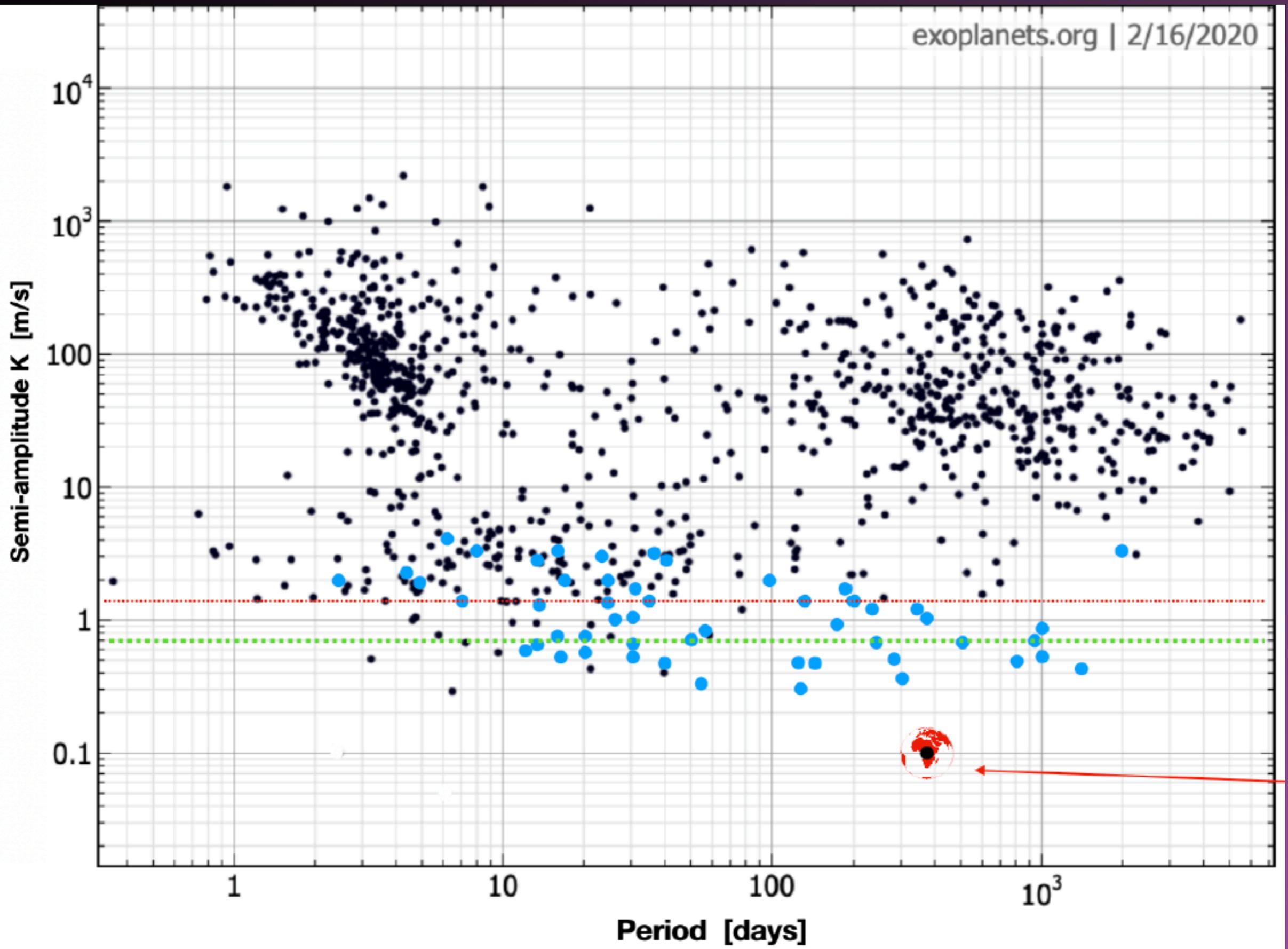
Gaussian Process Regression

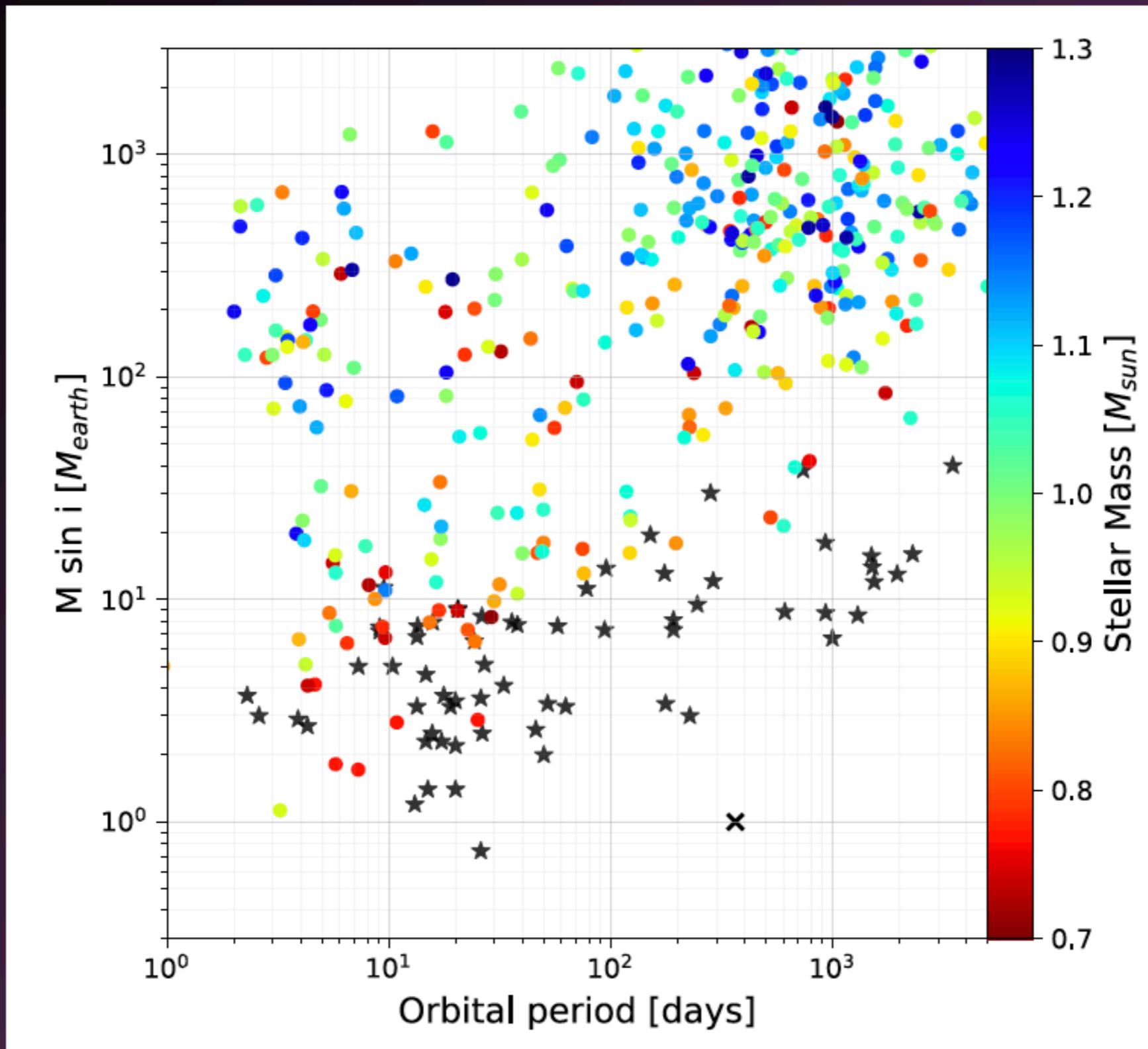


A. Collier Cameron

Residuals after Gaussian Process Regression

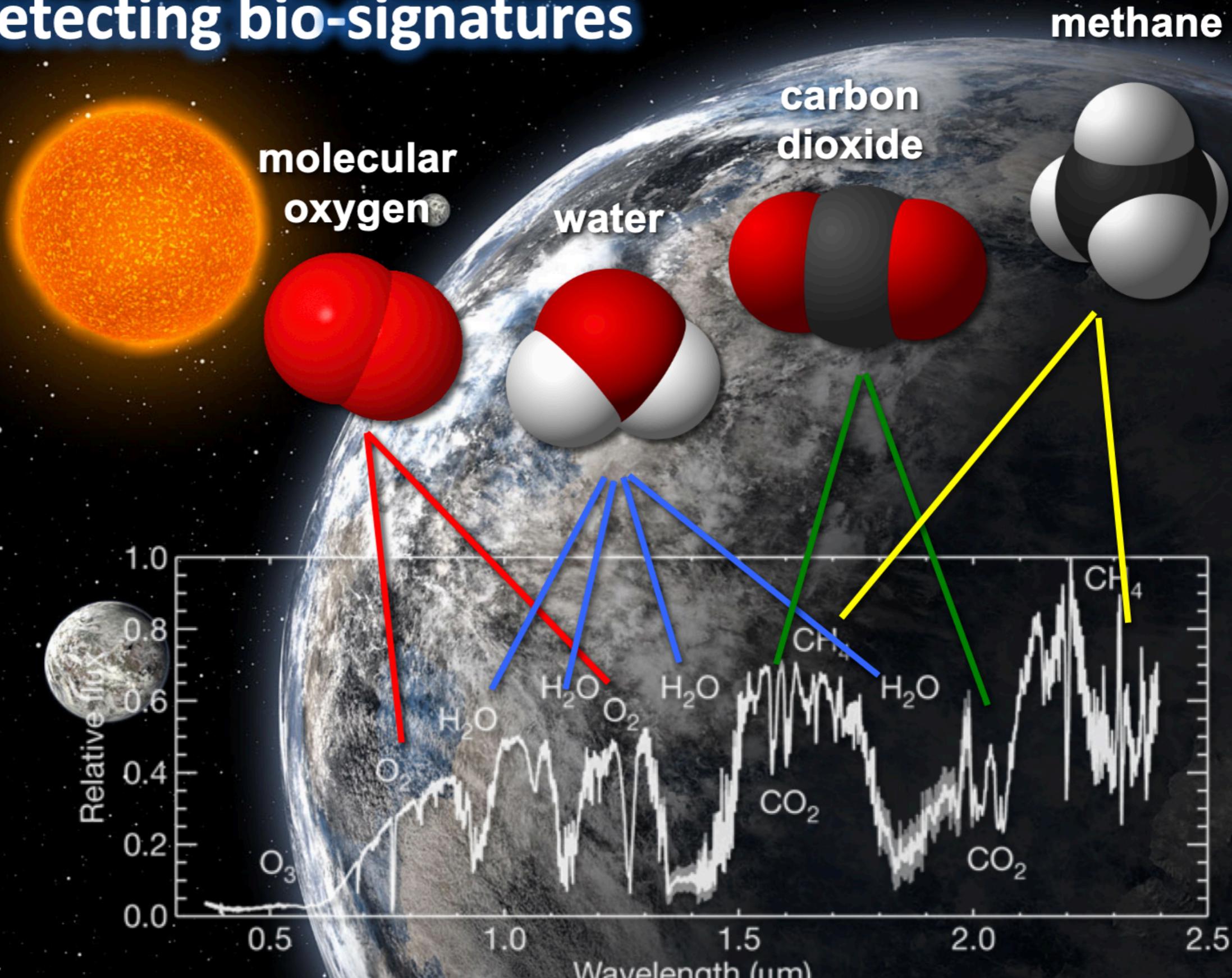






Cretignier 2022 , PhD (HARPS measurements , "*" New low mass candidates detected with the Yarara software)

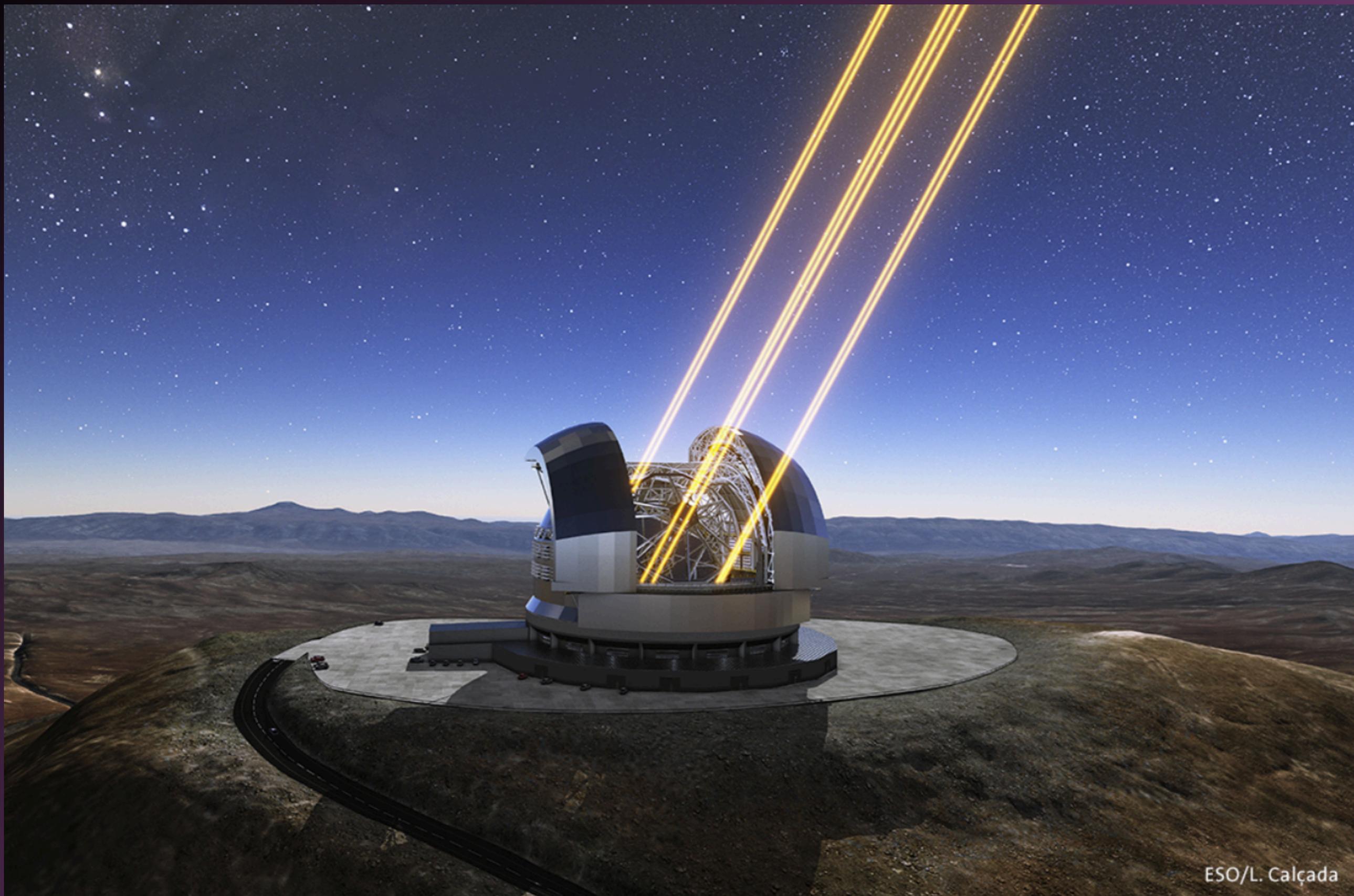
Exoplanets atmospheres, with the ultimate goal of detecting bio-signatures



E-ELT Un telescope ESO, diamètre 39 m

Cerro Armazones, Chile, 2026





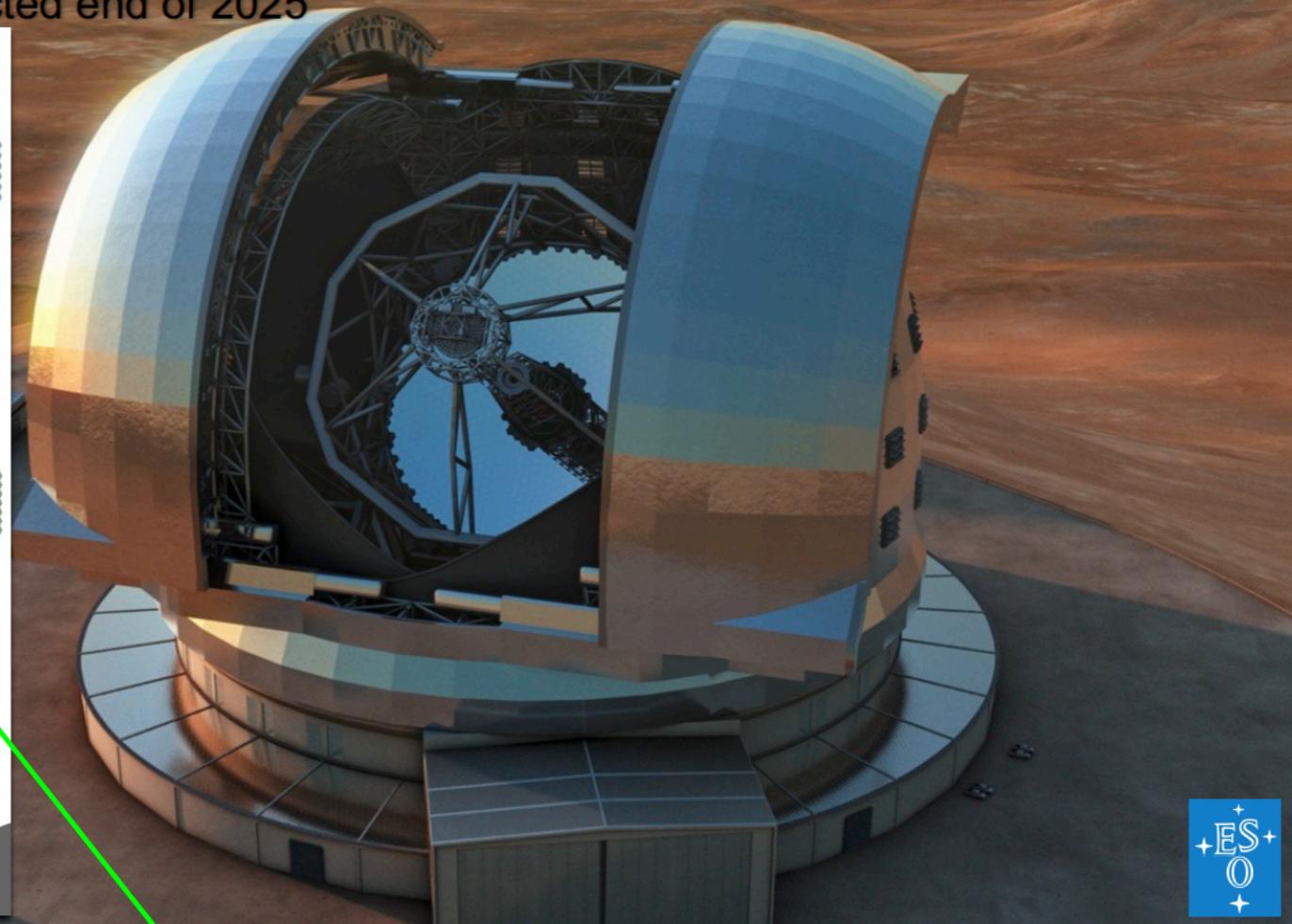
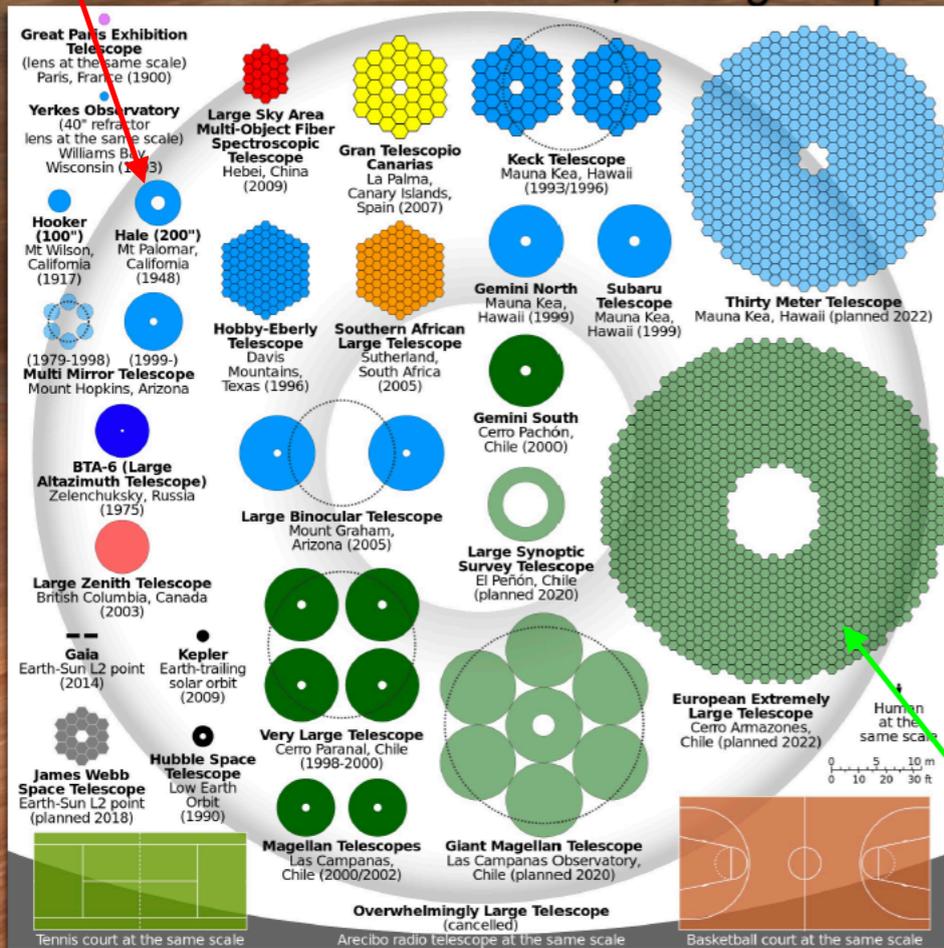


Palomar 5.08 m (1948)

Largest optical/infrared telescope in the world

- 39-m segmented primary mirror
- fully AO assisted telescope
- On Cerro Armazones, integral part of the Paranal system
- Construction started 2015, first light expected end of 2025

The European ELT



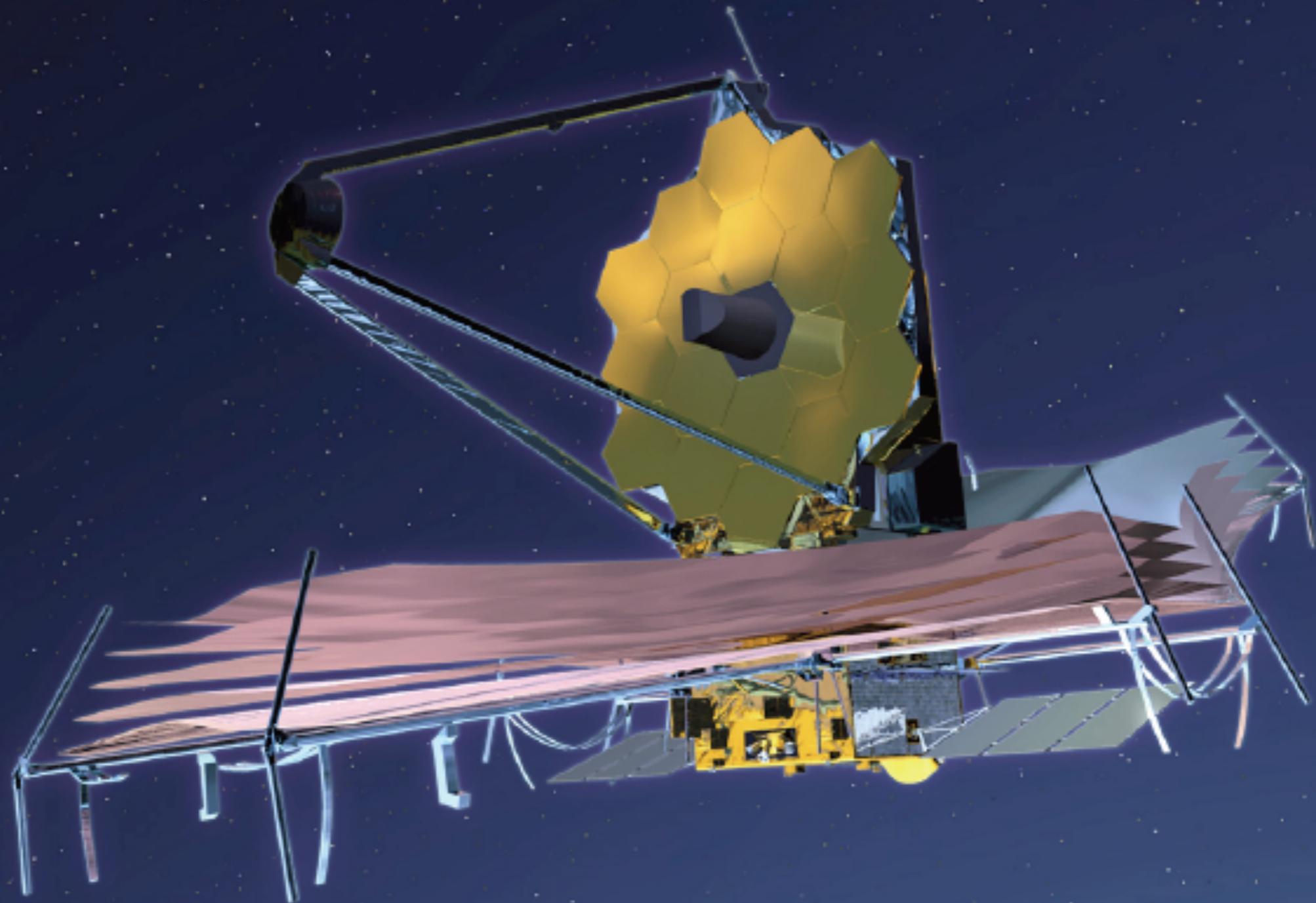
ESO ELT 39 m (2028)

Juin 2023



Credit :ESO

JWST



Merci

