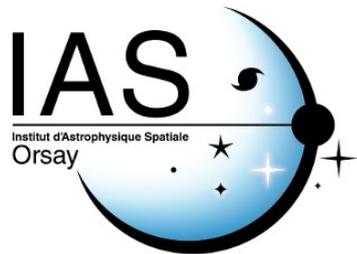


Observatoire de la Côte d'Azur

Nice – 8 avril 2014

Les exoplanètes découvertes par Corot



Pascal Bordé
Institut d'astrophysique spatiale
Université Paris-Sud



La mission spatiale Corot

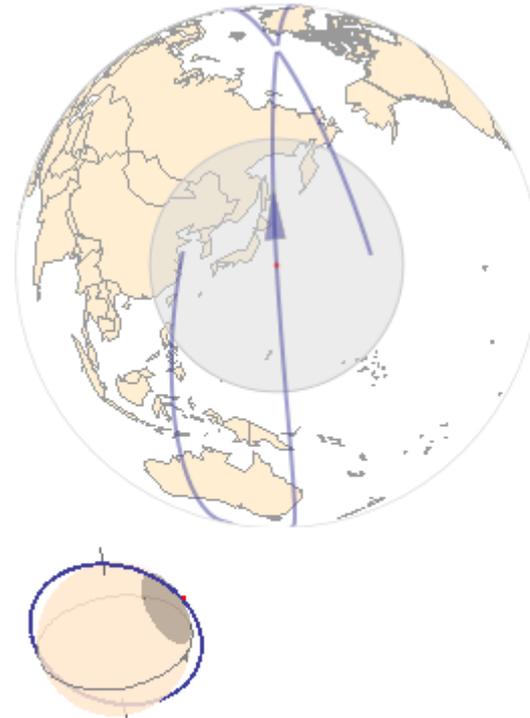


- Mission spatiale du CNES + partenaires européens + Brésil (165 M€)
- Objectifs : sismologie stellaire & détection d'exoplanètes
- Lancée le 27 déc. 2006, fin des observations le 2 nov. 2012
- Masse totale : 626 kg
- Orbite polaire basse : 900 km
- Télescope de 27 cm, champ de $3,5^\circ \times 2,8^\circ$, 4 détecteurs CCD

Lancement et orbite du satellite



Orbite polaire : 900 km ; 1h 43 min

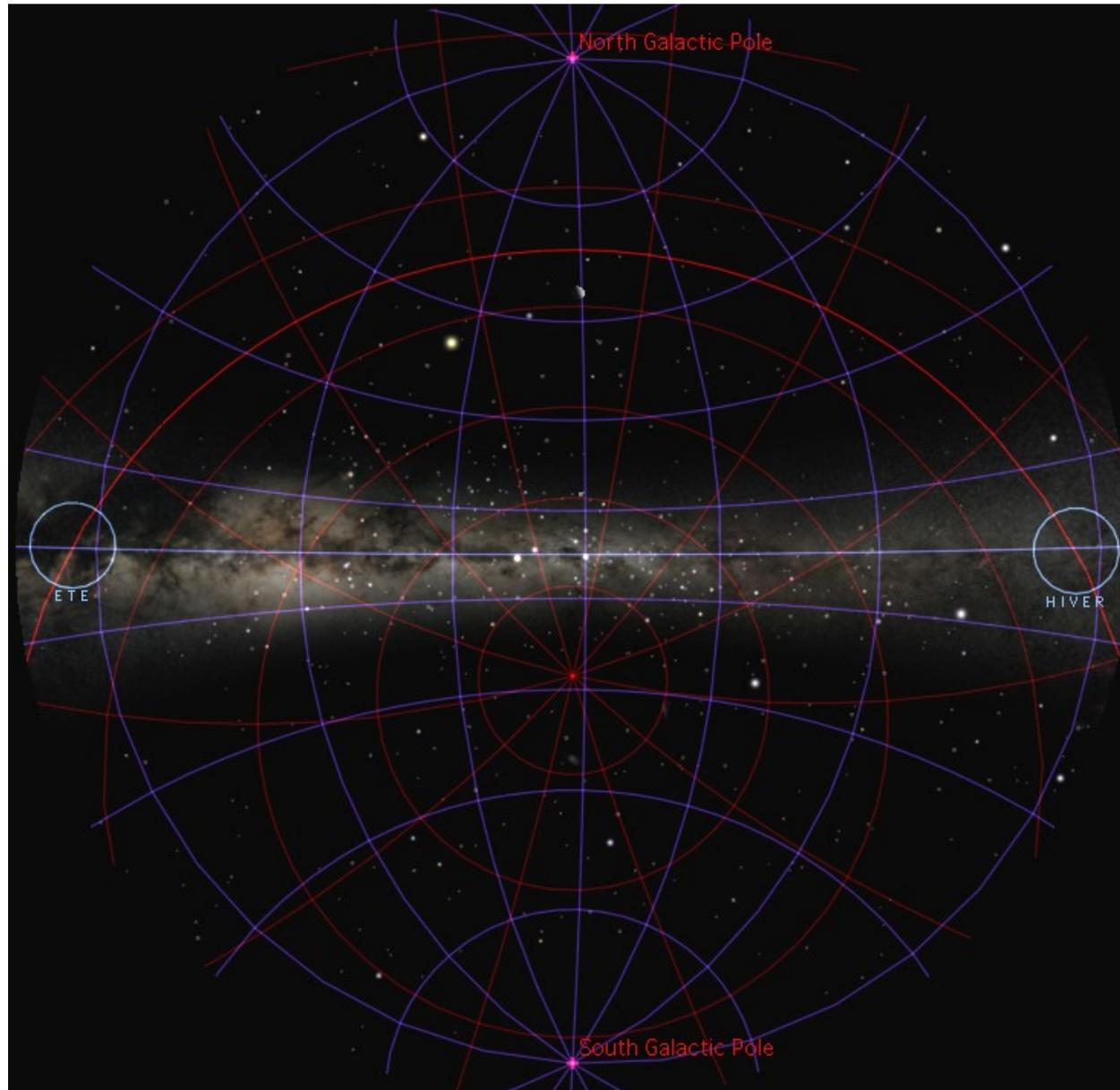


 **WolframAlpha**™ computational...
knowledge engine

Lancement depuis Baïkonour par une fusée Soyouz le 27 décembre 2006

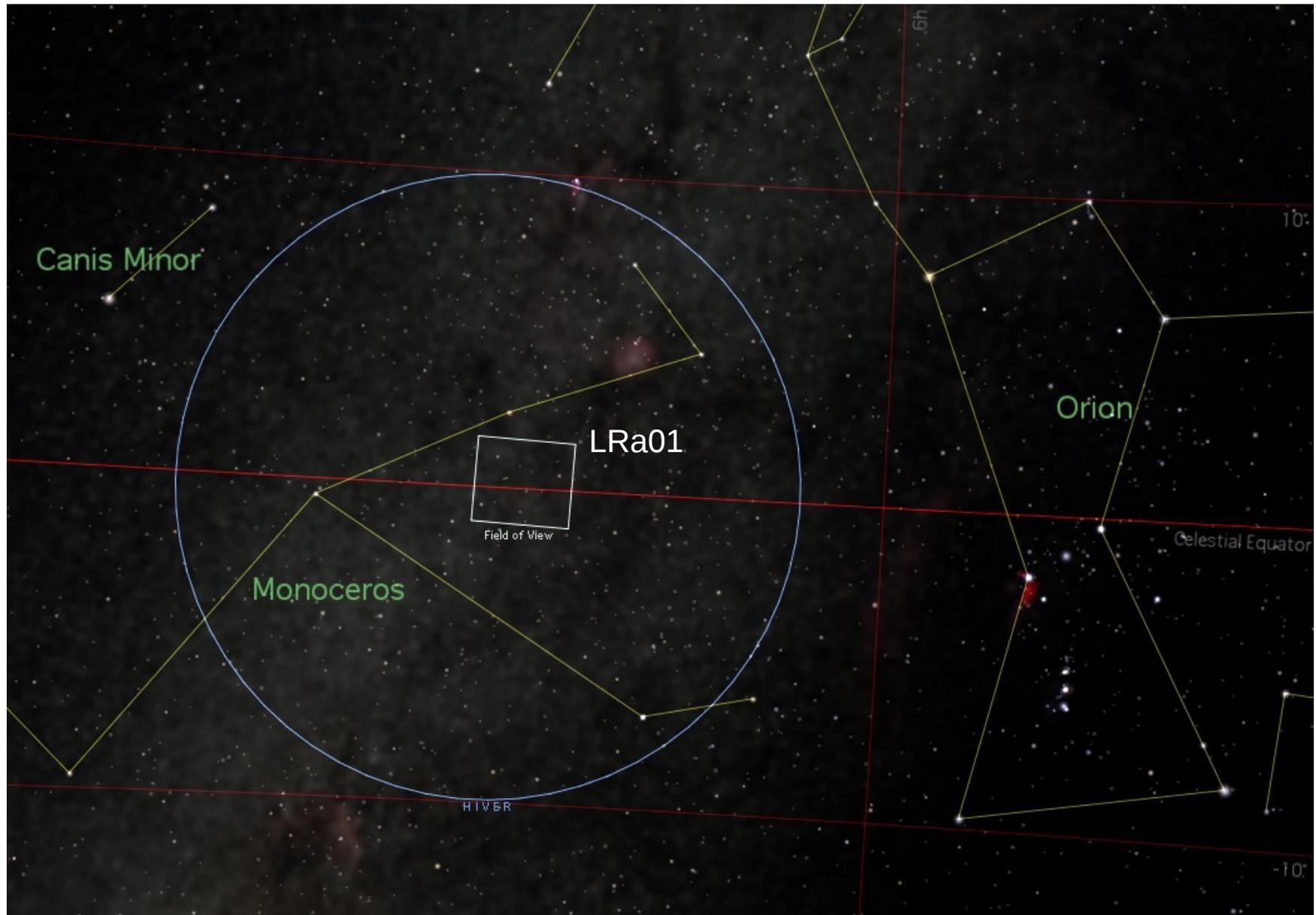
Les « yeux » de Corot

Aigle

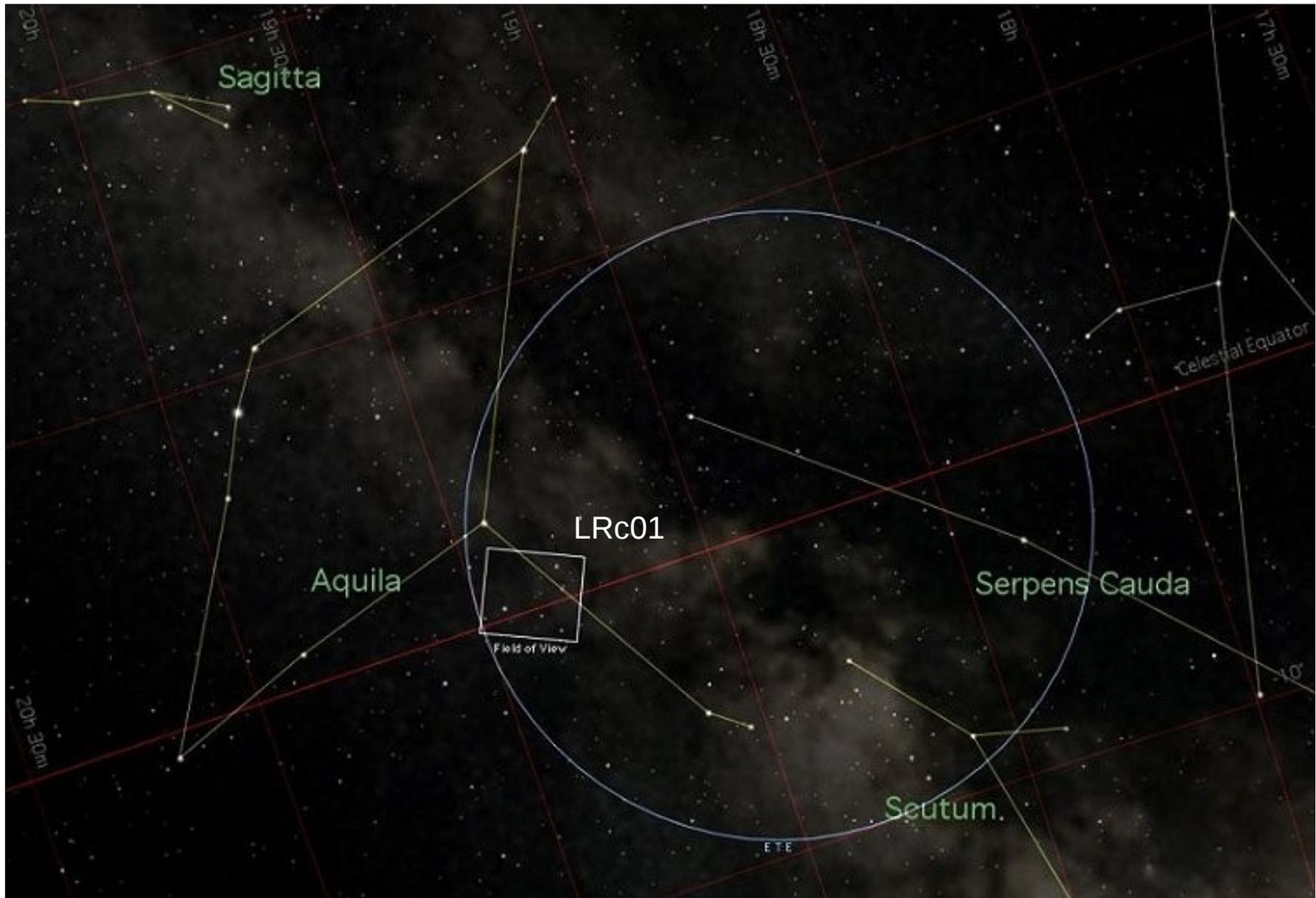


Licorne

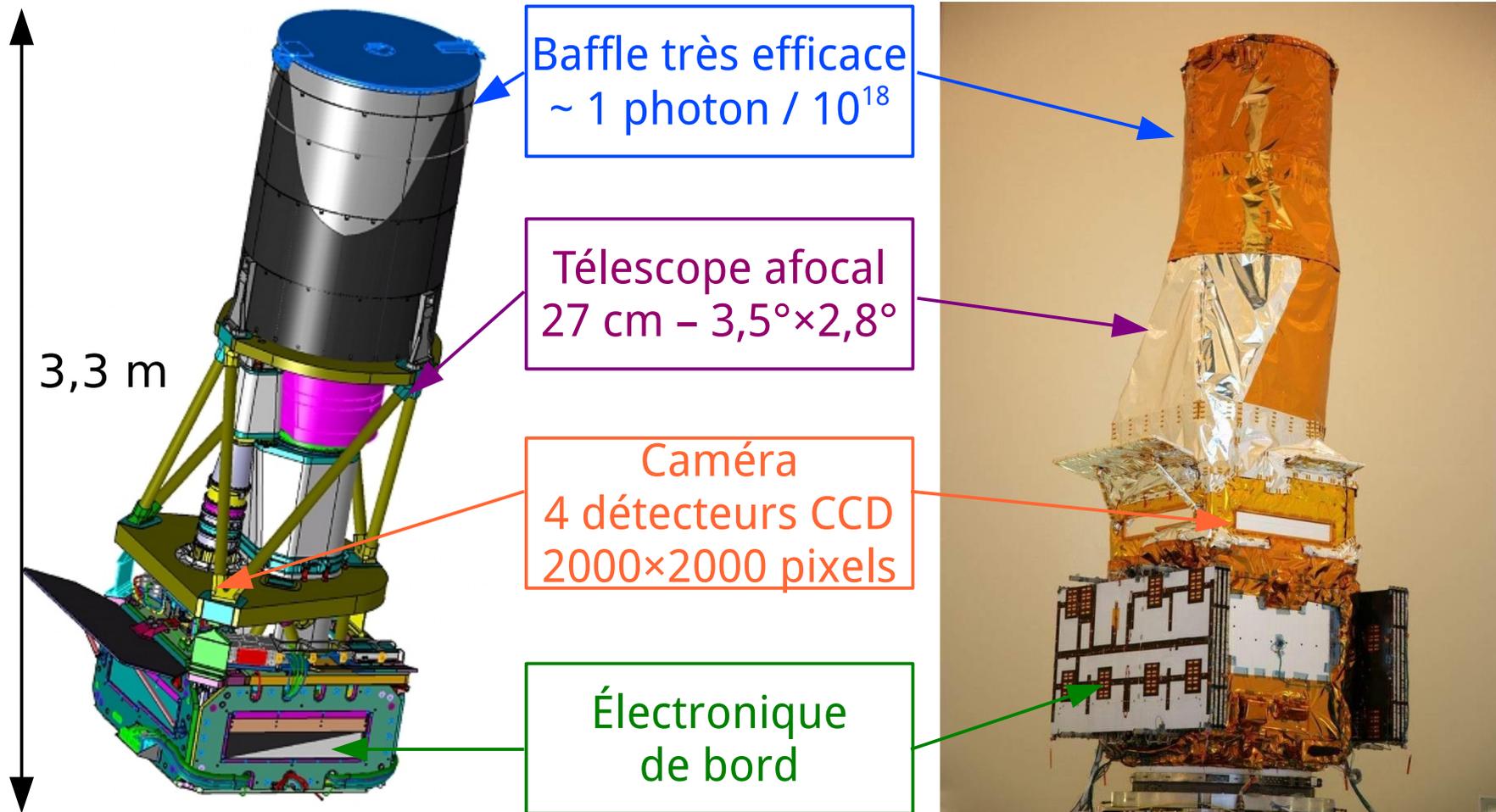
En hiver, la Licorne...



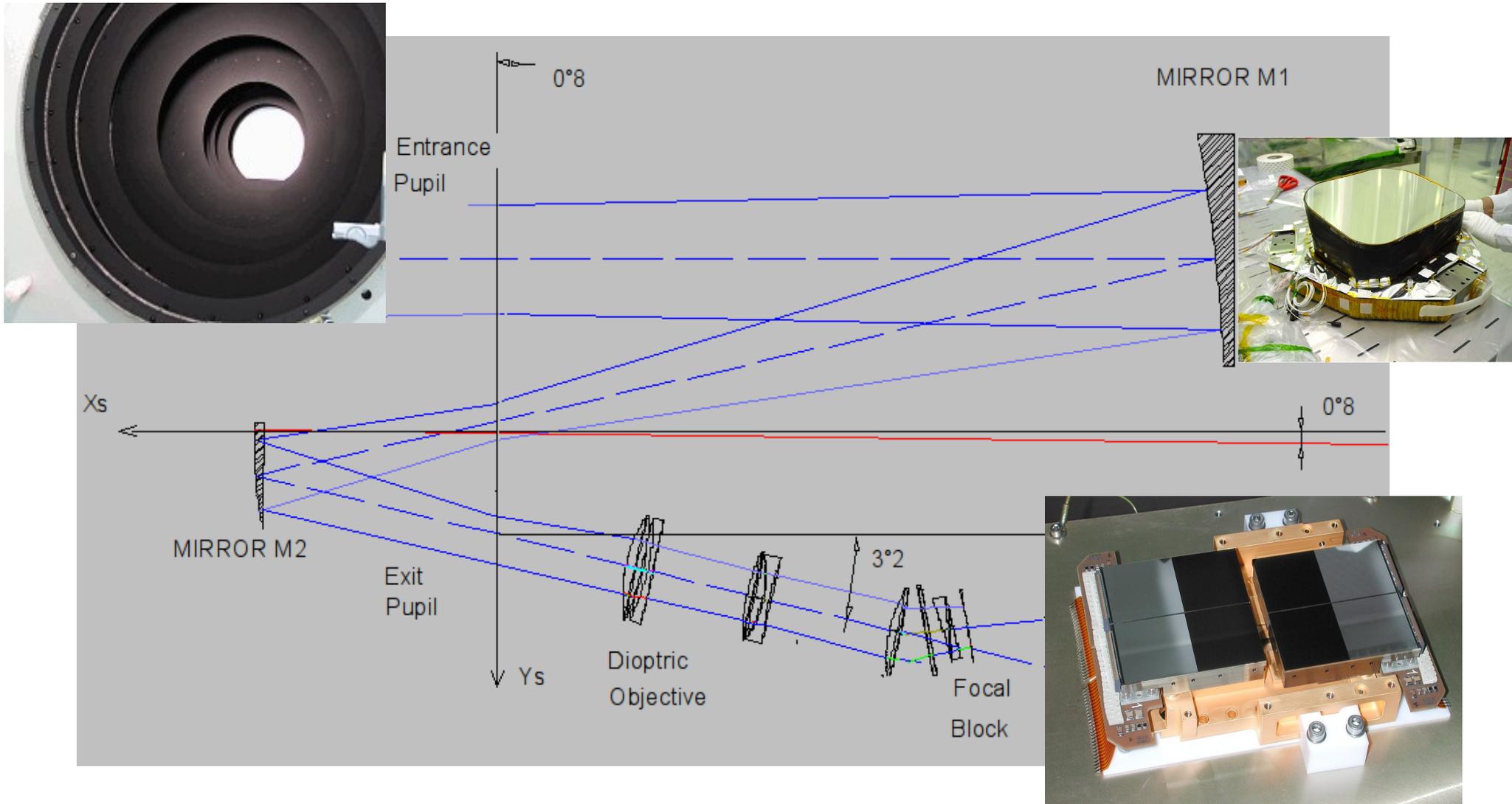
... et l'Aigle en été.



L'instrument Corot

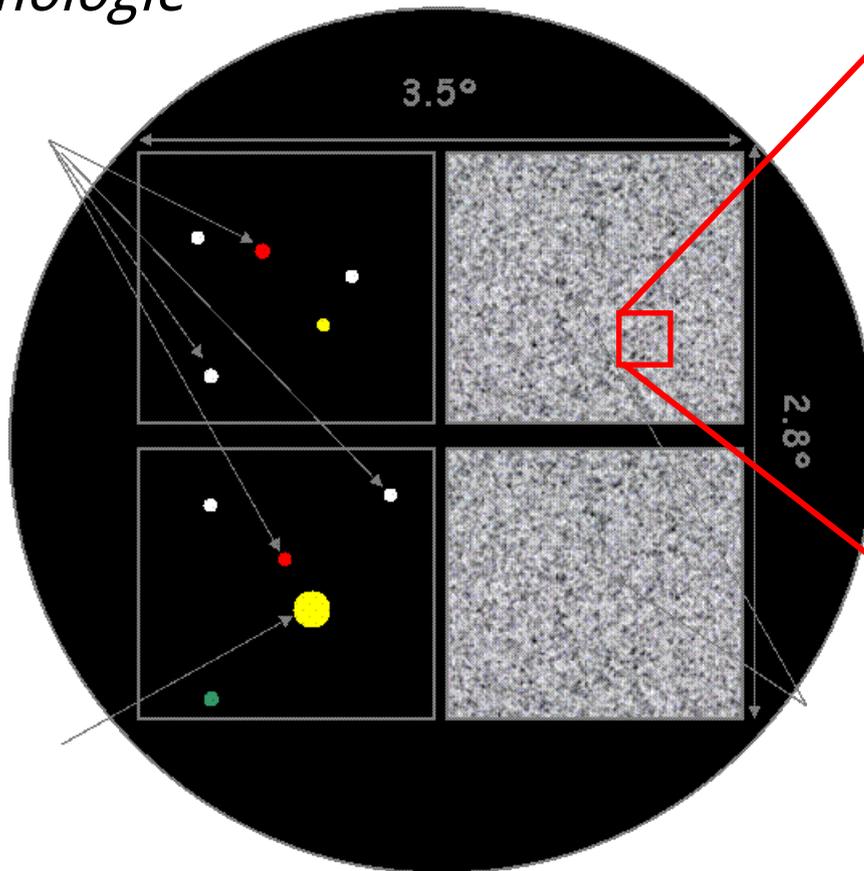


Trajet de la lumière dans Corot

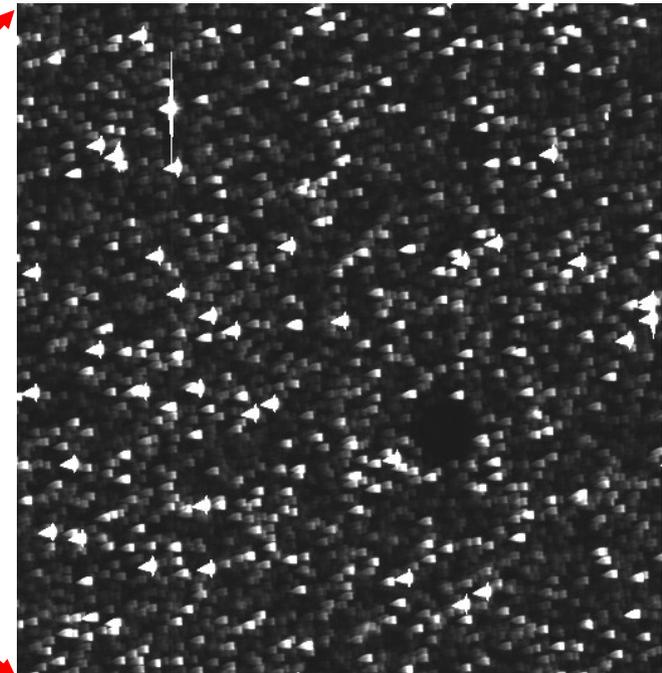


Le ciel vu par Corot

Voie *Sismologie*



Voie *Exoplanètes*

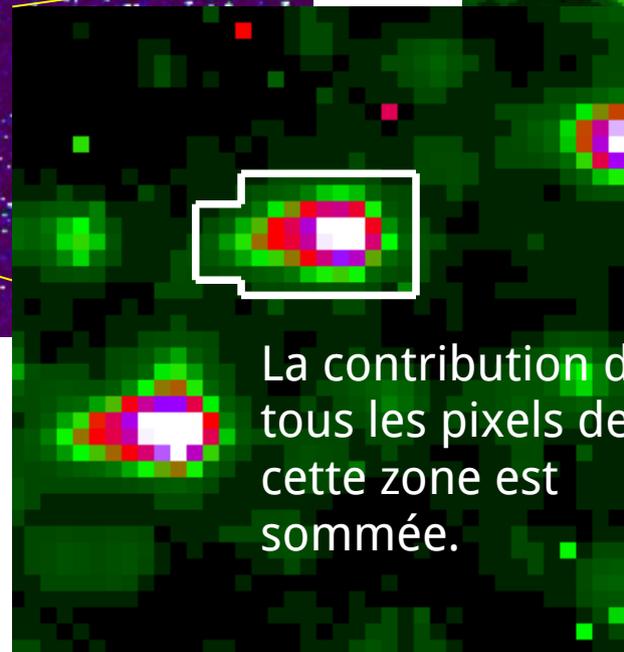
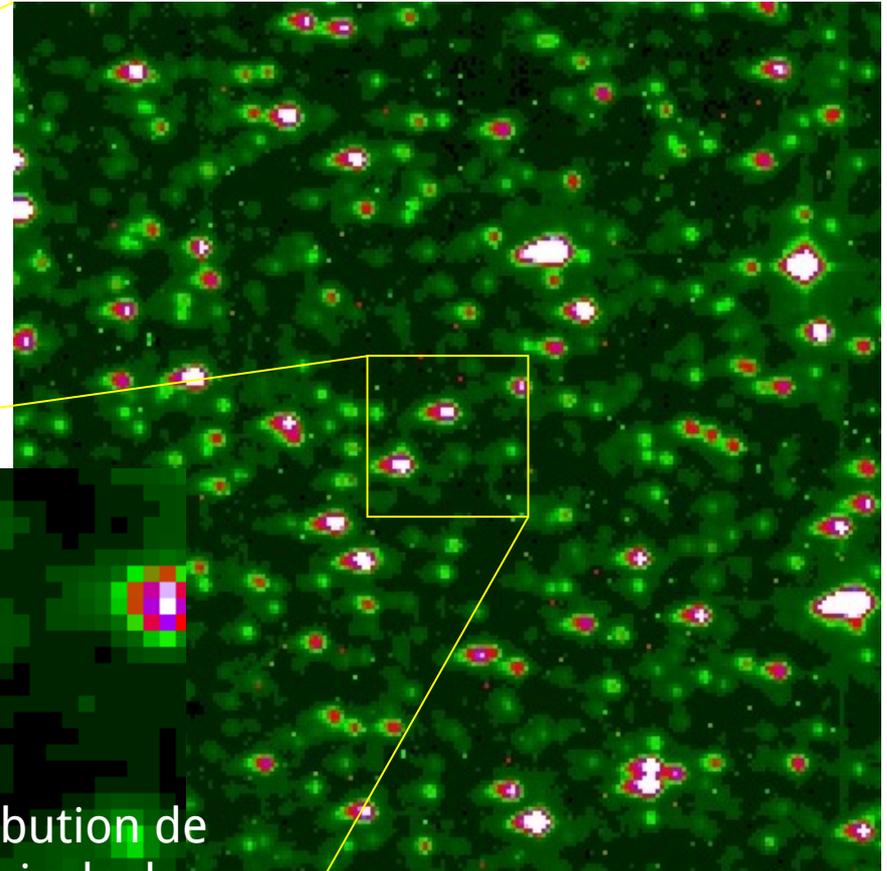
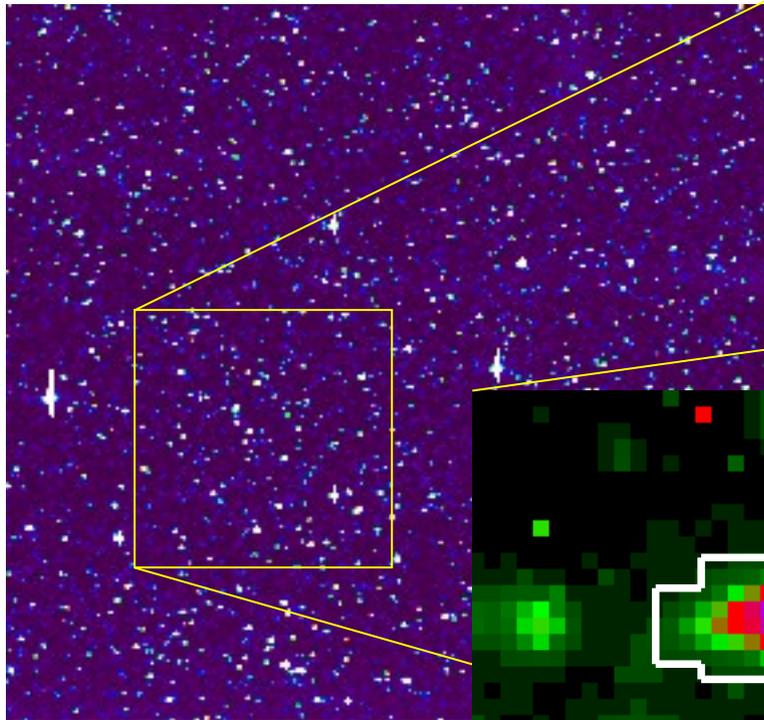


Env. 12 000 étoiles
simultanément mesurées

Image défocalisée (sismo)
ou dispersée (exo)

La photométrie : de l'image...

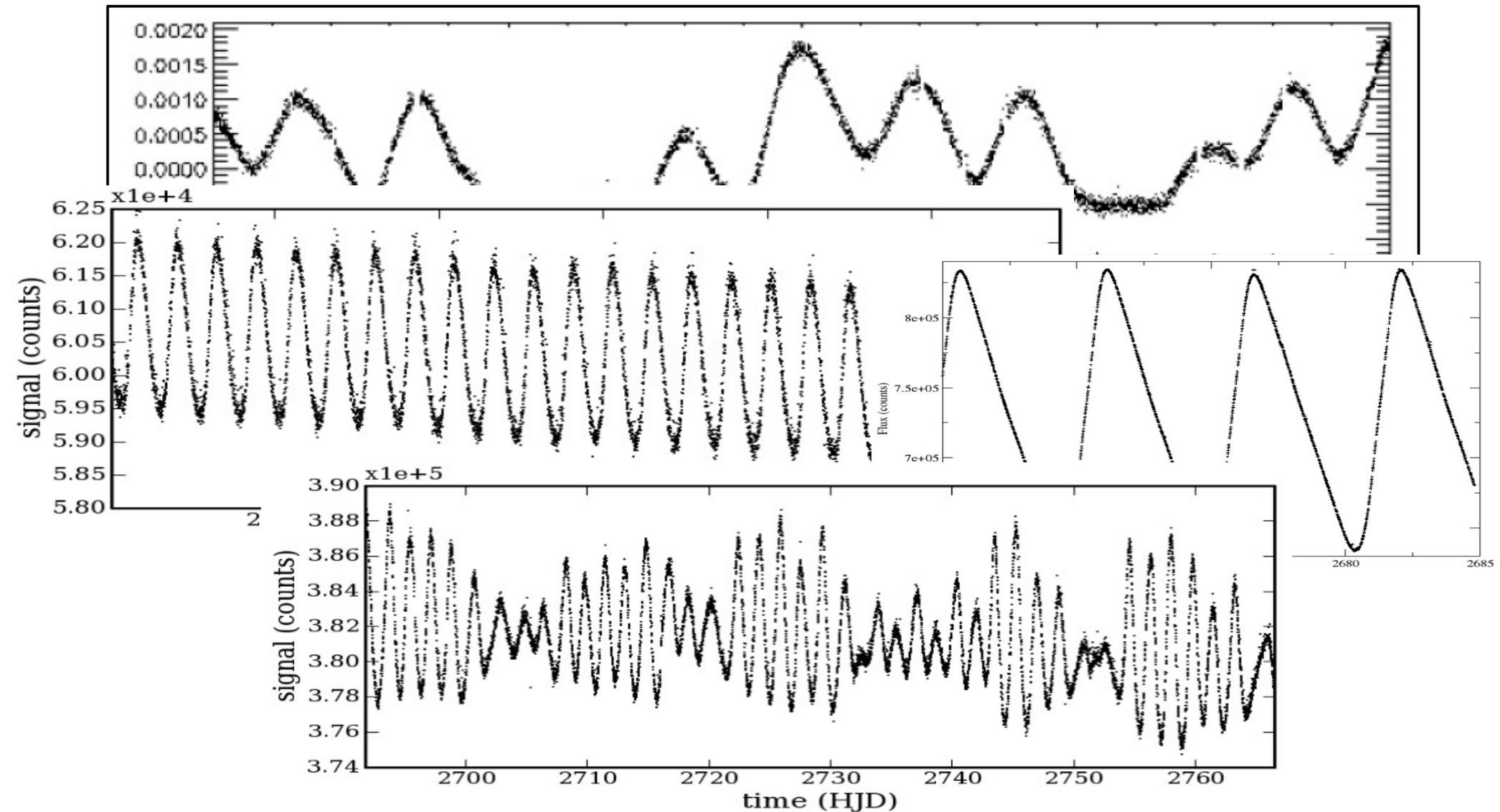
Une image toutes les 32 s



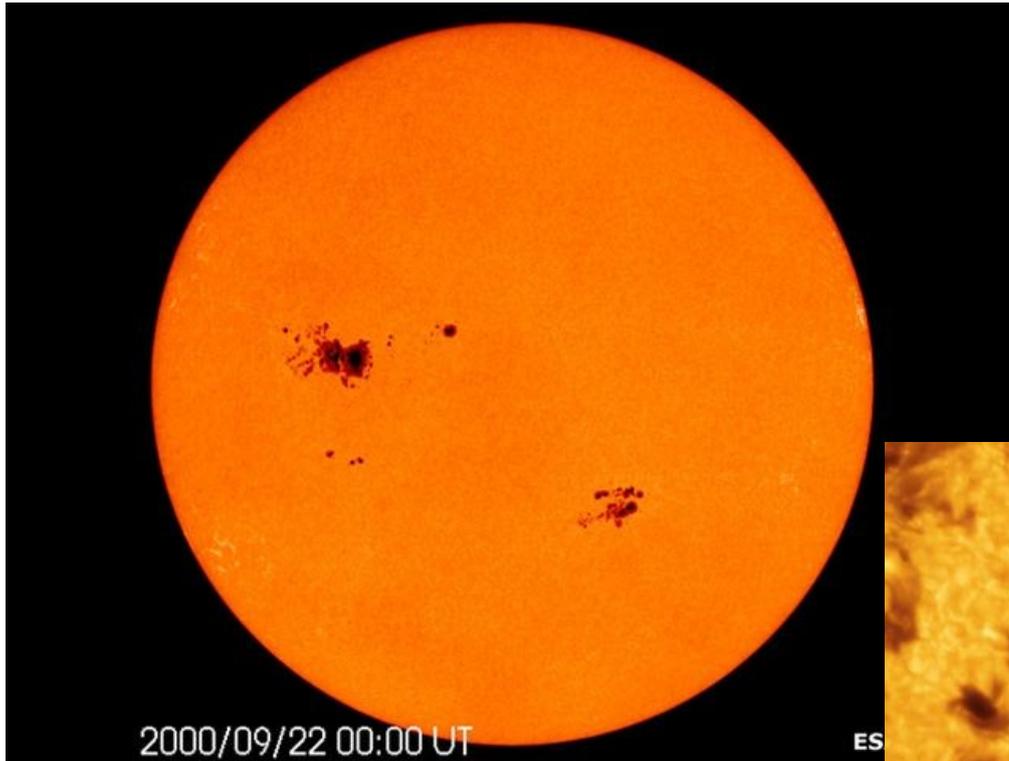
La contribution de
tous les pixels de
cette zone est
sommée.

... à la courbe de lumière

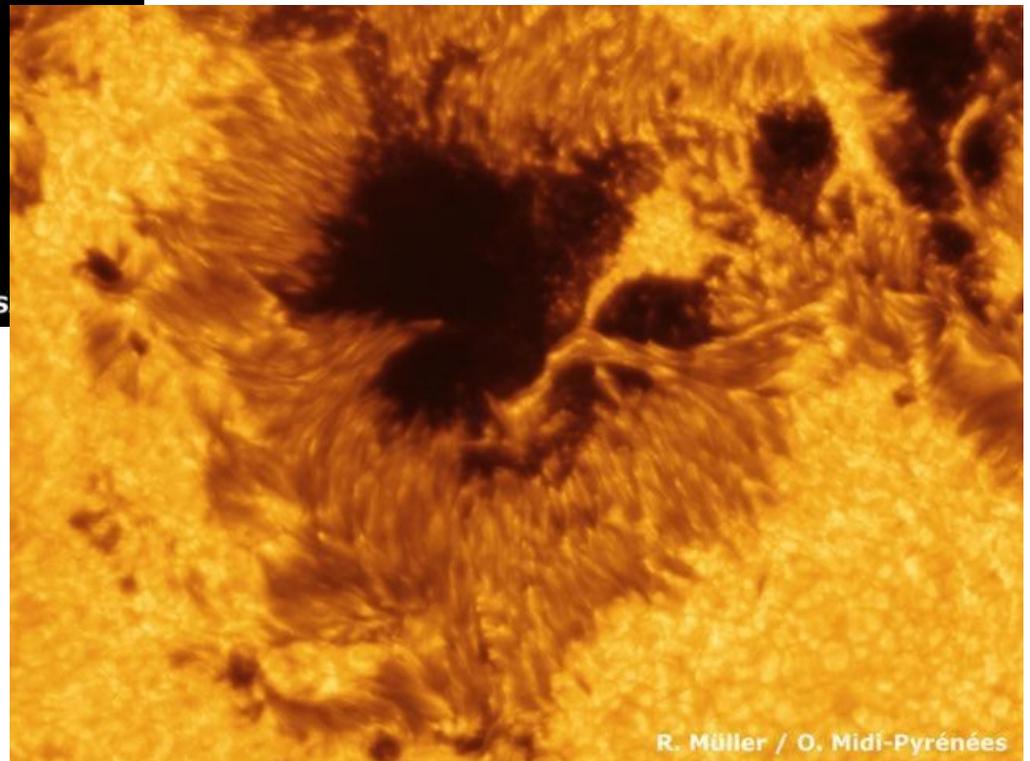
Pour chaque étoile : 1 point de mesure toutes les 8,5 minutes



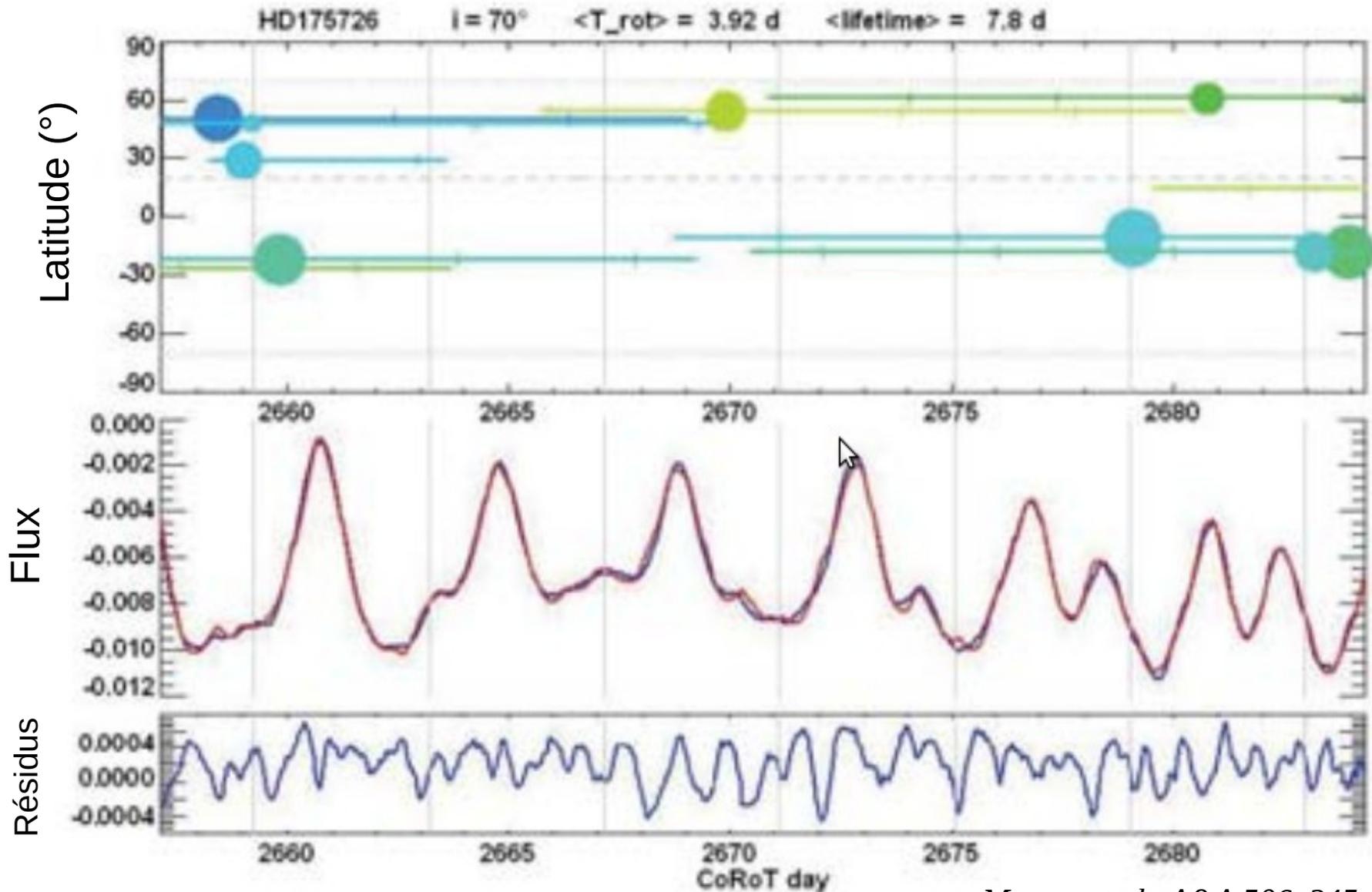
Activité magnétique des étoiles



Taches solaires

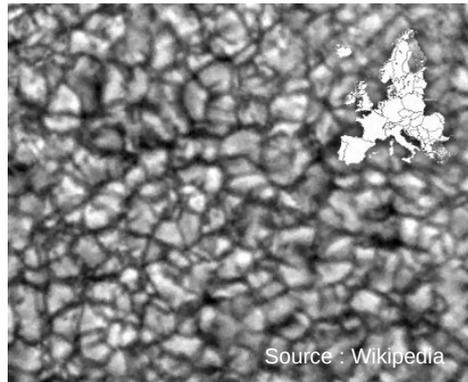


Taches stellaires et rotation

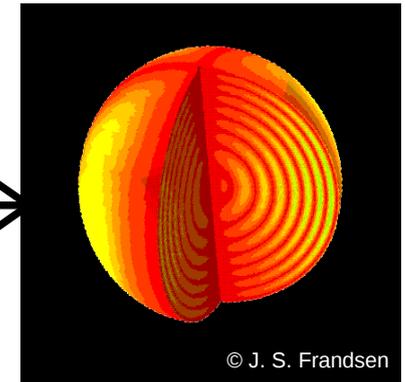
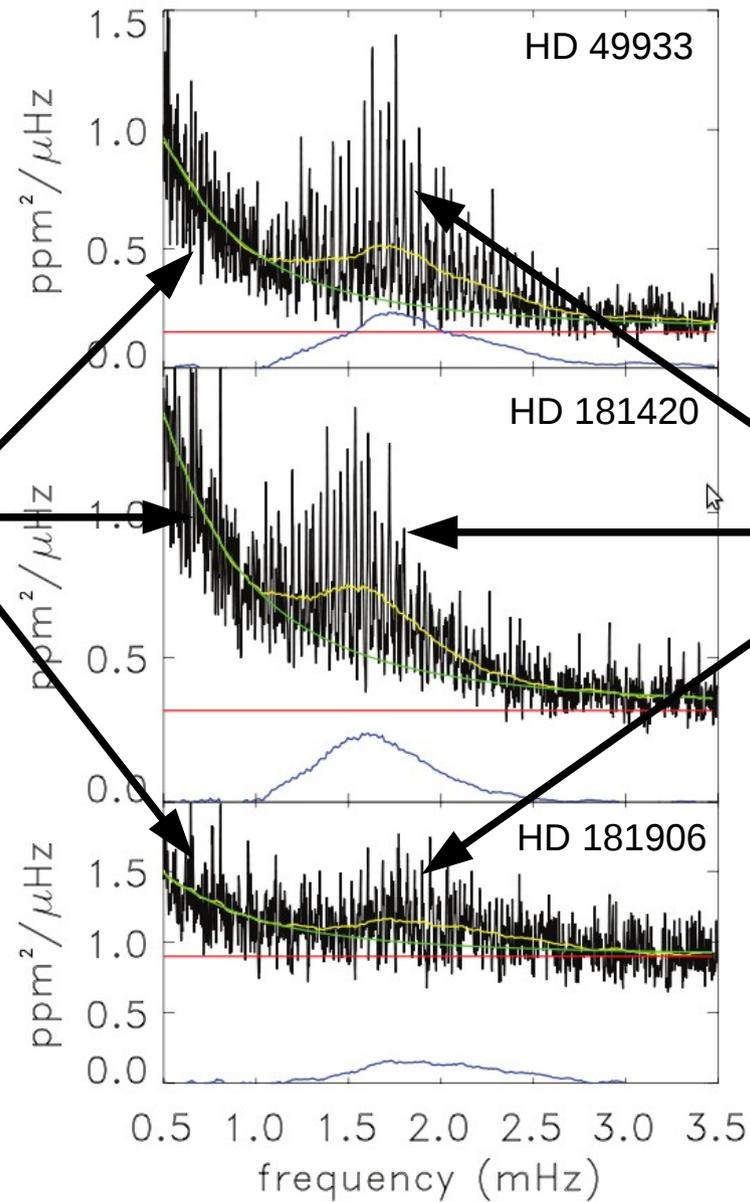


Mosser et al., A&A 506, 245 (2009)

Sismologie stellaire



granulation

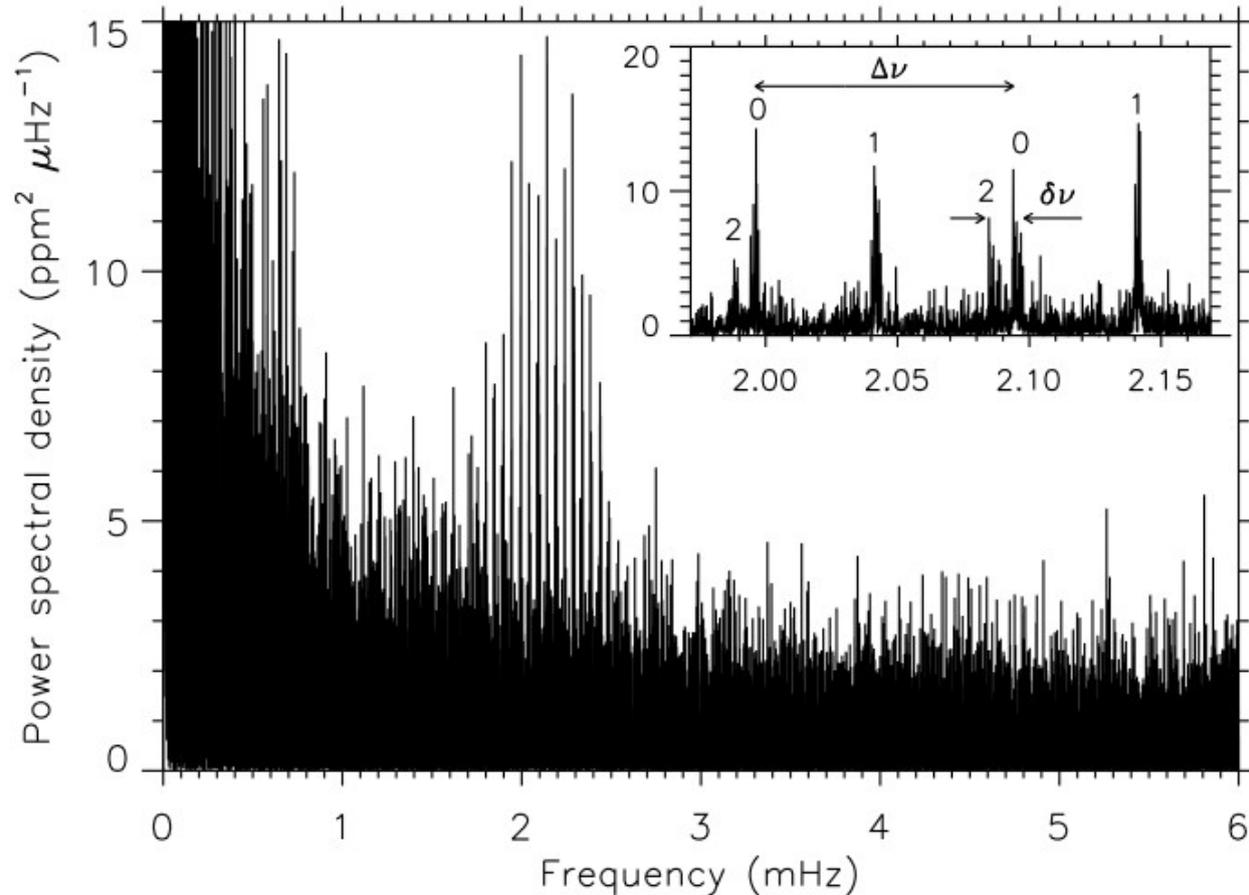


oscillations

Michel et al., Science 322, 558 (2008)

Sismologie stellaire

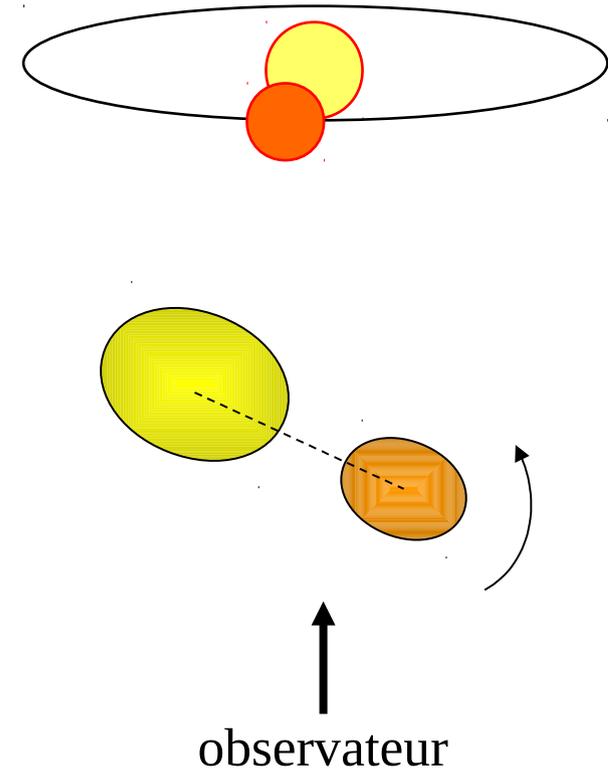
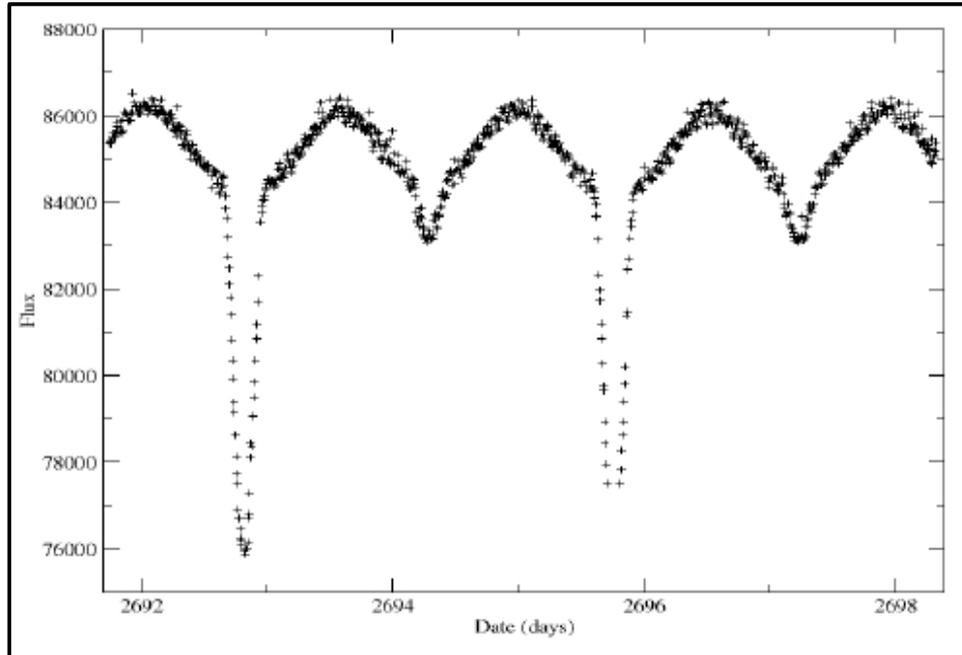
HD 52265 (V=6,3)



⇒ rayon et masse à 2 %
+ âge à 5 %

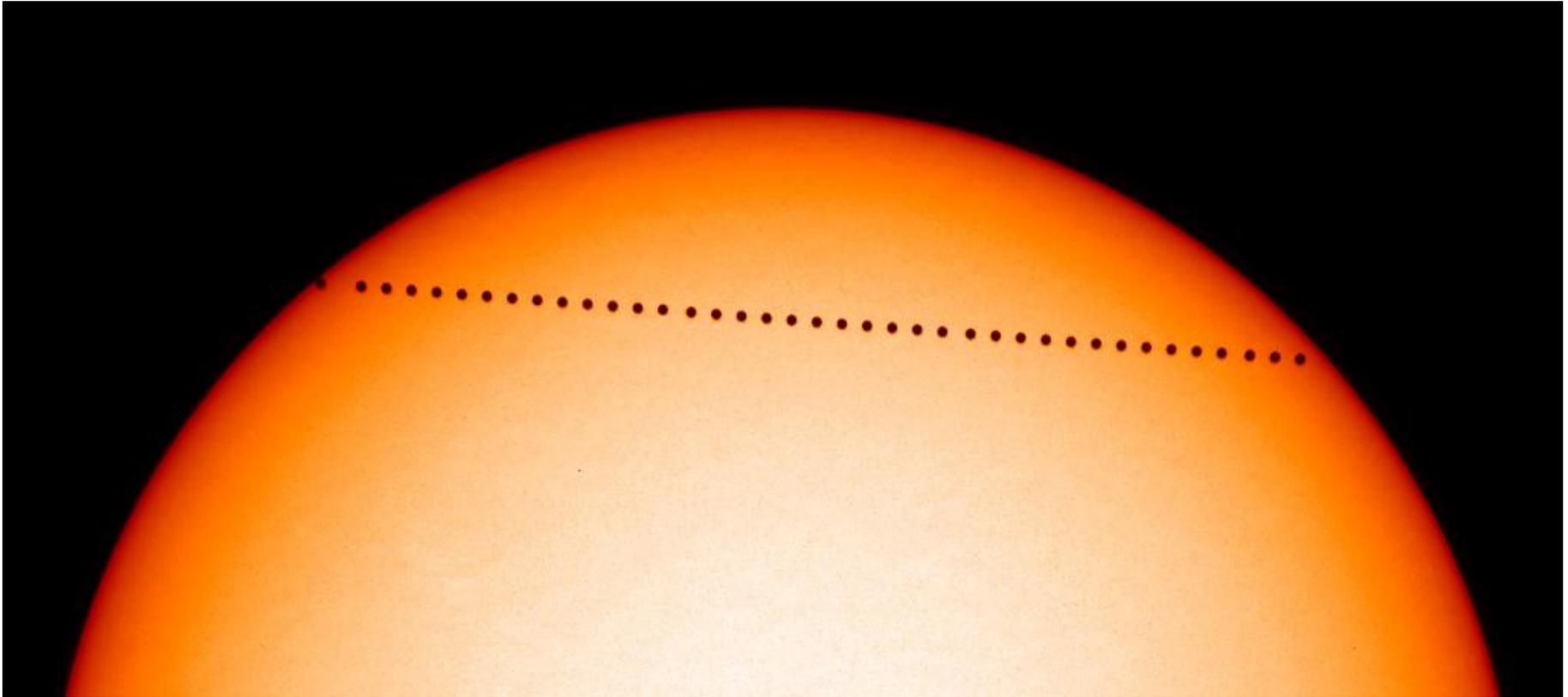
Gizon et al., PNAS 110, 13267 (2013)

Étoiles binaires à éclipses



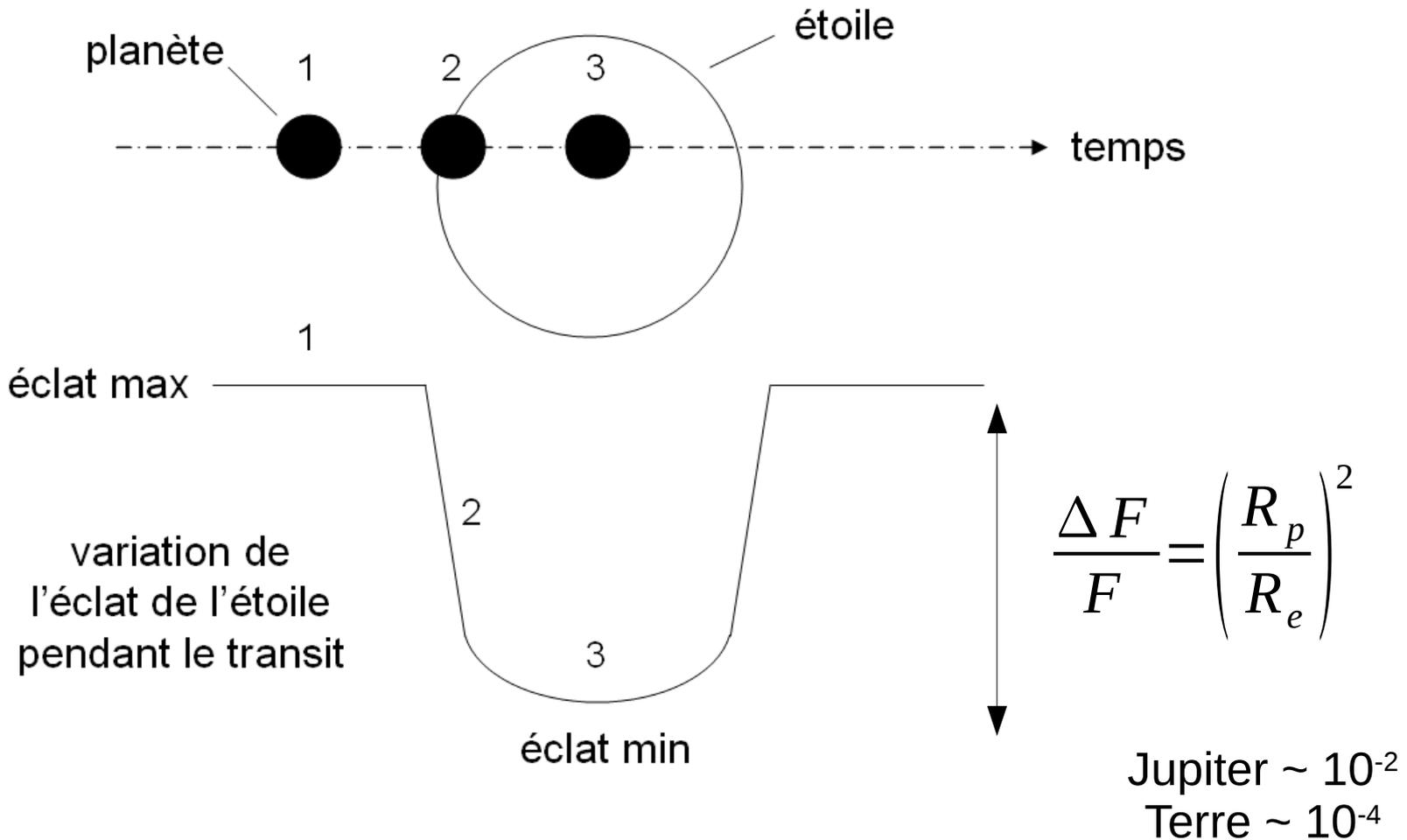
Détecter des exoplanètes ?

Transit planétaire

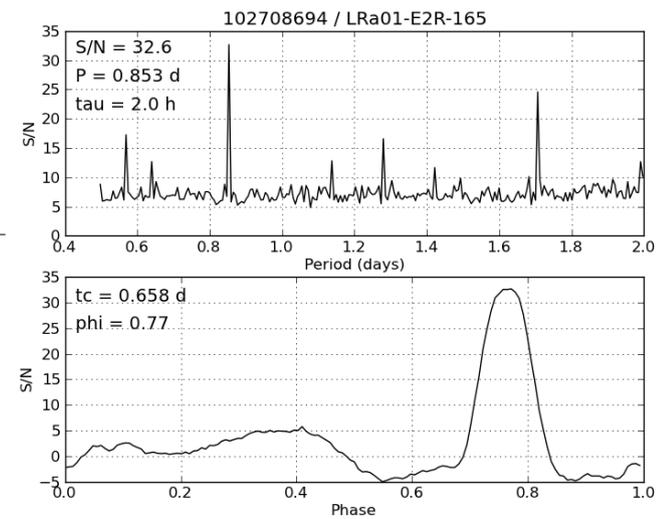
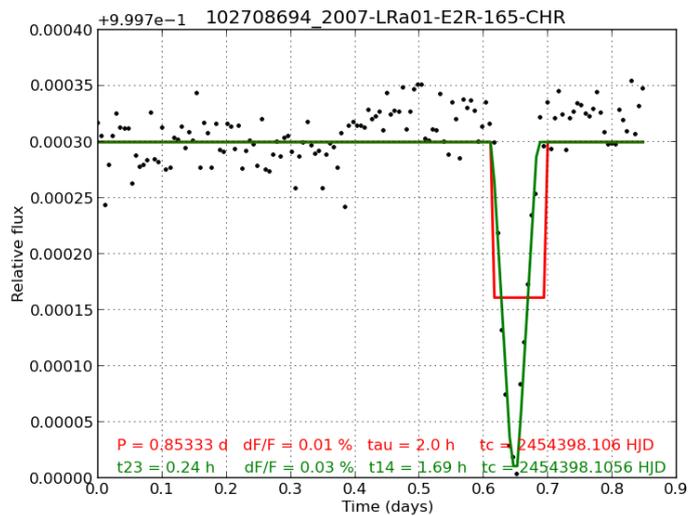
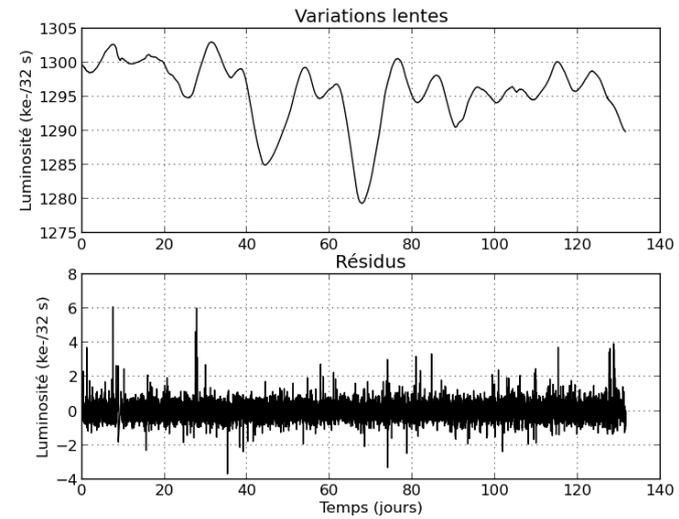
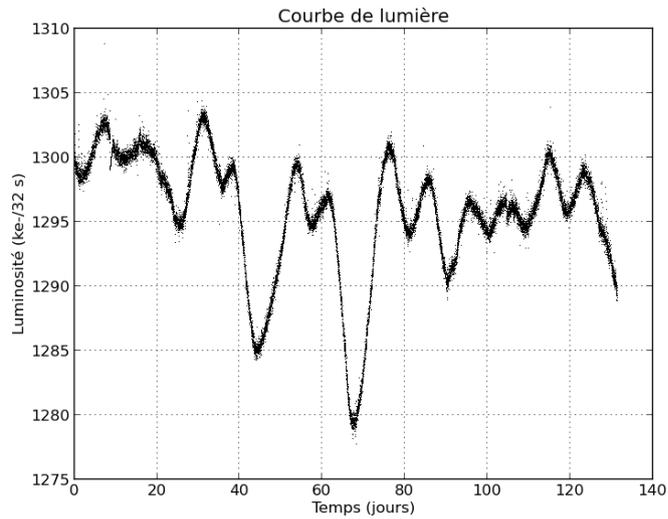


Transit de Mercure vu par SOHO le 7 mai 2003

Transit exoplanétaire

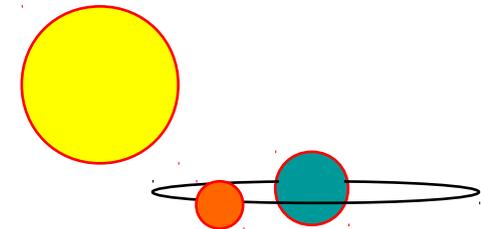
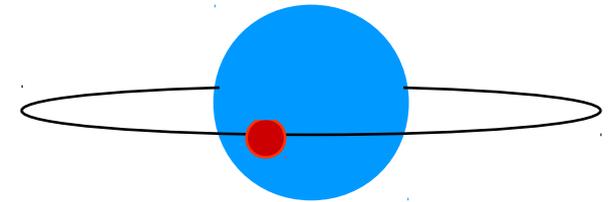
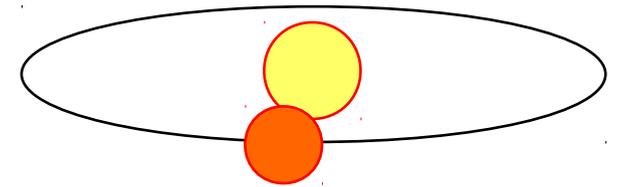


Détection des signaux de transits

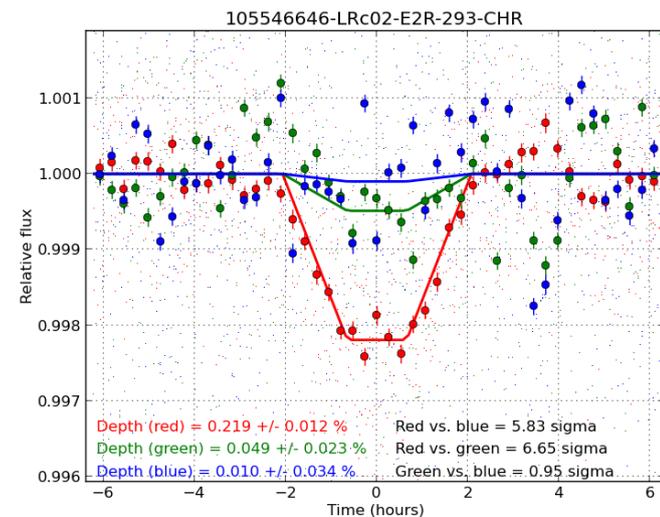
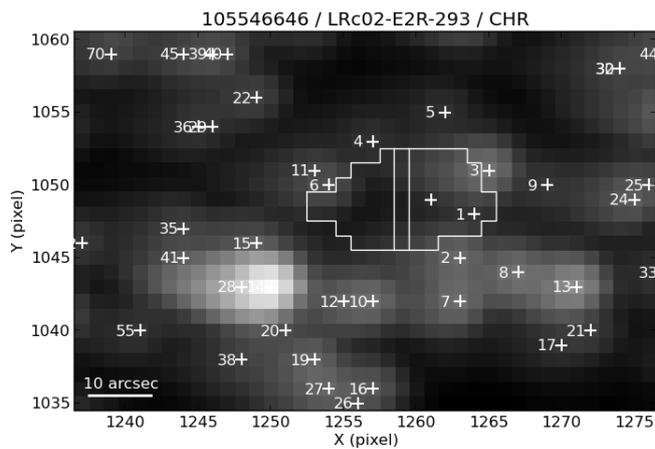
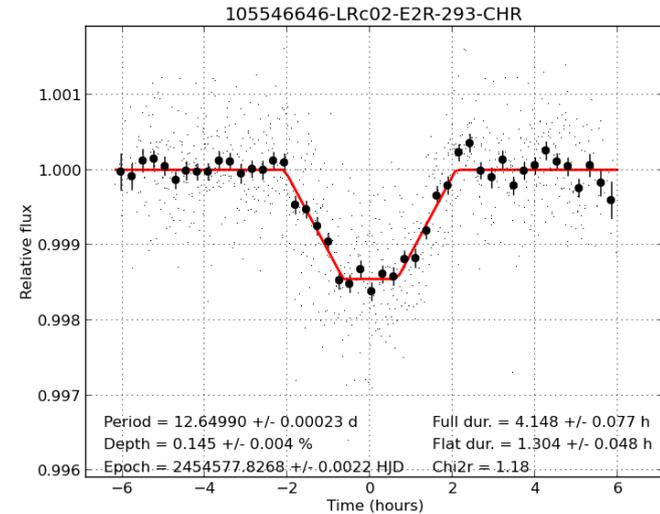
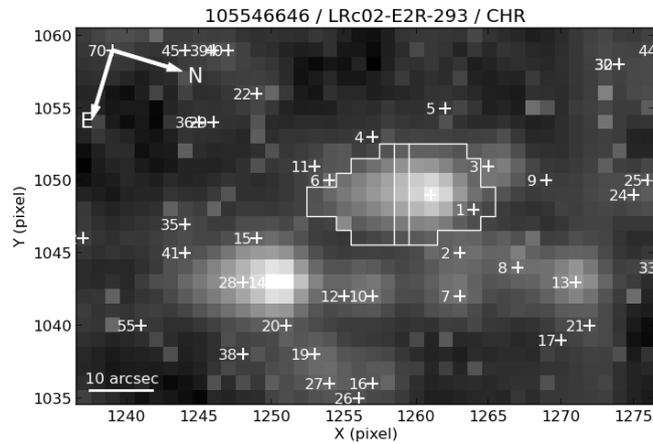


S'agit-il vraiment d'une planète ?

- Binaires à éclipses rasantes
- Binaire naine-géante
- Binaire de fond



Analyse de l'environnement



Tests d'hypothèse

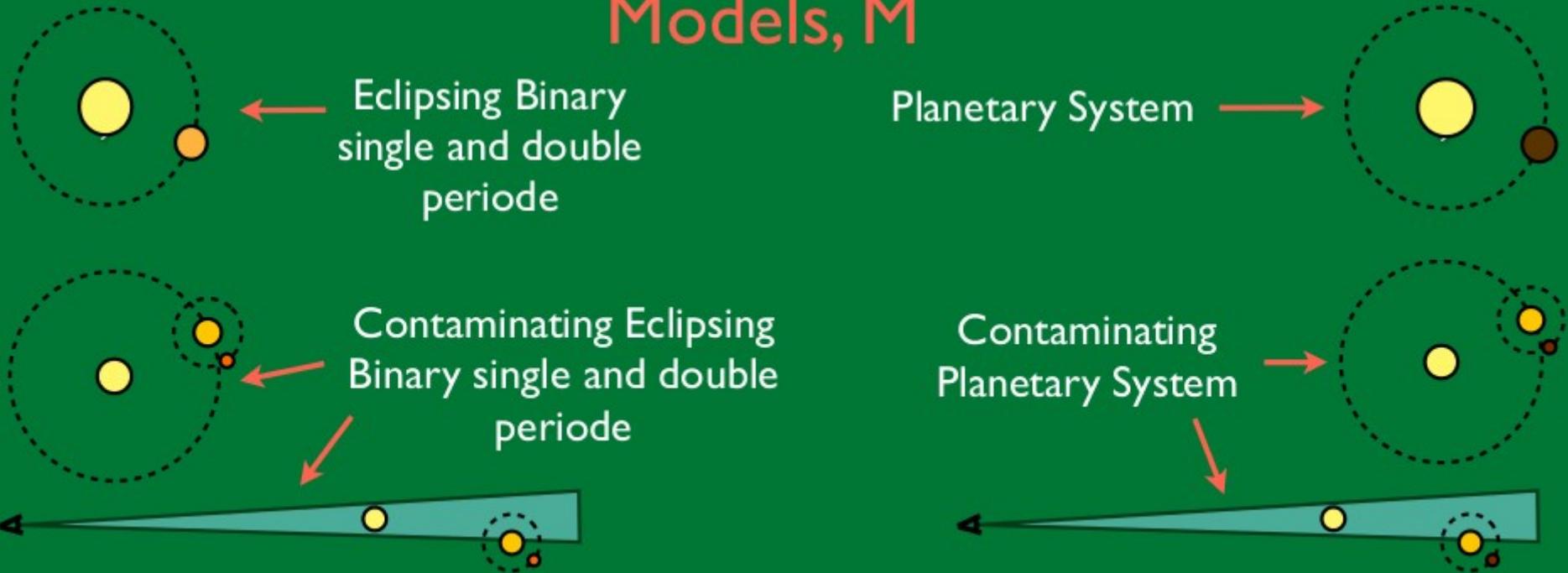
Posterior probability Likelihood Prior probability

$$\Pr(M|d, I) = \frac{\Pr(d|M, I) \Pr(M|I)}{\Pr(d|I)}$$

M : model (PS, EB, CEB ...)
d : data
I : context of the measurement

Marginalized likelihood (Normalization factor)

Models, M



Estimation des paramètres

Posterior probability density Likelihood Prior probability density

$$p(\boldsymbol{\theta}|d, M, I) = \frac{p(d|\boldsymbol{\theta}, M, I) p(\boldsymbol{\theta}|M, I)}{p(d|M, I)}$$

$\boldsymbol{\theta}$: Parameters

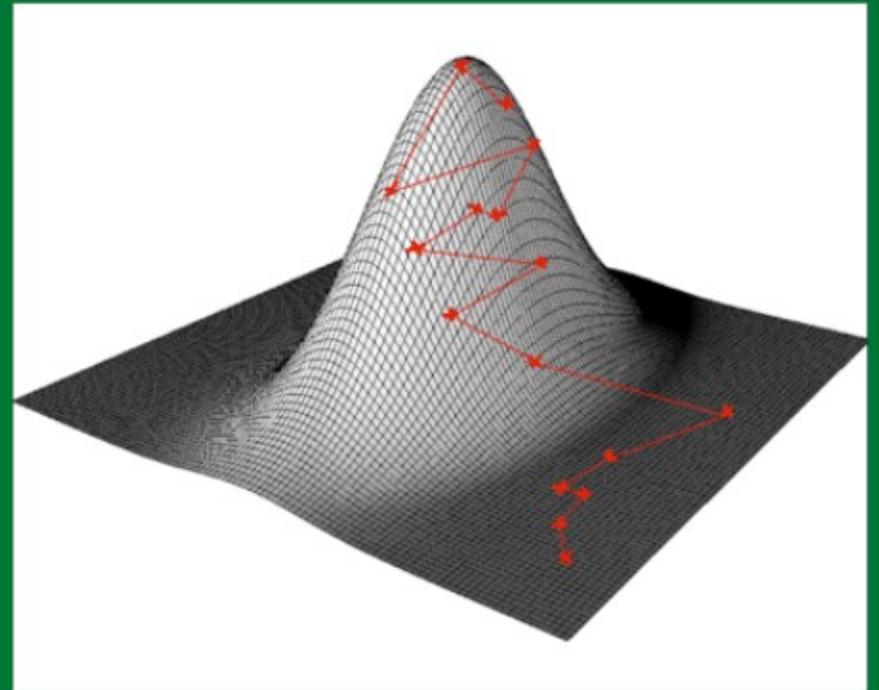
Marginalized likelihood (Normalization factor)

		EB (P, 2P)	CEB (P, 2P)
PS	CPS	<ul style="list-style-type: none"> • b impact parameter • $\frac{R_{\text{prim}}}{R_{\text{sec}}}$ radius ratio • ρ_{som} system density • P orbital periode • $\frac{T_{\text{prim}}}{T_{\text{sec}}}$ effective temperature ratio 	<ul style="list-style-type: none"> • b impact parameter • $\frac{R_{\text{prim}}}{R_{\text{sec}}}$ radius ratio • ρ_{som} system density • P orbital periode • $\frac{T_{\text{prim}}}{T_{\text{sec}}}$ effective temperature ratio • C contamination factor
<ul style="list-style-type: none"> • b impact parameter • $\frac{R_{\text{pl}}}{R_{\text{st}}}$ radius ratio • ρ_{st} stellar density • P orbital periode 	<ul style="list-style-type: none"> • b impact parameter • $\frac{R_{\text{pl}}}{R_{\text{st}}}$ radius ratio • ρ_{st} stellar density • P orbital periode • C contamination factor 	$\rho_{\text{som}} = \frac{M_{\text{prim}} + M_{\text{sec}}}{4/3\pi R_{\text{prim}}^3}$	

Calcul des probabilités

Monte Carlo par chaînes de Markov

- Fasten execution time :
MCMC exploration
Monte carlo integration
- Automatisation : **Personal adaptation** of P.C. Gregory (2005)
Adaptative Metropolis-Hasting algorithm (acceptance rate and trace correlation feedback) **more efficient with correlated parameters**



Thèse d'Olivier Demangeon, Univ. Paris-Sud (2013)

Classement des candidats

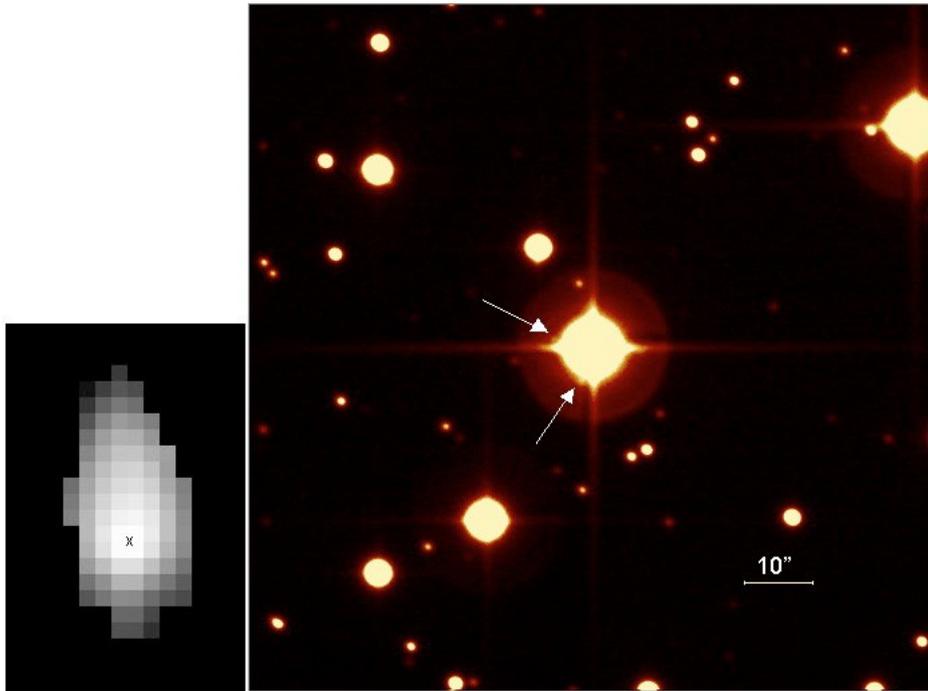
Bayesian analysis for the ranking of planetary candidates (Bart)

Résultats préliminaires sur le LRc02

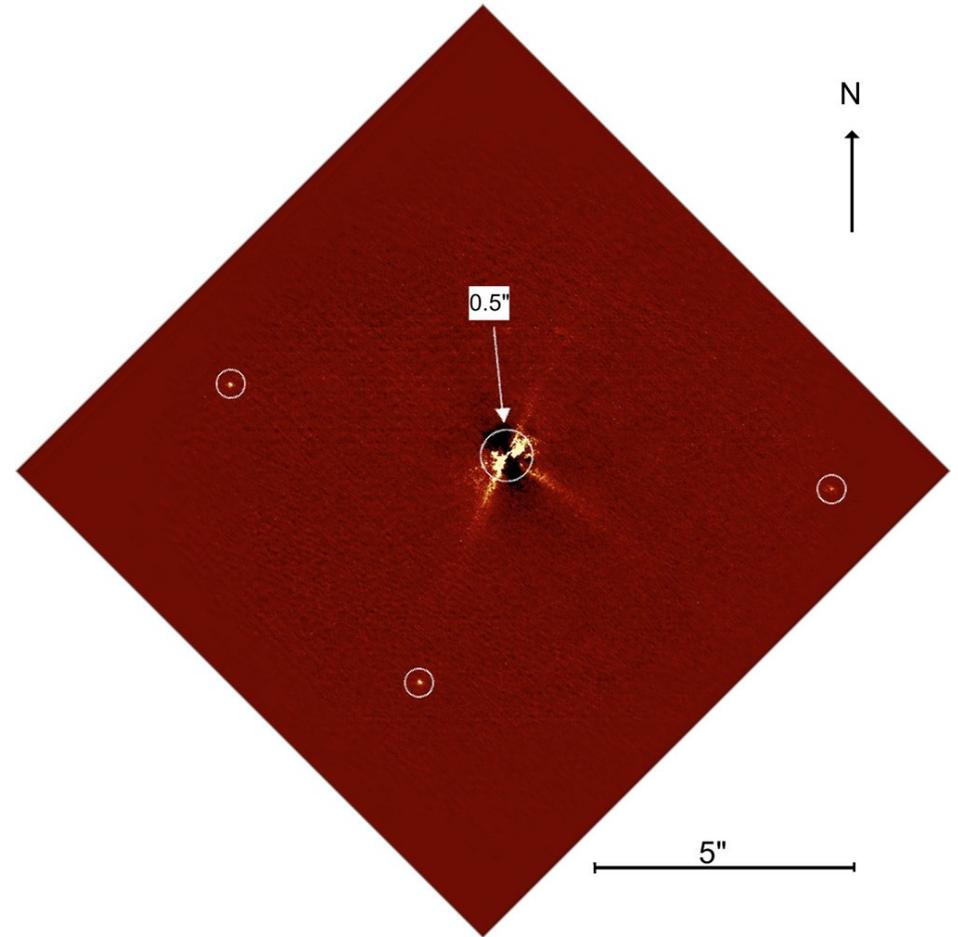
Rang	ID	Proba. (%)	Évidence (dB)	Le + probable	Suivi
1	106017681	99,8	+ 27	Planète	Corot-6b
2	106099419	99,8	+ 27	Planète	? (P3)
3	105793995	99,5	+ 23	Planète	Corot-25b
4	105688817	99,3	+ 22	Planète	? (P1)
5	105985045	$1,1 \cdot 10^{-2}$	- 40	Planète (env.)	? (P3)
6	105886280	$6,0 \cdot 10^{-3}$	- 42	Binaire	? (P3)
7	105729575	$5,5 \cdot 10^{-4}$	- 53	Binaire	Binaire (env.)
8	106082164	$2,6 \cdot 10^{-6}$	- 76	Binaire (2P)	? (P3)
9	105546646	$3,8 \cdot 10^{-7}$	- 84	Planète (env.)	Binaire (env.)
10	105819653	10^{-11}	- 130	Binaire (env.)	Corot-22b
11	105833549	10^{-15}	- 170	Planète (env.)	Corot-11b

Thèse d'Olivier Demangeon, Univ. Paris-Sud (2013)

Suivi photométrique au sol



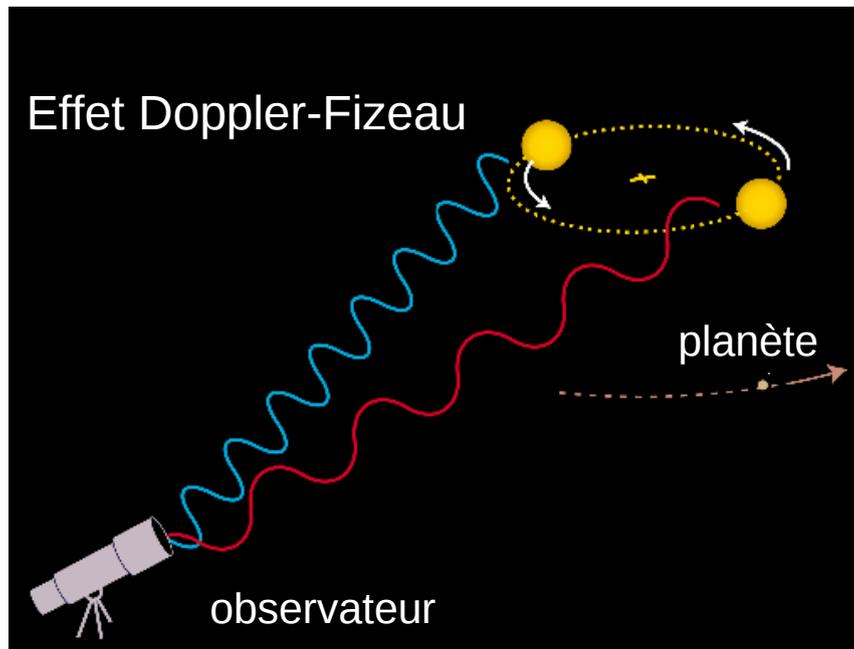
CFHT-MEGACAM



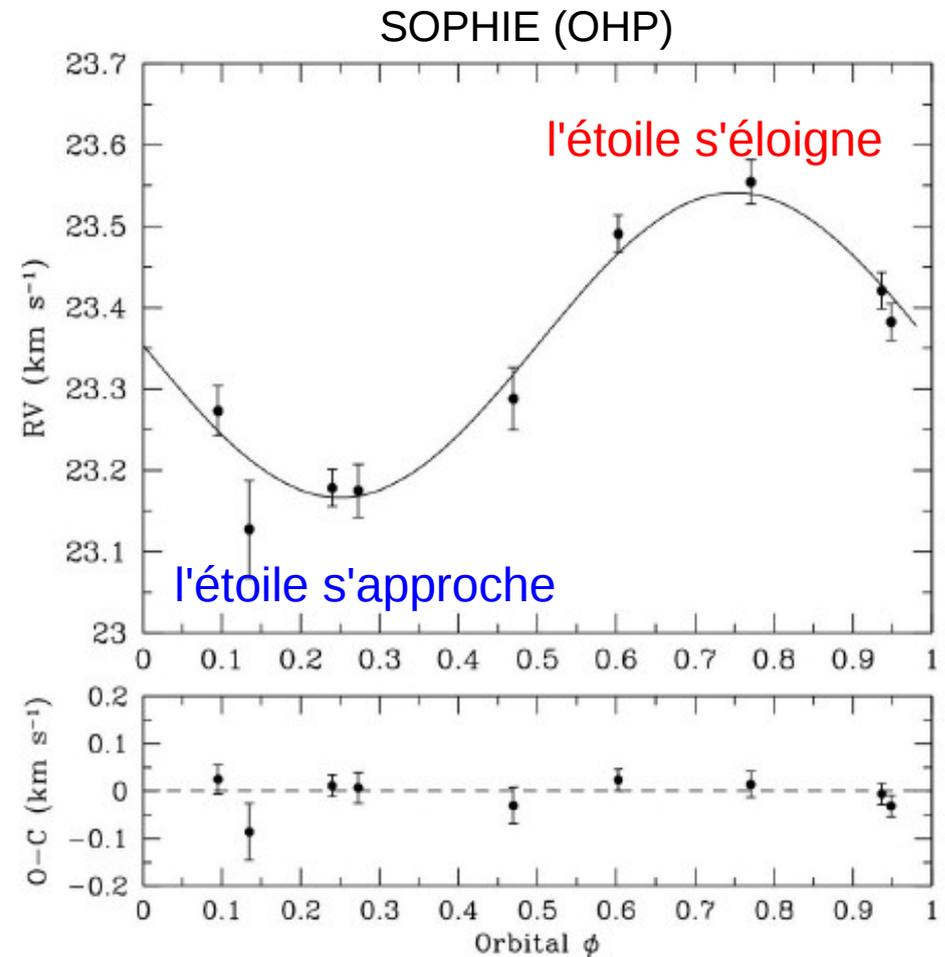
VLT-NAOS-CONICA

Léger et al., A&A 506, 287 (2009)

Mesure de la vitesse radiale

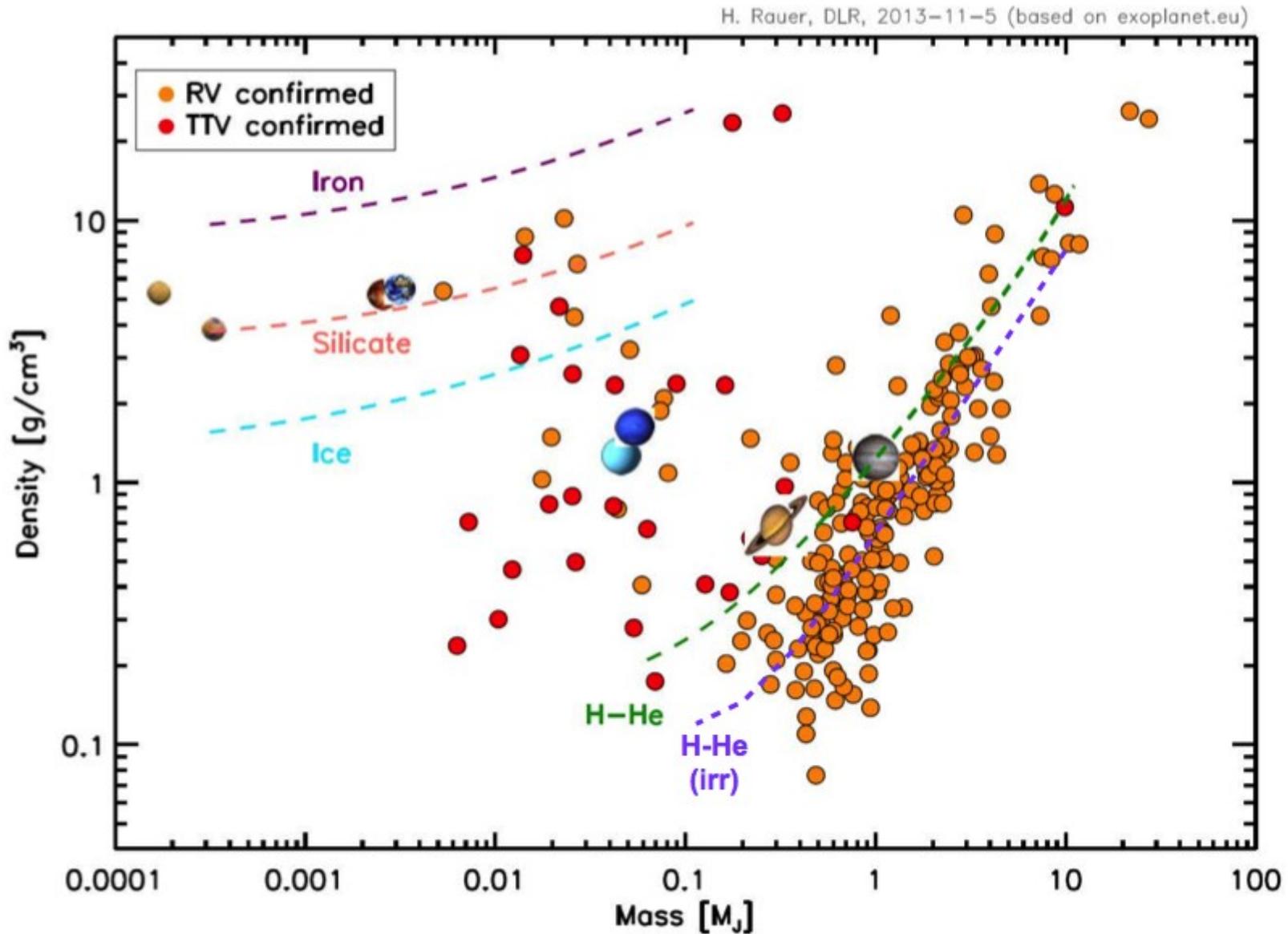


⇒ $M_p \times \sin(i)$ connaissant M_*



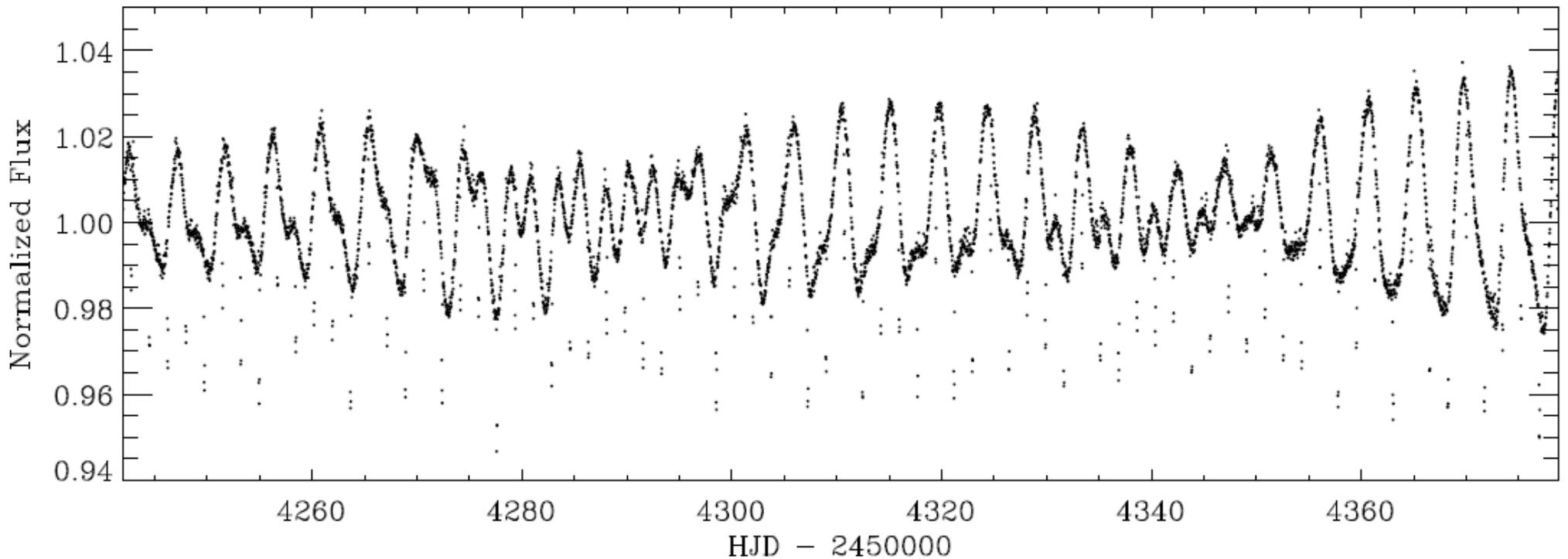
Barge et al., A&A 482, L17 (2008)

Nature des exoplanètes



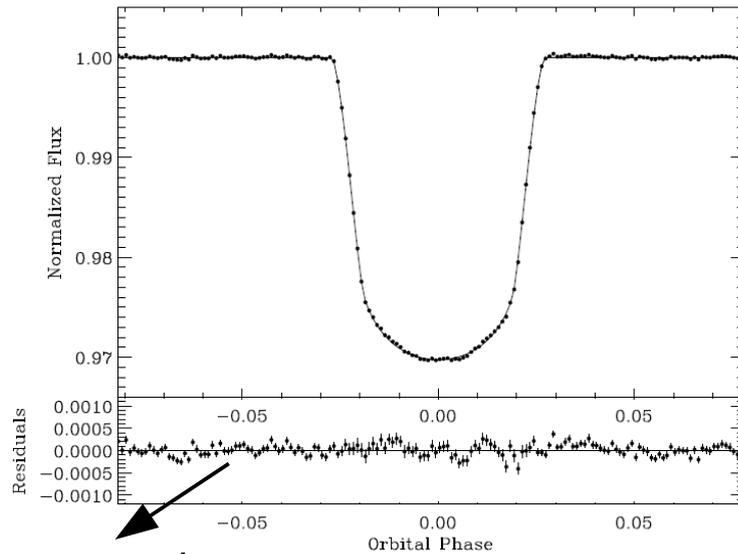
Corot-2b

78 transits en 152 j !

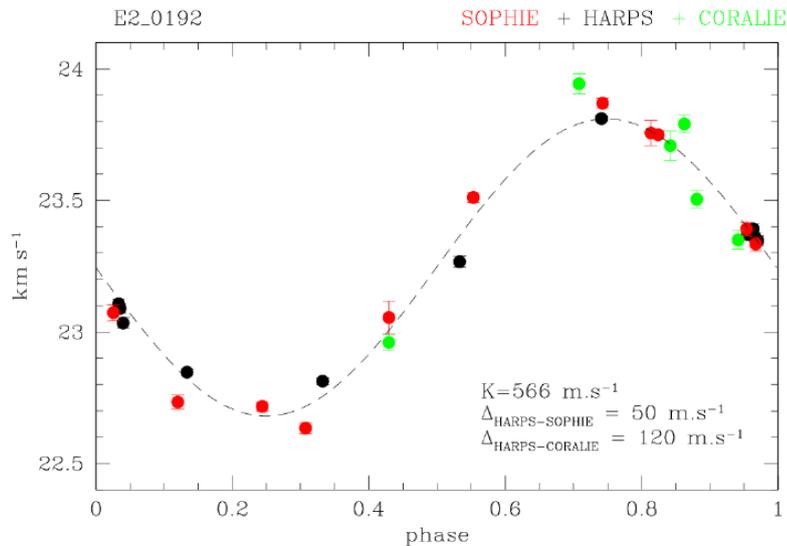


Alonso et al., A&A 482, L21 (2008)

Corot-2b



$$\sigma = 1,07 \times 10^{-4}$$

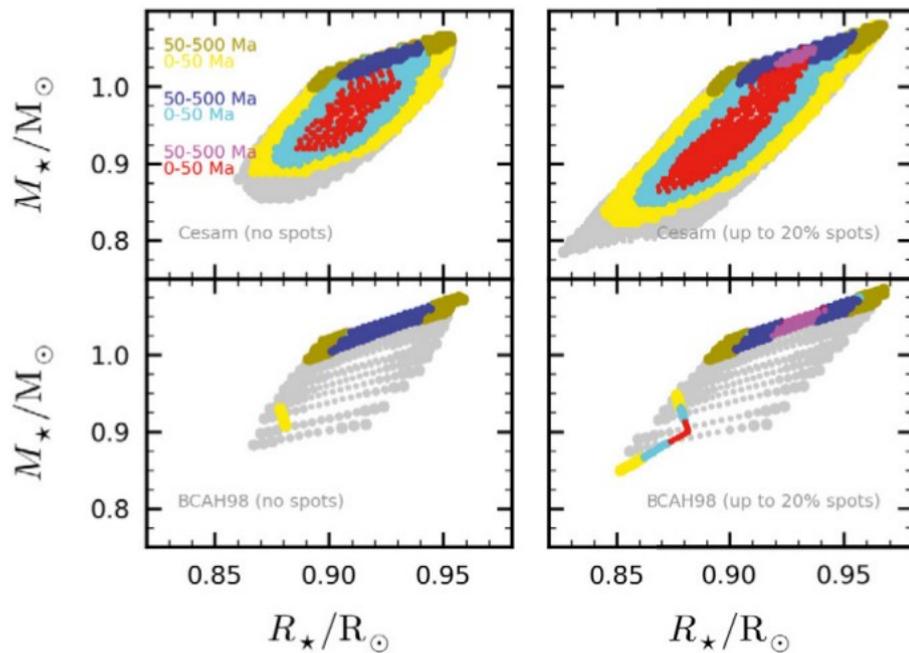


- étoile-hôte : G7 V (V=12,6)
- rayon : $1,429 \pm 0,047 R_{\text{Jup}}$
- masse : $3,53 \pm 0,24 M_{\text{Jup}}$
- densité : $1,50 \pm 0,18$
- période : $1,7429964 \pm 0,0000017 \text{ j}$
- demi-grand axe : $0,030 \text{ UA}$

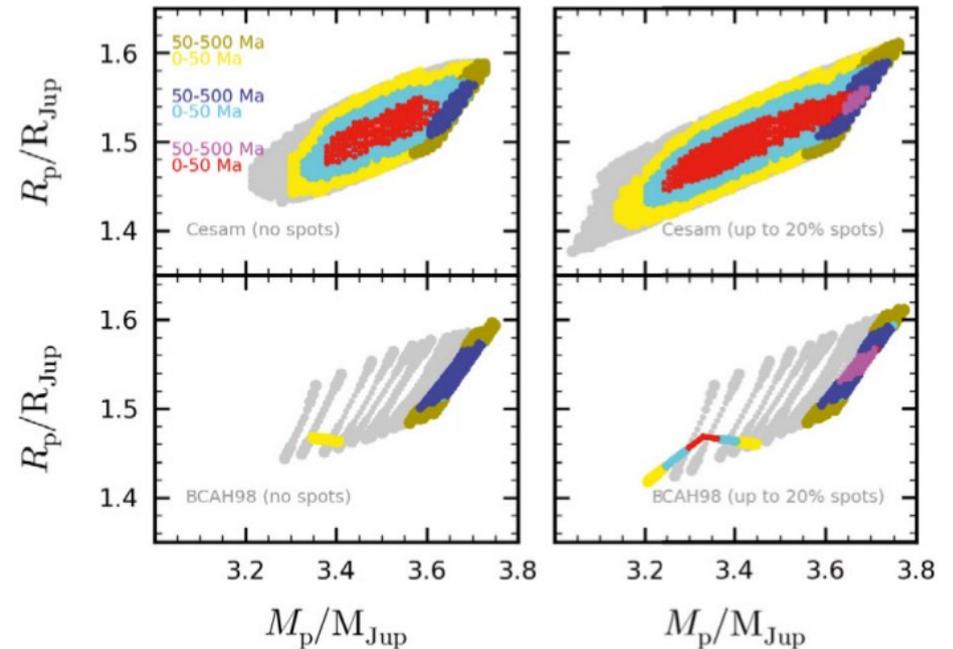
Alonso et al., A&A 482, L21 (2008)

Bien caractériser l'étoile

Corot-2



Corot-2b

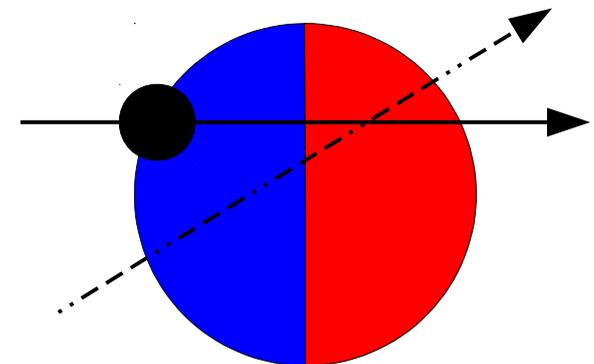
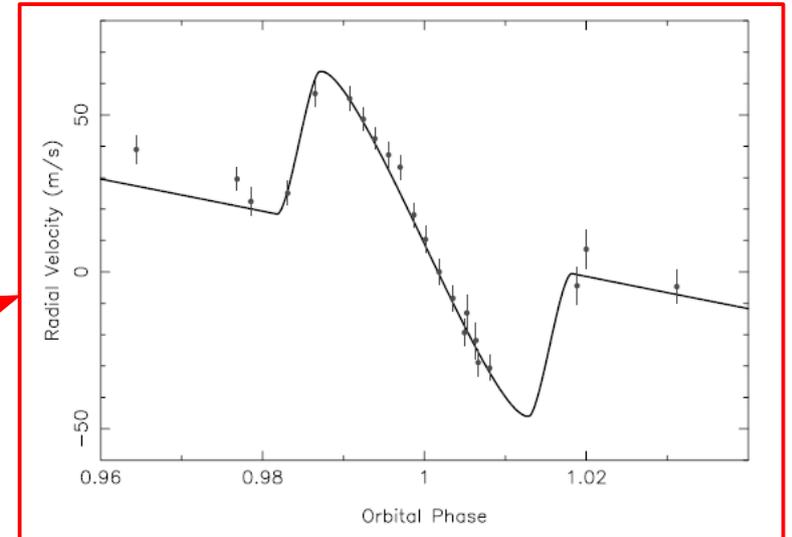
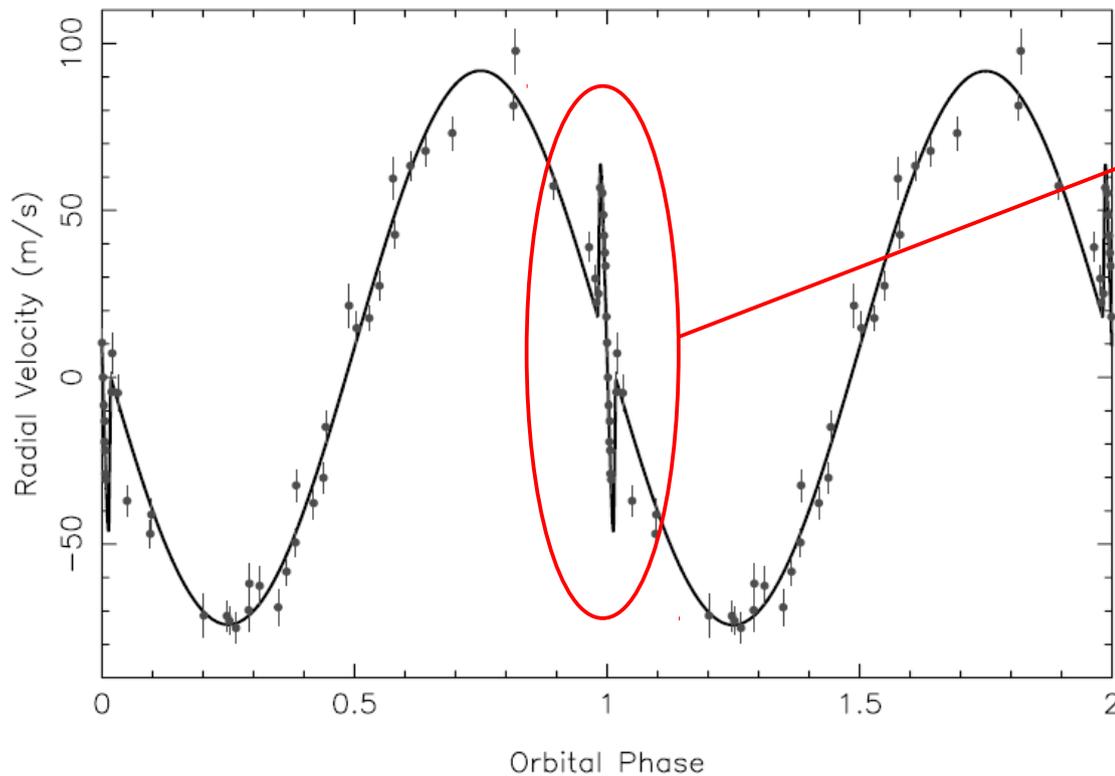


Guillot & Havel, A&A 527, A20 (2011)

Transit spectroscopique

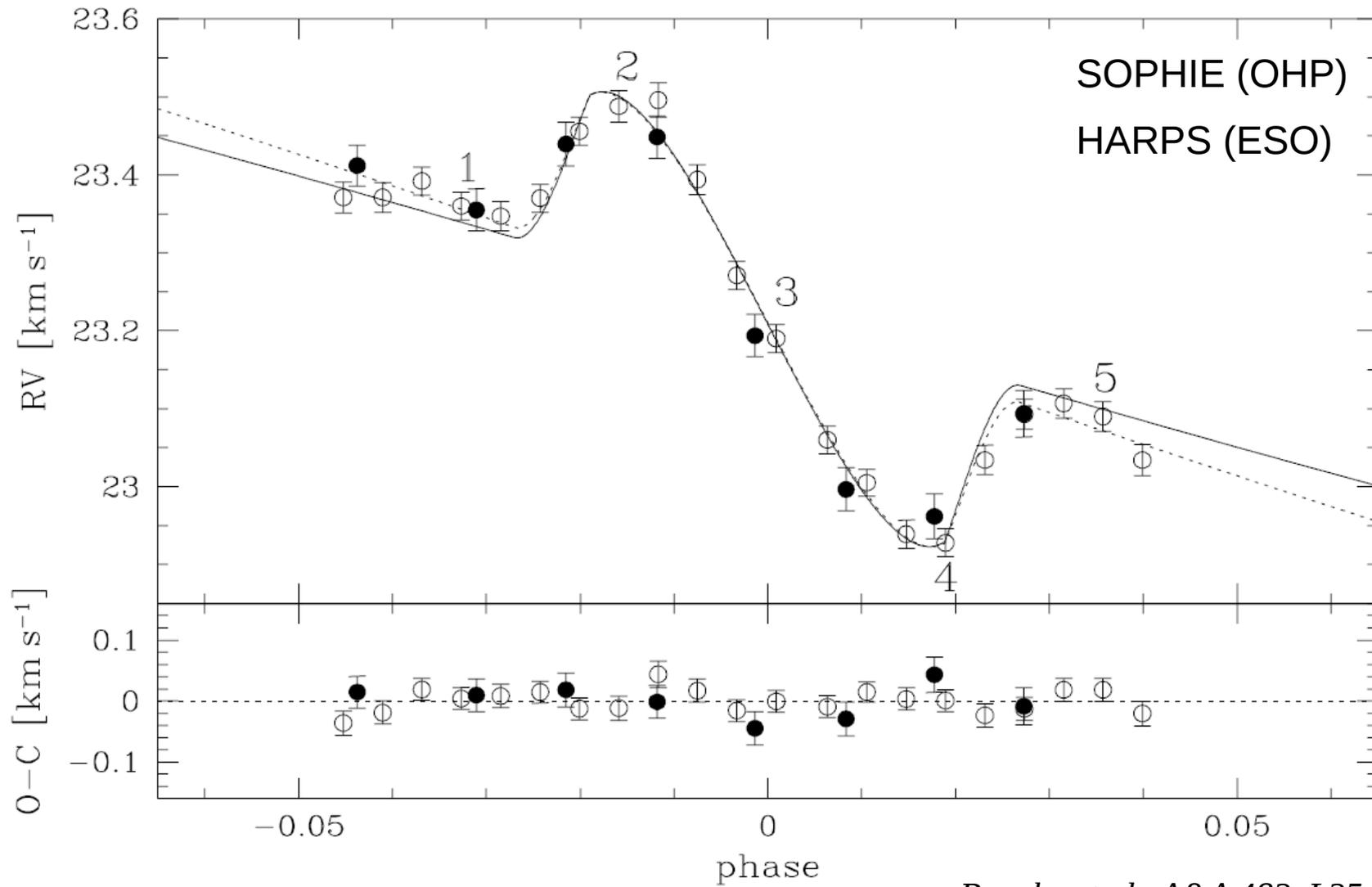
Effet Rossiter-McLaughlin

HD 209458 b



Wittenmyer et al., ApJ (2005)

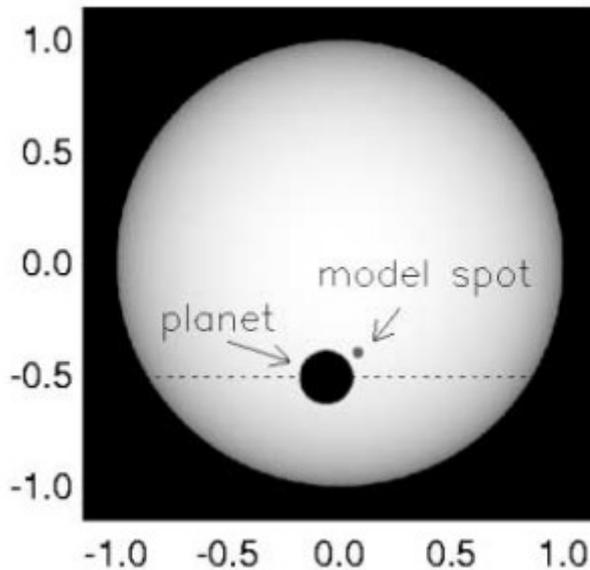
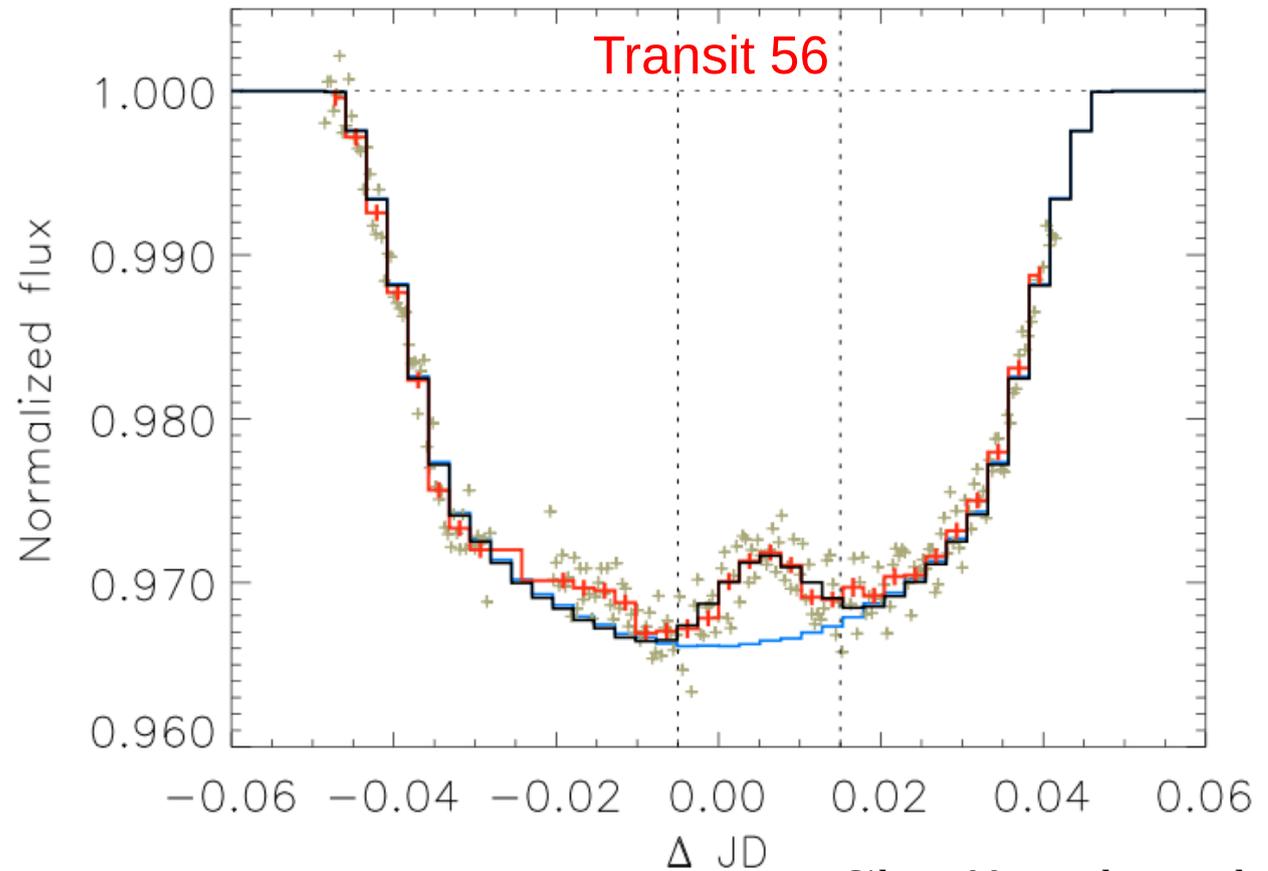
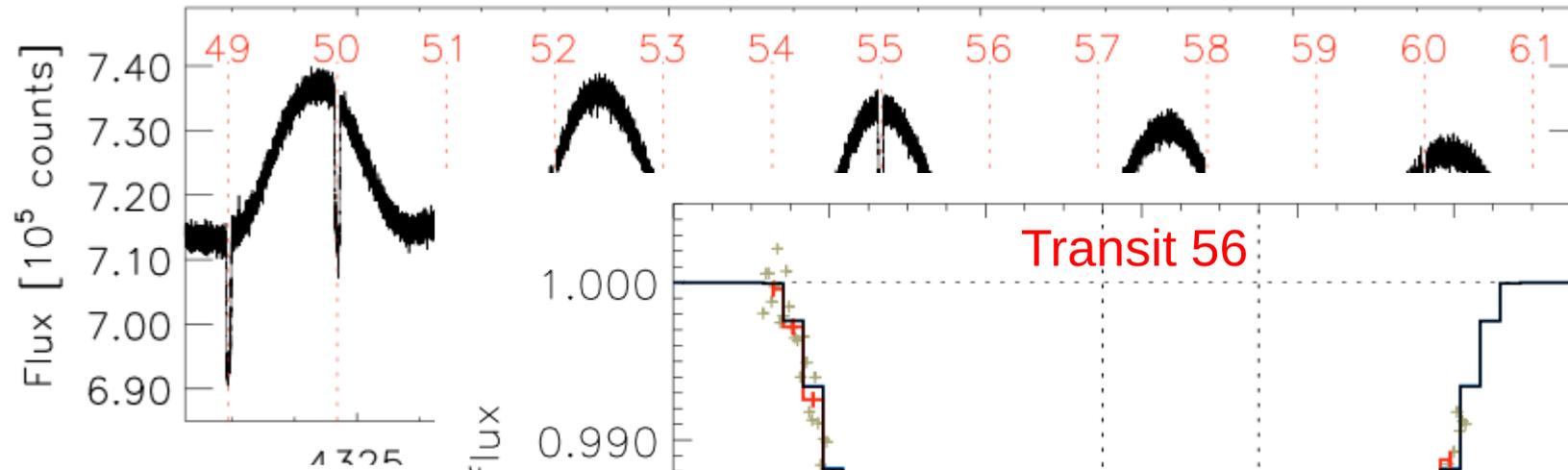
Corot-2b



Bouchy et al., A&A 482, L25 (2008)

Effet des taches stellaires

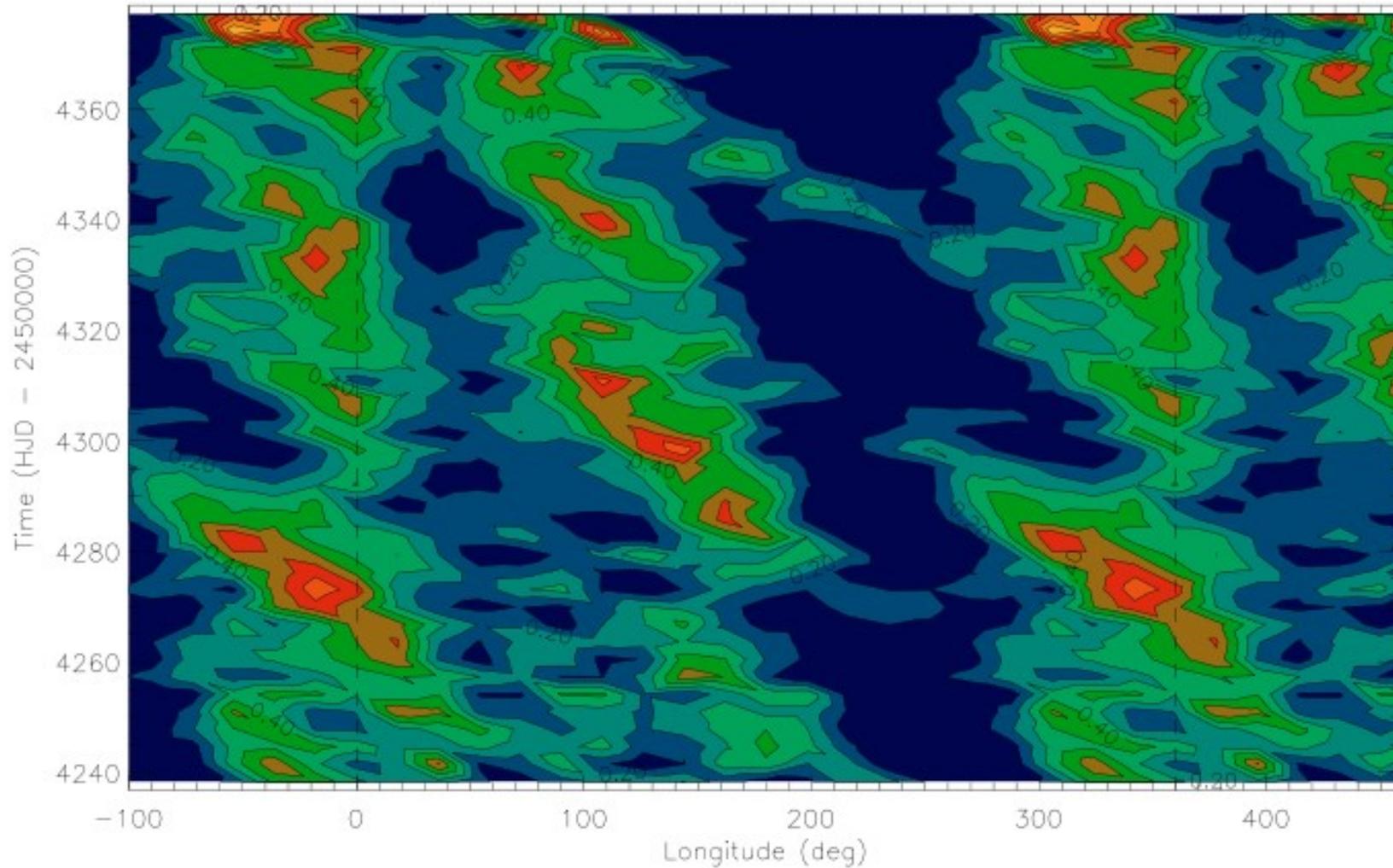
Corot-2



Silva 2003, Wolter et al. 2009

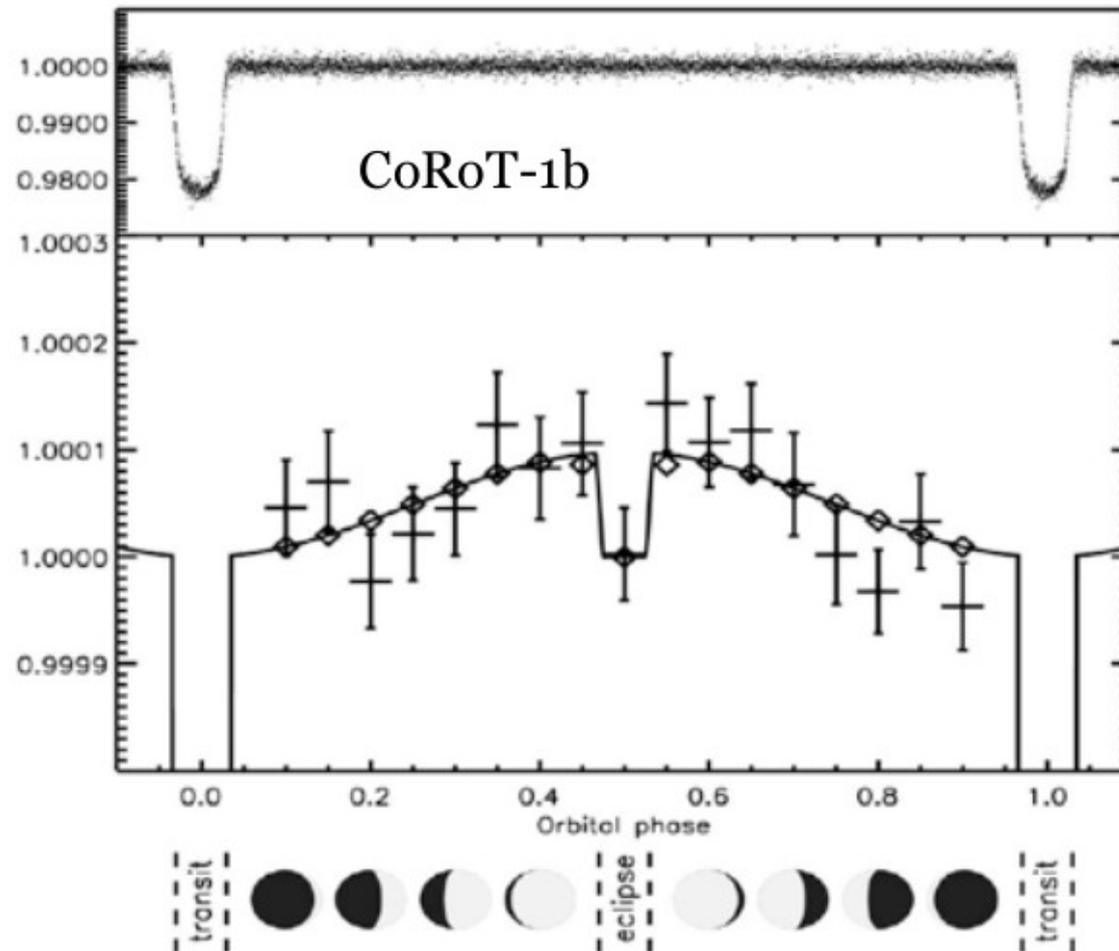
Cartographie des taches

Corot-2



Lanza et al., A&A 493, 193 (2009)

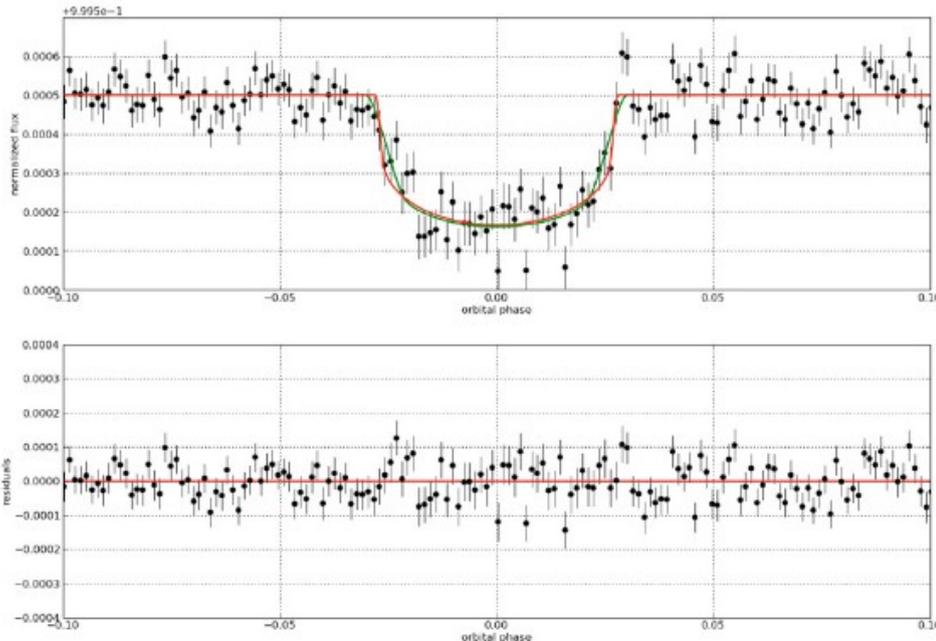
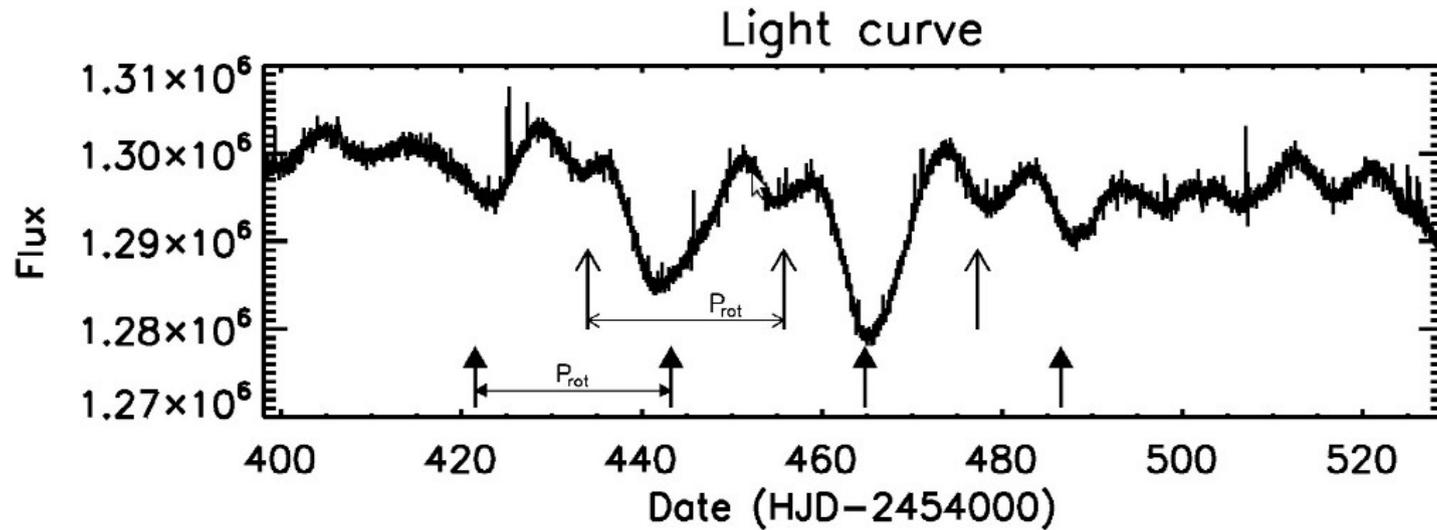
Corot-1b : phase & anti-transit



Albédo $< 0,2$; Température = $2330 +120/-140$ K

Snellen et al., Nature 459, 543 (2009) ; Alonso et al., A&A 506, 353 (2009)

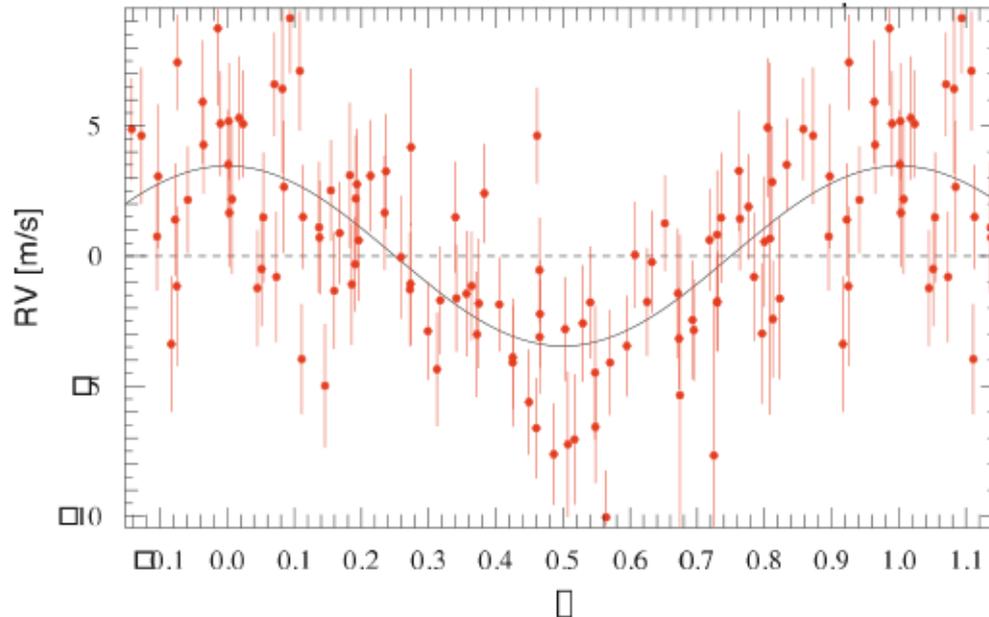
Corot-7b



Parameter	Value	Uncertainty
Period (day)	0.853585	$\pm 2.4 \cdot 10^{-5}$
a (AU)	0.0172	$\pm 2.9 \times 10^{-4}$
a/R_{\star}	4.27	± 0.20
T_{14} (h)	1.125	± 0.05
impact parameter z	0.61	± 0.06
$k = R_{pl} / R_{\star}$	0.0187	$\pm 3 \times 10^{-4}$
R_{pl} / R_{Earth}	1.68	± 0.09
M_{pl} / M_{Earth}	< 21	
i (deg)	80.1	± 0.3

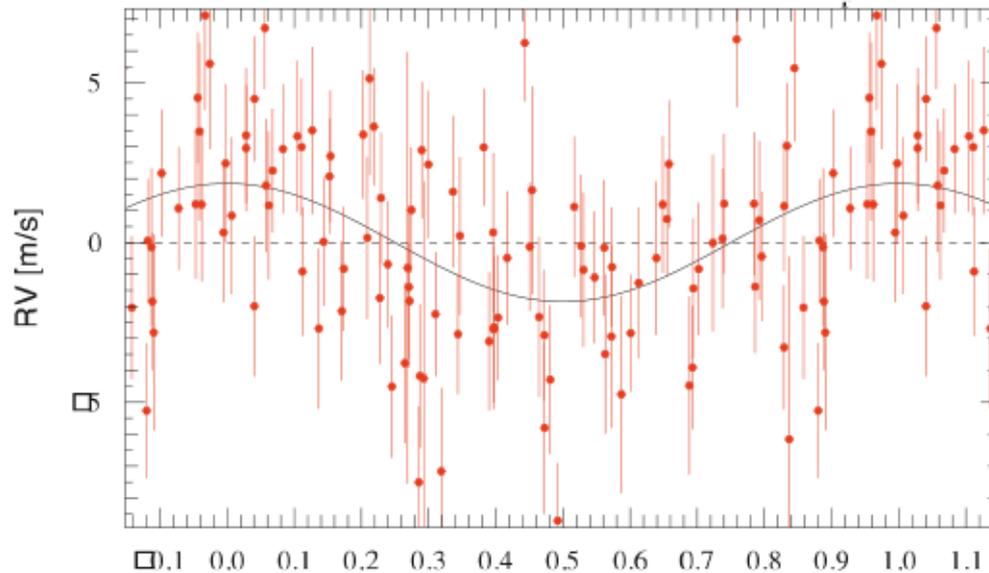
Léger et al., A&A 506, 287 (2009)

Le système de Corot-7



Corot-7c

- 3,7 j
- 0,046 UA
- 8,4 M_{Terre}

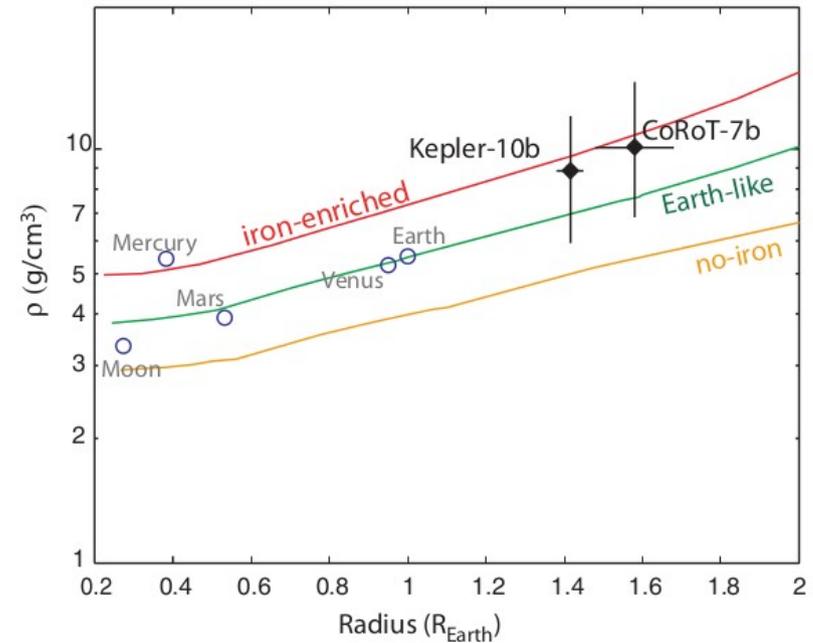
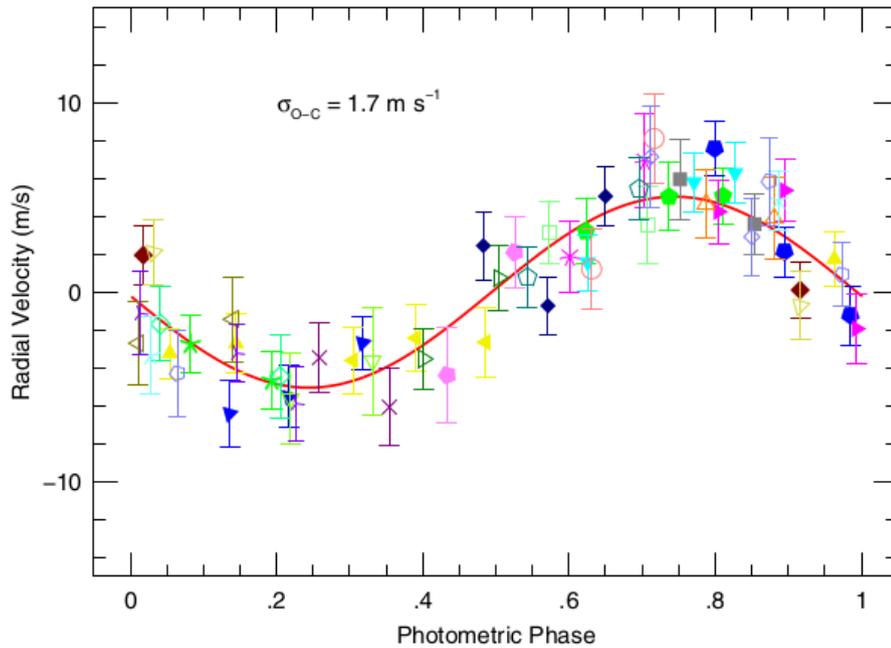


Corot-7b

- 0,85 j
- 0,017 UA
- 1,7 R_{Terre}
- 4,8 M_{Terre}

Queloz et al., A&A 506, 303 (2009)

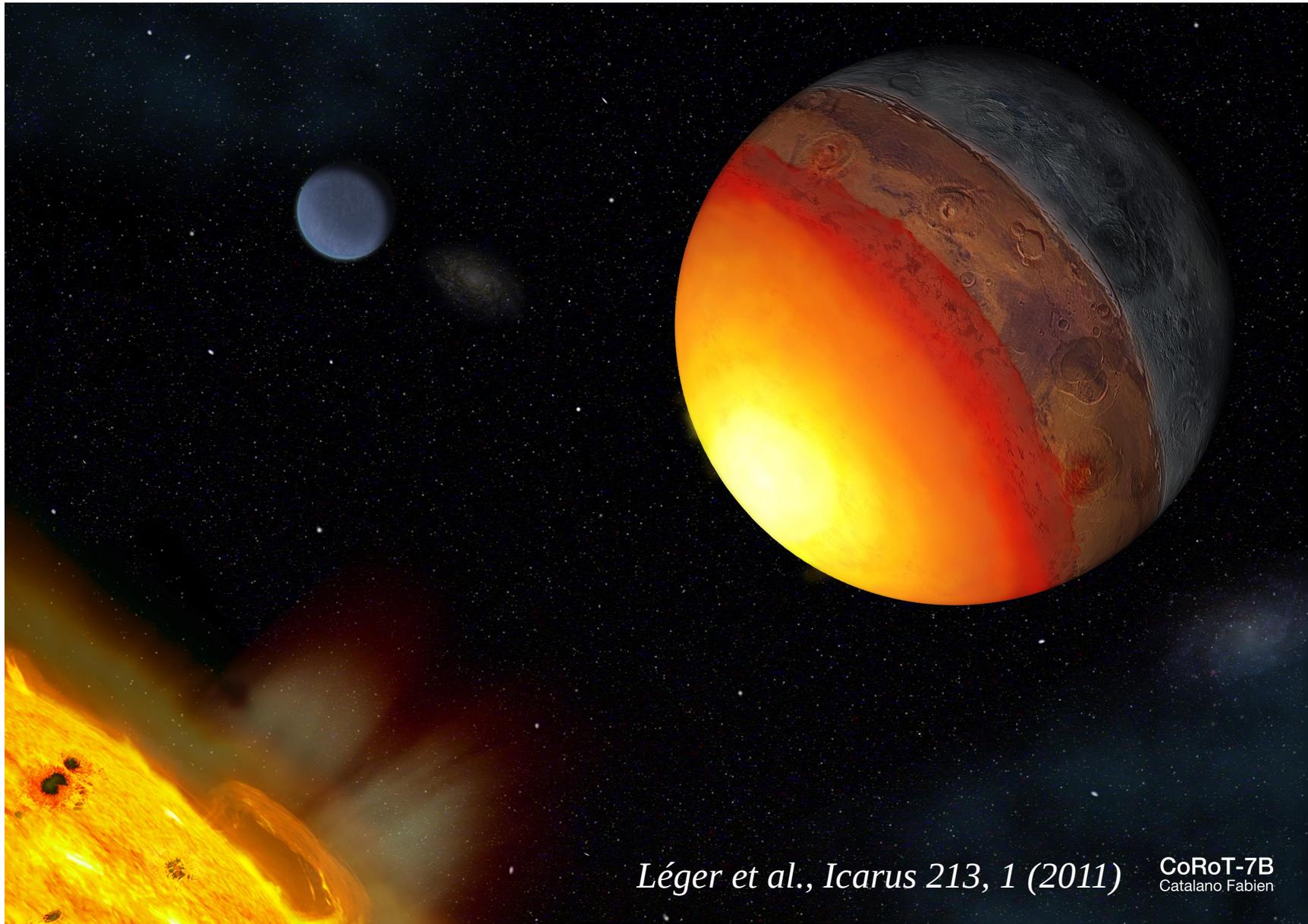
Débat autour de la masse



$$R_p = 1,68 \pm 0,09 R_{\oplus} ; M_p = 7,42 \pm 1,21 M_{\oplus} ; \rho_p = 10,4 \pm 1,8 \text{ g/cm}^3$$

Hatzes et al., ApJ 743, 75 (2011)

Corot-7b : « feu et glace »

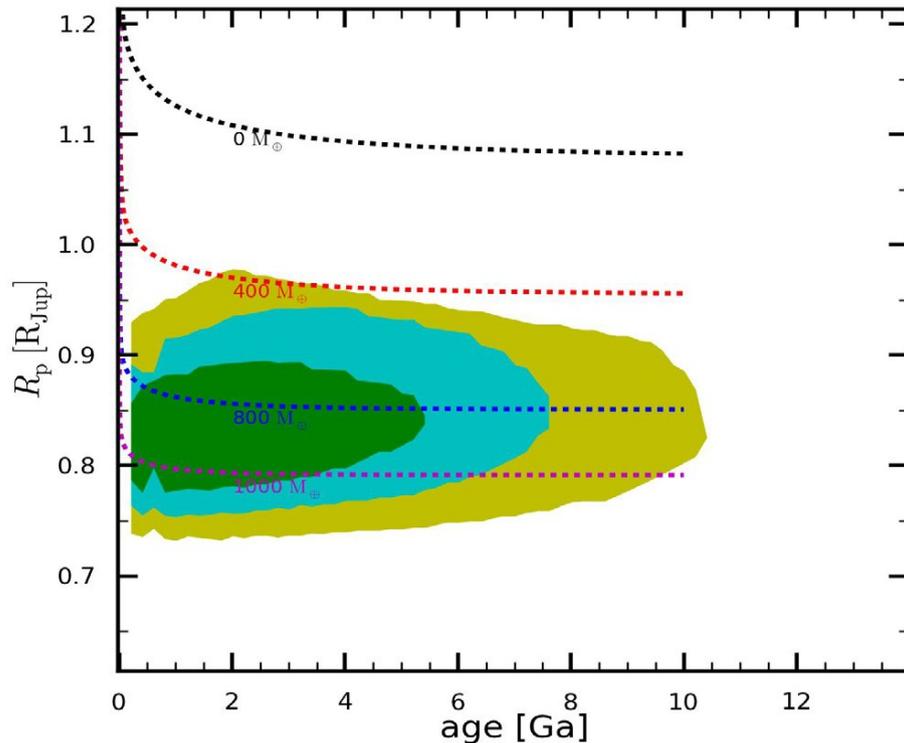


Léger et al., Icarus 213, 1 (2011)

CoRoT-7B
Catalano, Fabien

Corot-20b et 26b : anormales ?

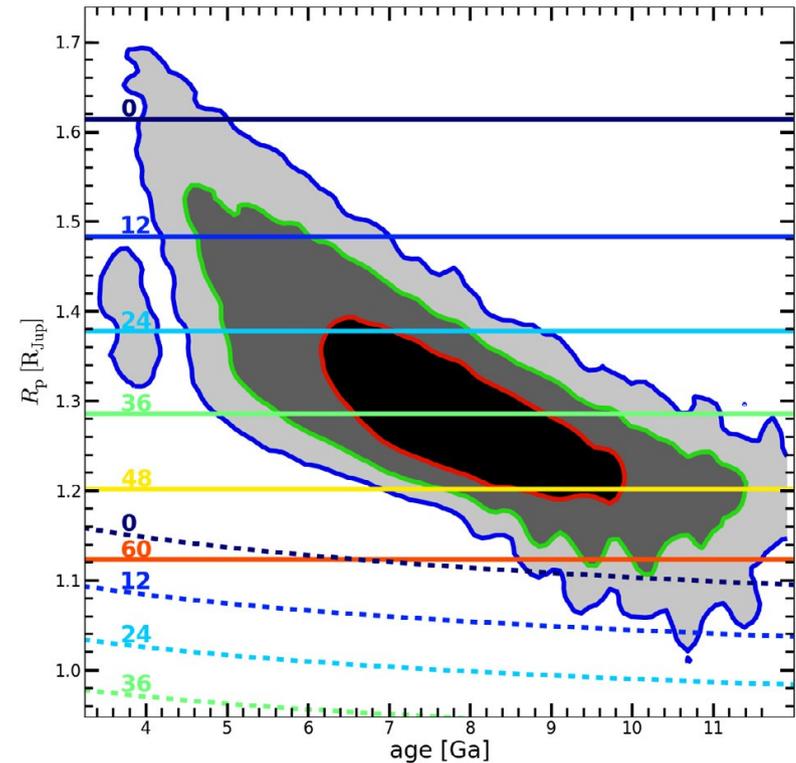
Corot-20b : trop dense ?



$$\rho_p = 8,87 \pm 1,10 \text{ g/cm}^3$$

Deleuil et al., A&A 538, A145 (2012)

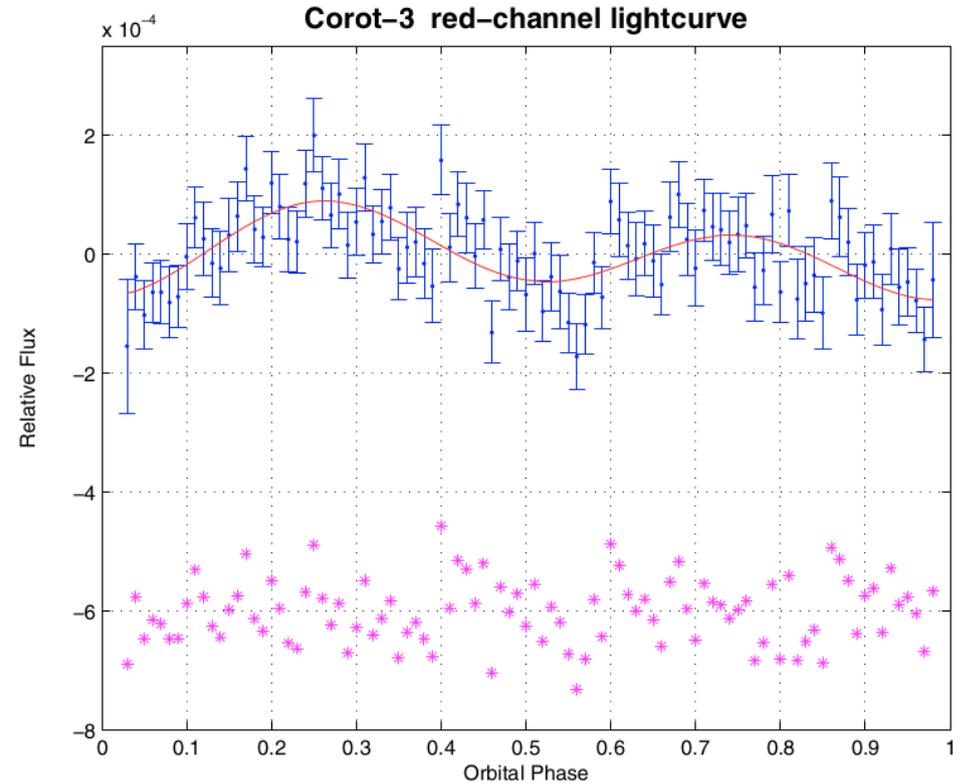
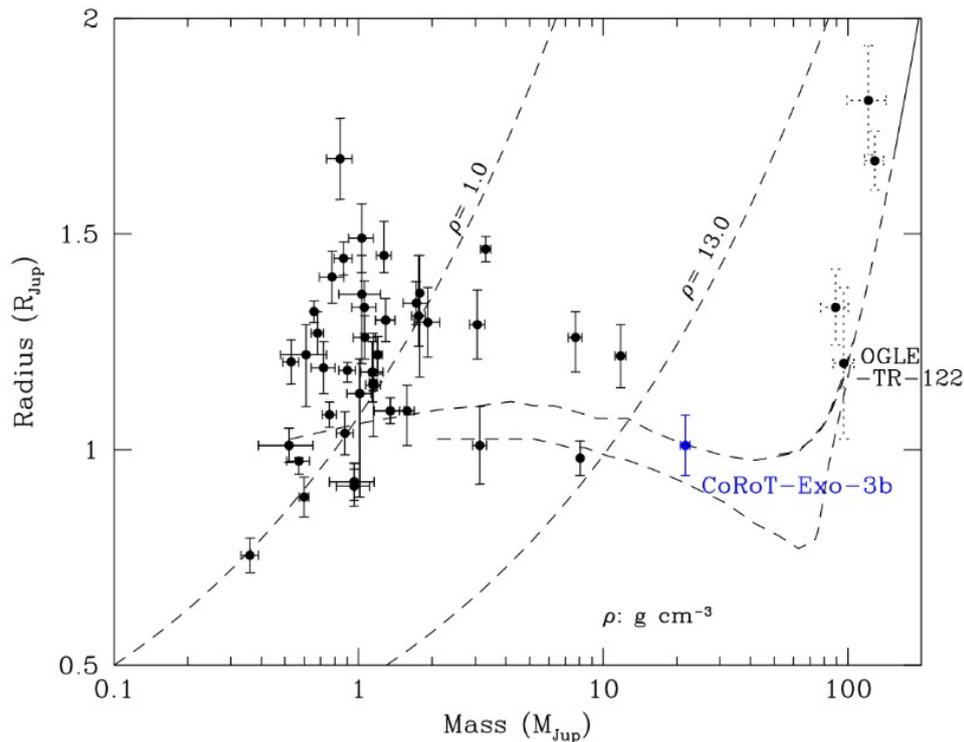
Corot-26b : pas assez dense ?



$$\rho_p = 0,28 \pm 0,08 \text{ g/cm}^3$$

Almera et al., A&A 555, A118 (2013)

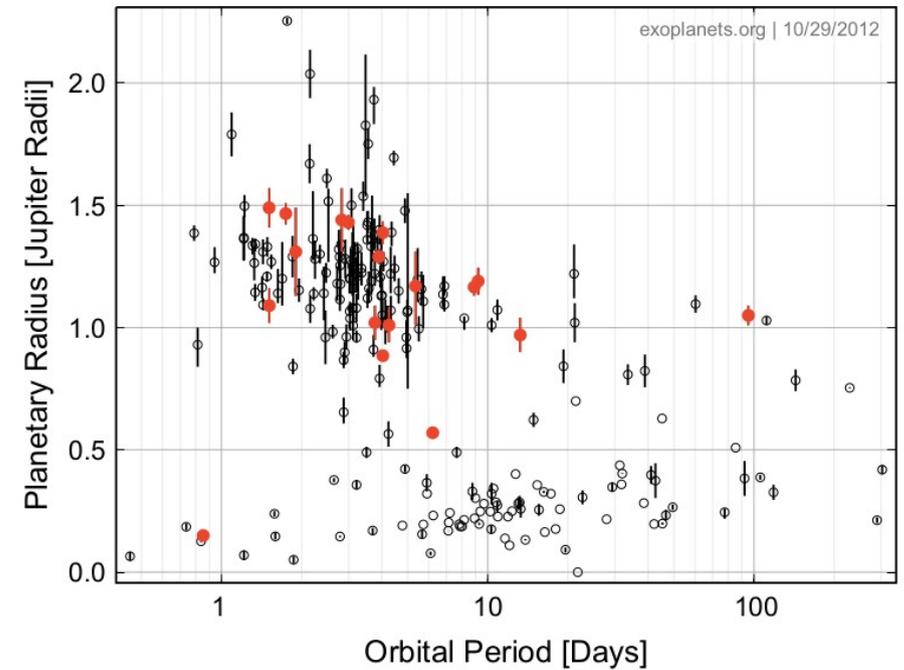
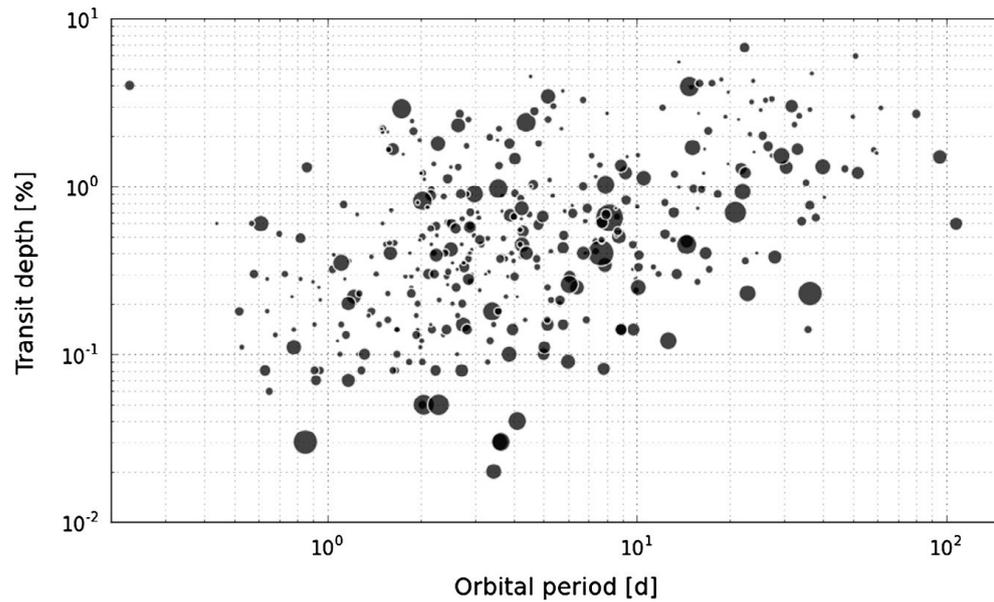
Corot-3b : une naine brune



$$R_p = 1,01 \pm 0,07 R_J ; M_p = 21,7 \pm 1,0 M_J ; \rho_p = 26,4 \pm 5,6 \text{ g/cm}^3$$

Deleuil et al., A&A 491, 889 (2008) ; Mazeh & Faigler, A&A 521, L59 (2010)

La moisson de Corot



Moutou et al., Icarus 226, 1625 (2013)

Corot et les exoplanètes

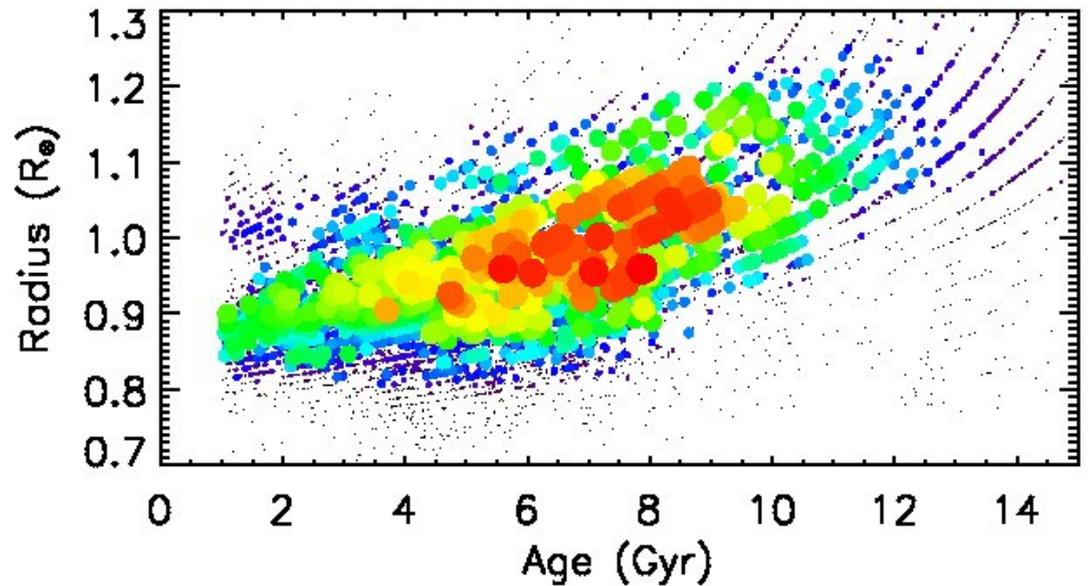
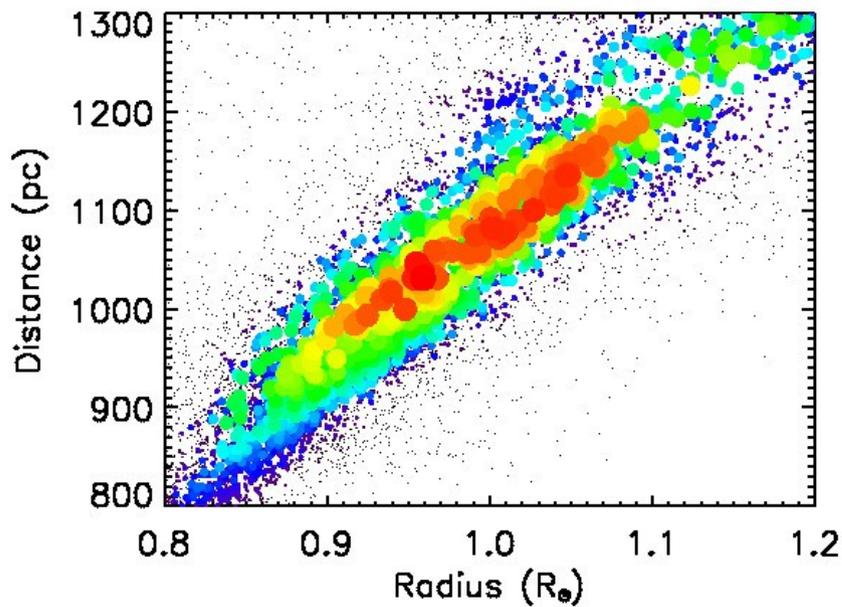
Un tableau de chasse d'une grande variété :

- la première *naine brune* avec un rayon et une masse mesurés (Corot-3b) ;
- la première *planète rocheuse* avec un rayon et une masse mesurés (Corot-7b) ;
- la planète géante qui transite avec *la plus longue période* (Corot-9b) ;
- des planètes de densité très élevée (Corot-20b) ou très faible (Corot-26b)...

Une trentaine de planètes bien caractérisées, plus de 500 candidats et un suivi qui se poursuit.

Complément

Corot-30



$$R_{*} = 0,97 \pm 0,08 R_{\odot} ; M_{*} = 0,94 \pm 0,04 M_{\odot} ; \text{âge} = 7,2 \pm 2,0 \text{ Gans}$$

Orlagh Creevey (2014) ; Bordé et al. (en préparation)