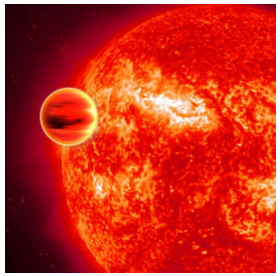
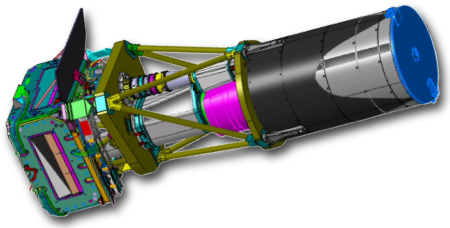
The CoRoT Exoplanet programme: an overview of results





D. Rouan, Observatoire de Paris and the CoRoT Exoplanet Science Team

CoRoT Exoplanet Science Team

- France :

-IAS : P. Bordé, A. Léger, M. Ollivier, B. Samuel, C. Cavarro

- LAM : A. Bonomo, C. Moutou, M. Deleuil, J.C. Gazzano, A. Santerne, P. Guterman, L. Jorda, A. Santerne, P. Barge

- OHP : F. Bouchy, G. Hébrard

- LESIA : D. Rouan

- Luth : J. Schneider

- Obs Nice : T. Guillot, D. Valencia

- Germany : A. Eriksson, E. Guenther, A. Hatzes, P. Kabath, M. Paetzold, H. Rauer, J. Cabrera, G. Wurchterl, S. Csizmadia, L. Carone

- Spain : J.M. Almenara, H. Deeg, B. Tingley

- England : S. Aigrain, N. Gibson, C. Cameron

- ESA : M. Fridlund, D. Gandolfi, S. Carpano

- Belgium : M. Gillon

- Geneva : D. Queloz, R. Alonso, M. Mayor

- Tel Aviv : T. Mazeh, A. Ofir

- USA : M. Endl, D. Ciardi, W. Cochran,A. Shporer

The CoRoT satellite

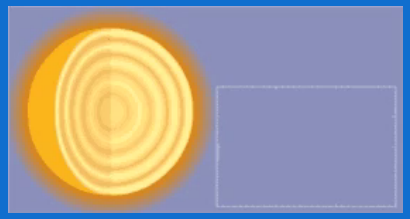
COROT : a European project

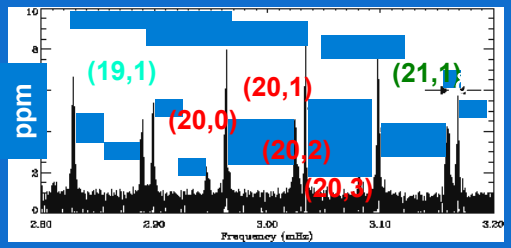
- *CoRoT : Convection Rotation **Transit***
- France (80%) :
  - CNES main contractor
  - Alcatel Alenia Space
  - Institutes : LESIA (Observatoire de Paris), LAM (Marseille), IAS (Orsay)
- Other partners : Austria, Spain, Germany, Belgium, ESA, Brazil
- Operation started in 2007
- Mission extended until end 2013 (more in discussion)

CoRoT: a photometric satellite

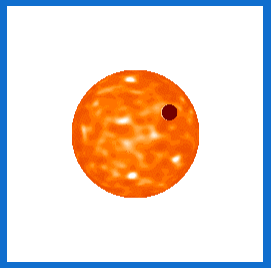
- Continuously monitors thousands of stars during periods of 5 months each (+ some 2-4 weeks periods)
- Two programmes conducted in parallel :

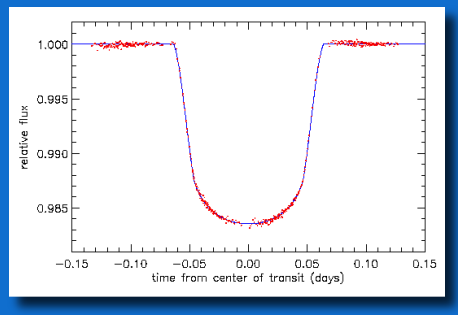
- Asterosismology:
  - ~ 15 stars
  - One exposure / sec





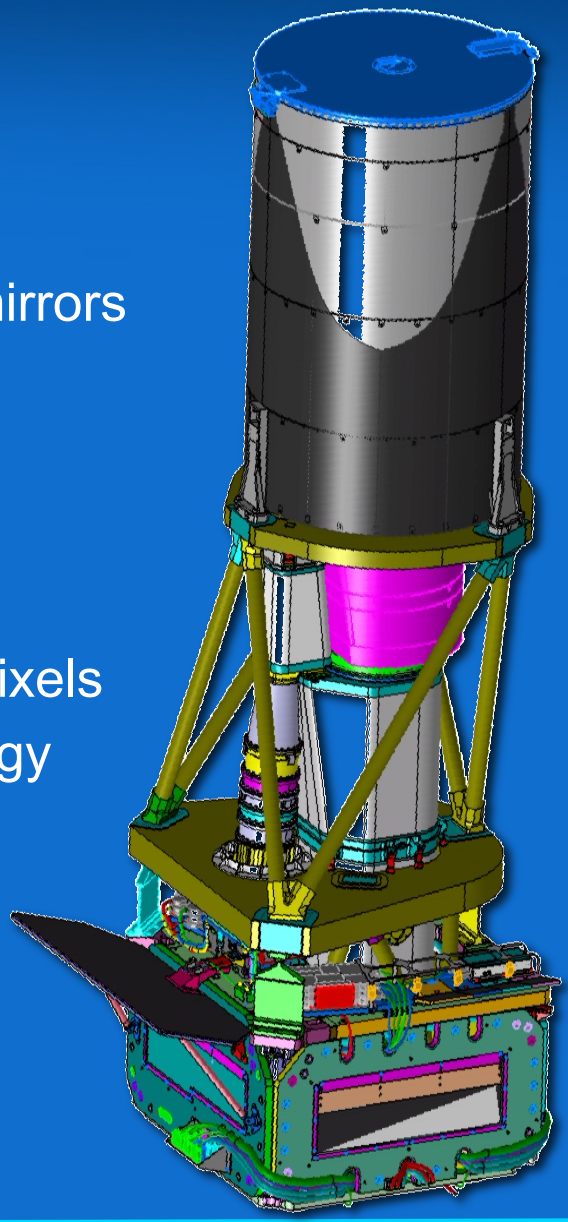
- Exoplanets (transits) :
  - ~ 12.000 stars
  - One exposure /32 sec
  - 3 *colors*

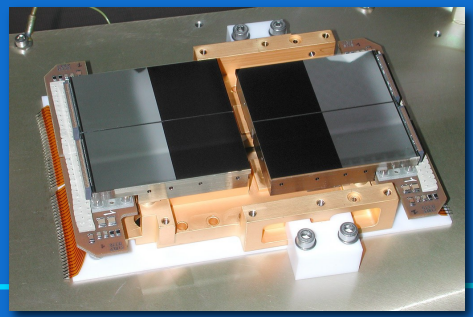




The CoRoT Instrument

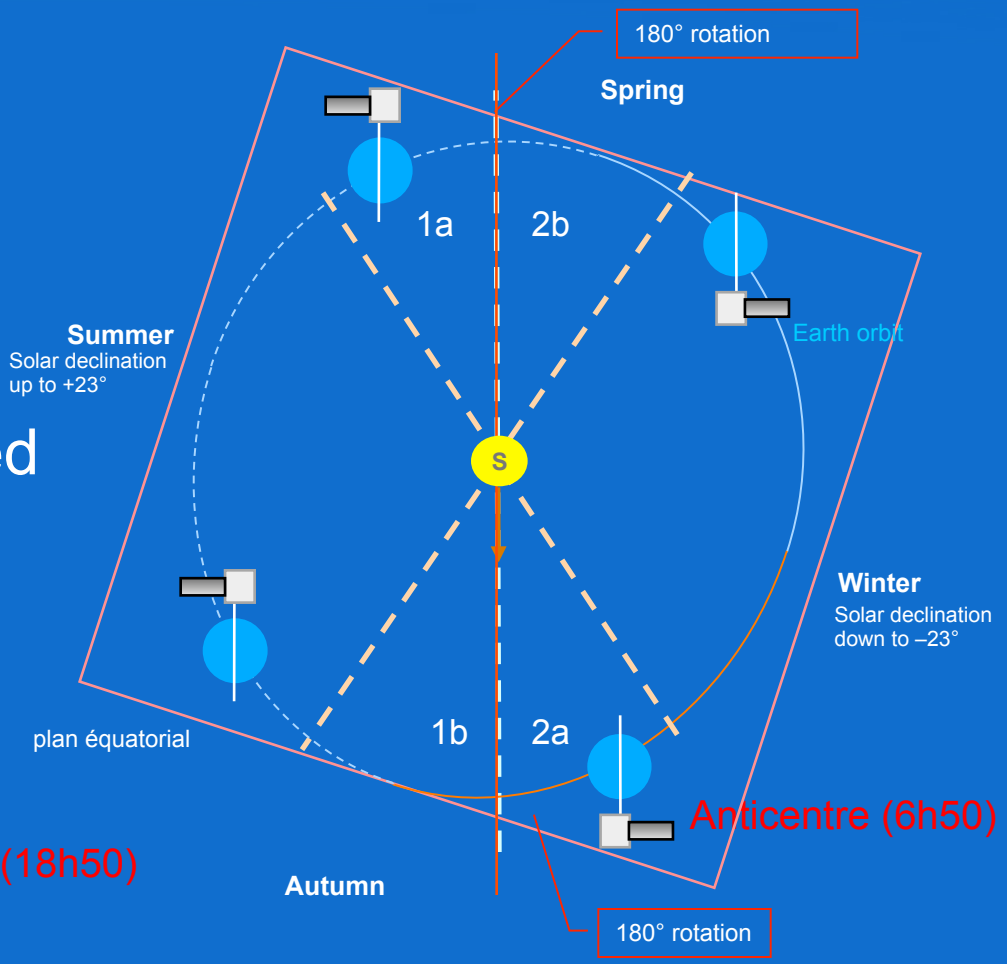
- Télescope
  - Pupil diameter : 27 cm
  - Afocal telescope : 2 parabolic mirrors
  - Long baffle
- Wide field camera
  - Dioptric objective w 6 lenses
  - Focal plane : 4 CCD of 2048^2 pixels
    - 2 (➜1) CCD astero-sismology
    - 2 (➜1) CCD exoplanets
  - Exoplanet field : $3.45(°)^2$





Observing strategy

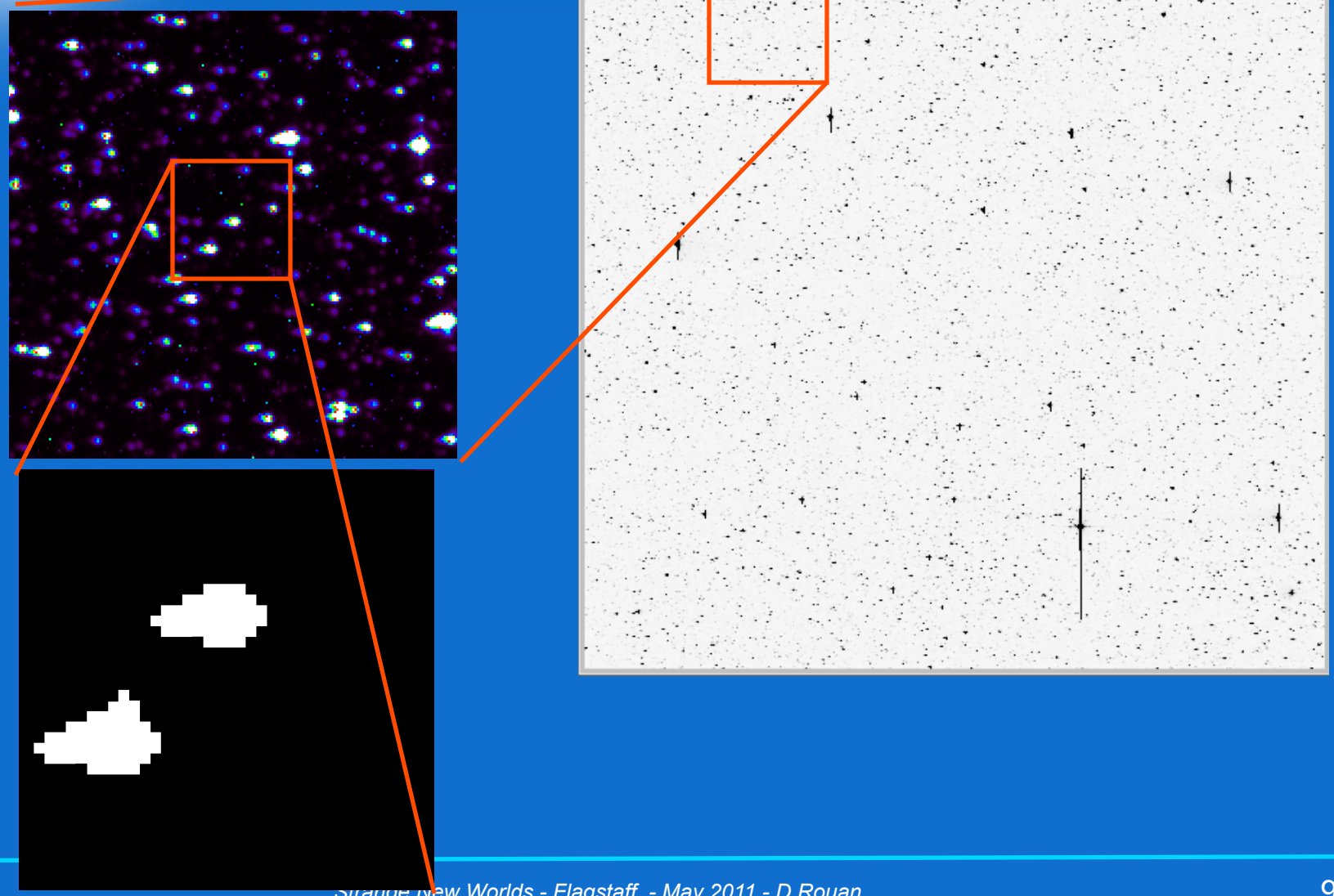
- Polar orbit
- Sun *in the back* ➜
  Flip each semester
- Up to 150 days of continous observation on each field
- 16 fields already observed
  - 5 short
  - 6 medium
  - 5 long



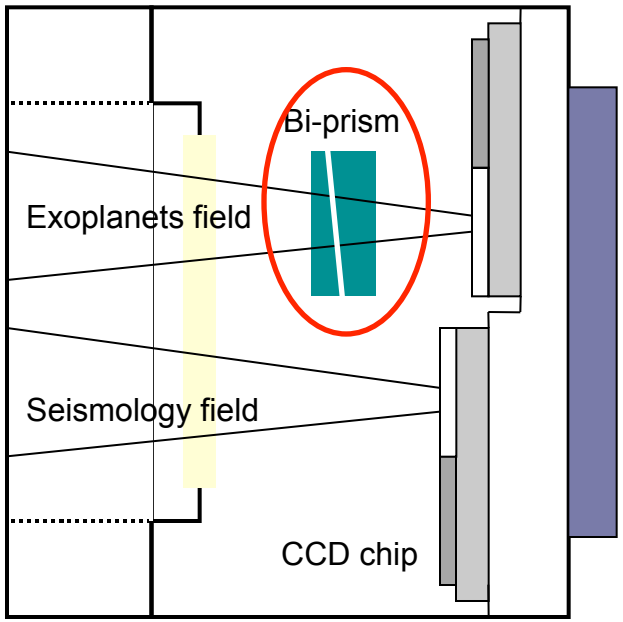
Launch

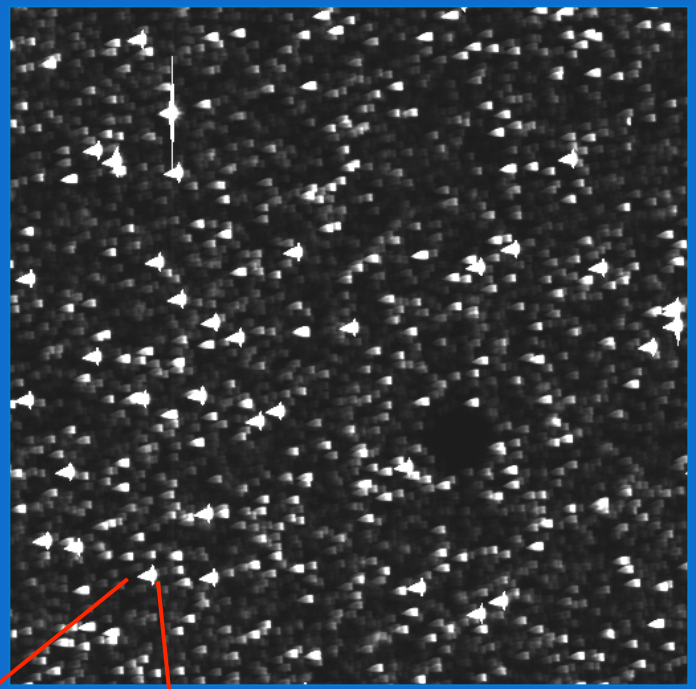
With a good old faithful Soyuz

Exoplanet field: 2 (now 1) × 6000 stars

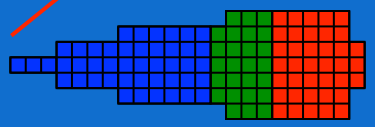


The focal plane





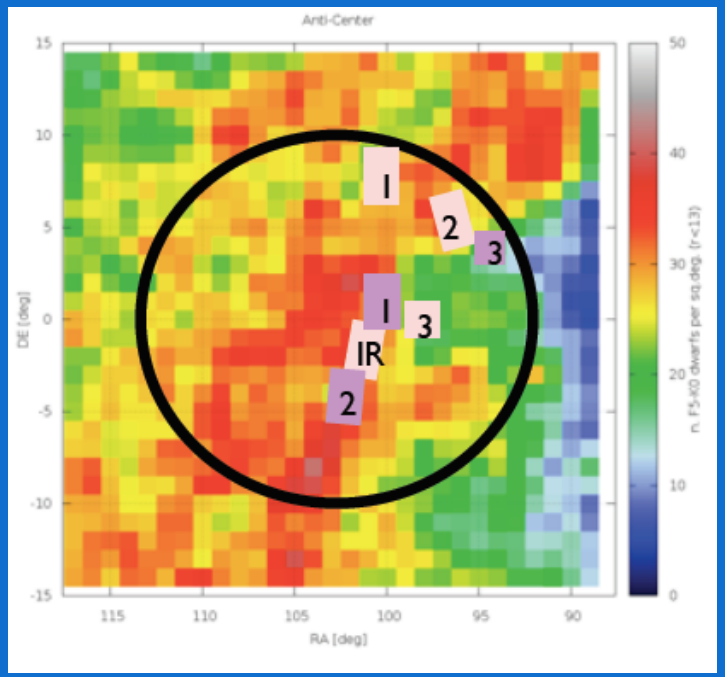
Photometry in 3 « colors »



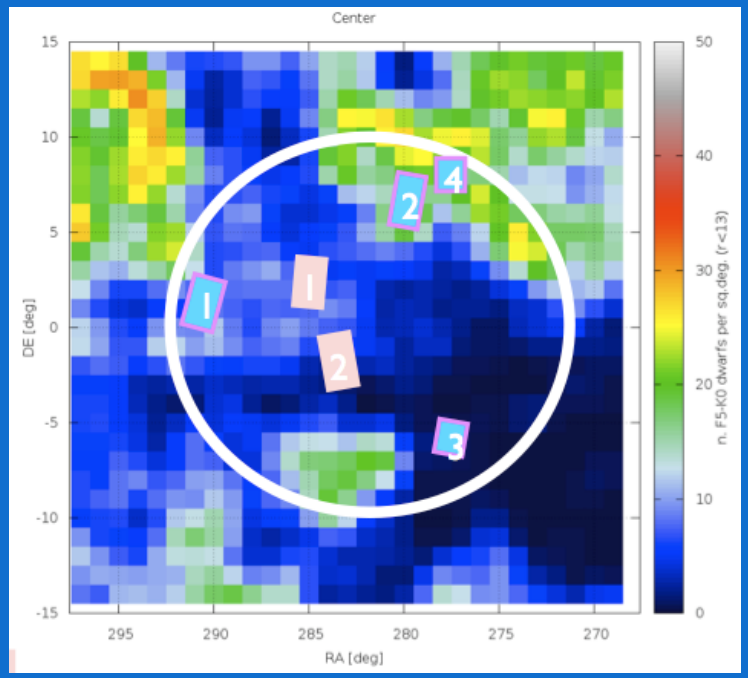
PSF : 60 - 80 pixels
Depending on magnitude

CoRoT “eyes”:different stellar densities

$11 \leq V \leq 16$



10° radius circle

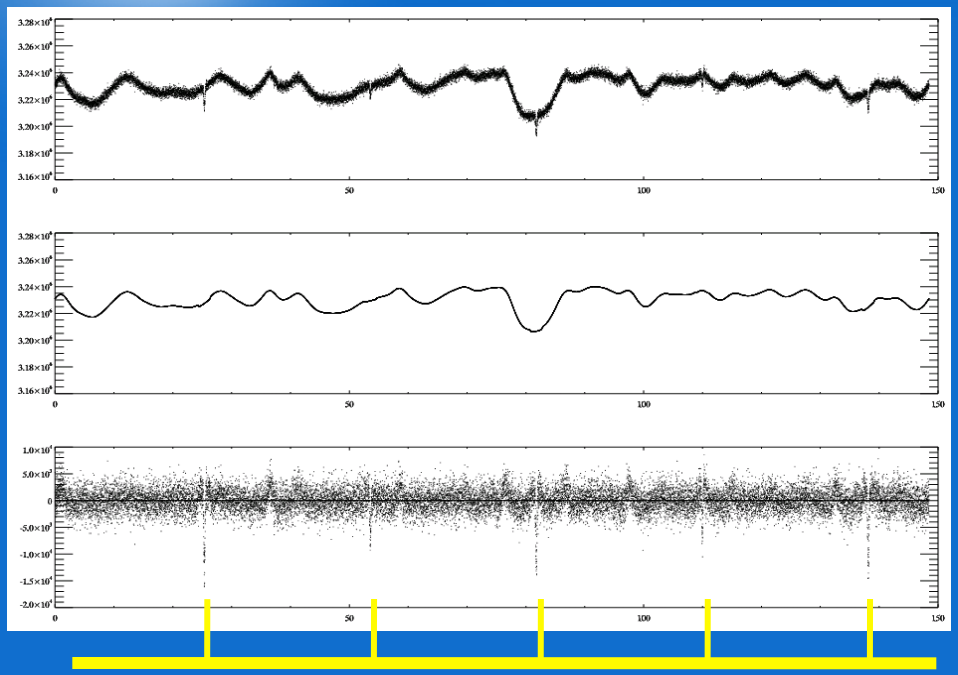


“anti-center”
centered at 6h50

Short Run (SR)
Long Run (LR)

“center”
centered at 18h50

Processing of a light curve



Original

Low frequencies :
stellar fluctuations

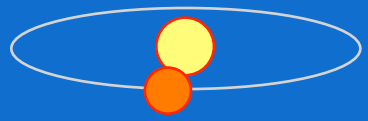
High frequencies :
transits

- Detection of a planet candidate : at least three transit-like periodic events

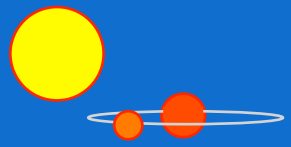
  ➜ orbital periods T < 50 days

Beware of *false positives*

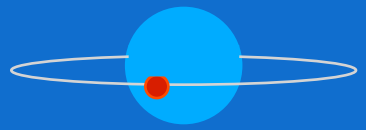
- The ennemy : the false positive !
  produces a signal that mimics a transiting planet



- The star is a Grazing Eclipsing Binary (GEB)



- Eclipsing Binary in the Background (BEB)



- Eclipsing Binary in a dwarf/giant system

- FOLLOW-UP FROM THE GROUND IS MANDATORY !

How identifying a liar ? Follow-up !

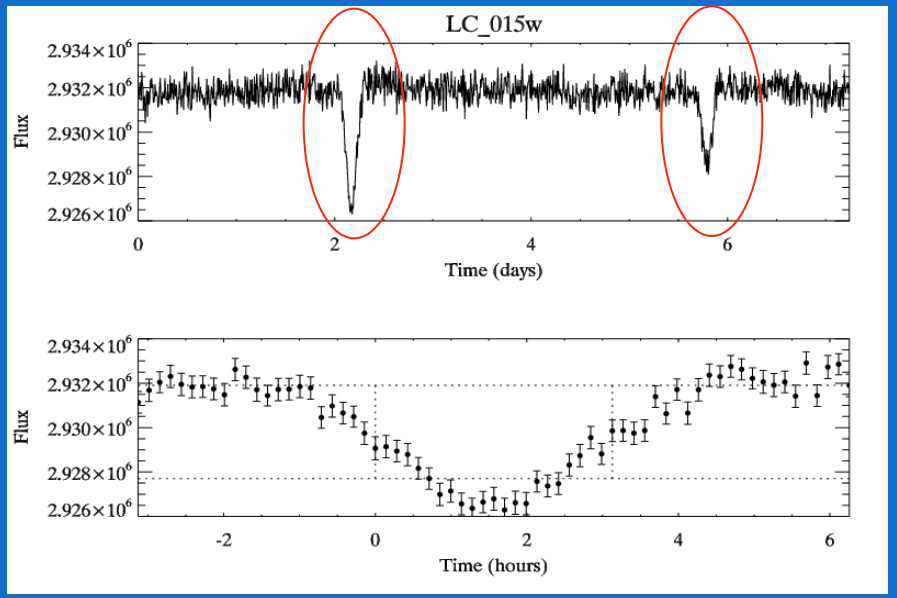
- Transit : V-shape and secondary eclipse
  - ➜ grazing binary

  Corot LC
- CoRoT Coulours of the transit
  - ➜ binary system
- Radial Velocity
  - ➜ mass of secondary :

  HARPS, HIRES, SOPHIE
- Spectroscopy
  - ➜ giant star or blend :

  HARPS, Tautenburg, SOPHIE
- ON/OFF Photometry of field stars
  - ➜ background eclipsing binaries

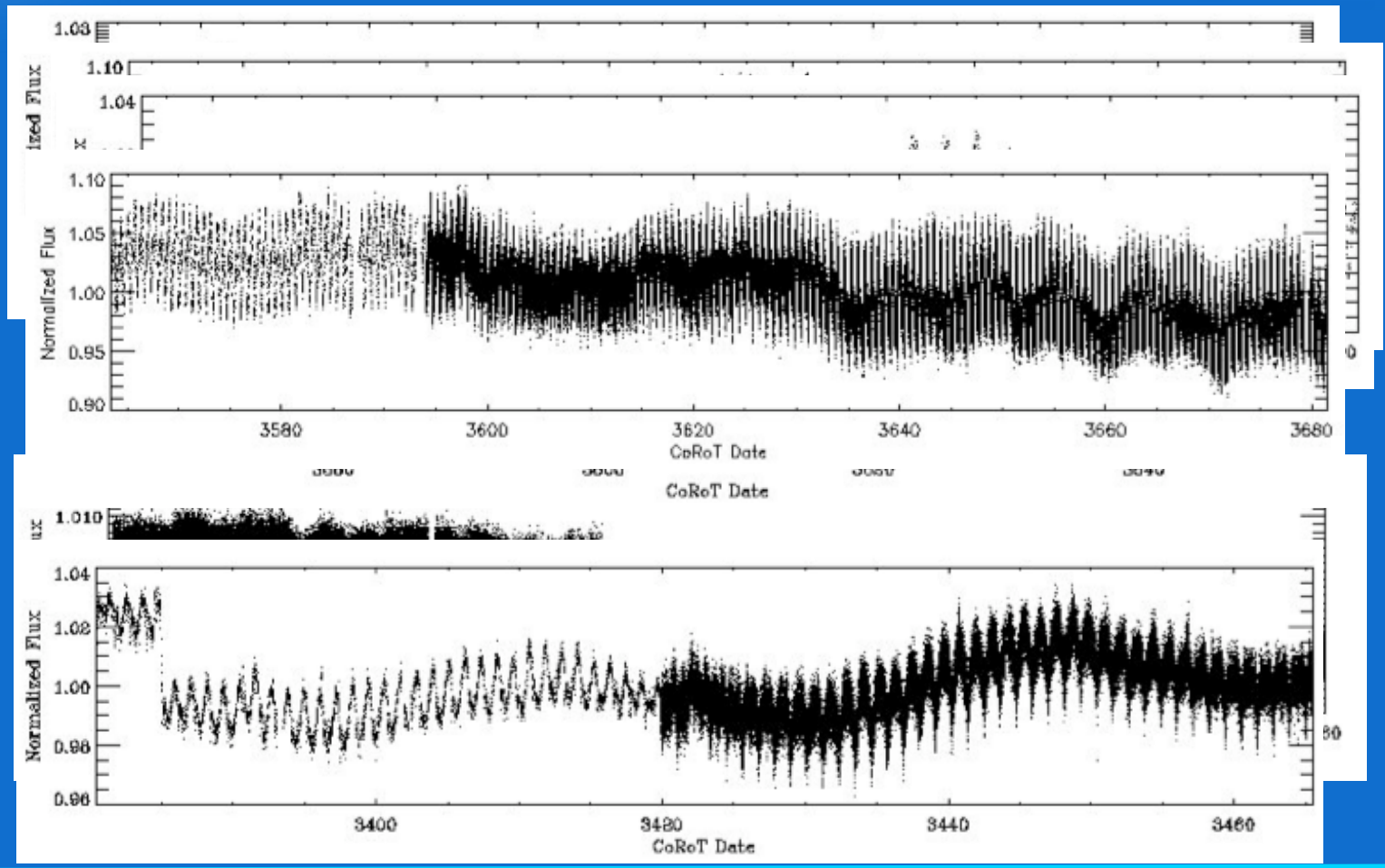
  CFHT-Megacam, IAC-80, WISE, OHP, BEST,..
- Adaptive Optics (NACO):
  - ➜ Identification of blends



The CoRoT planets sample

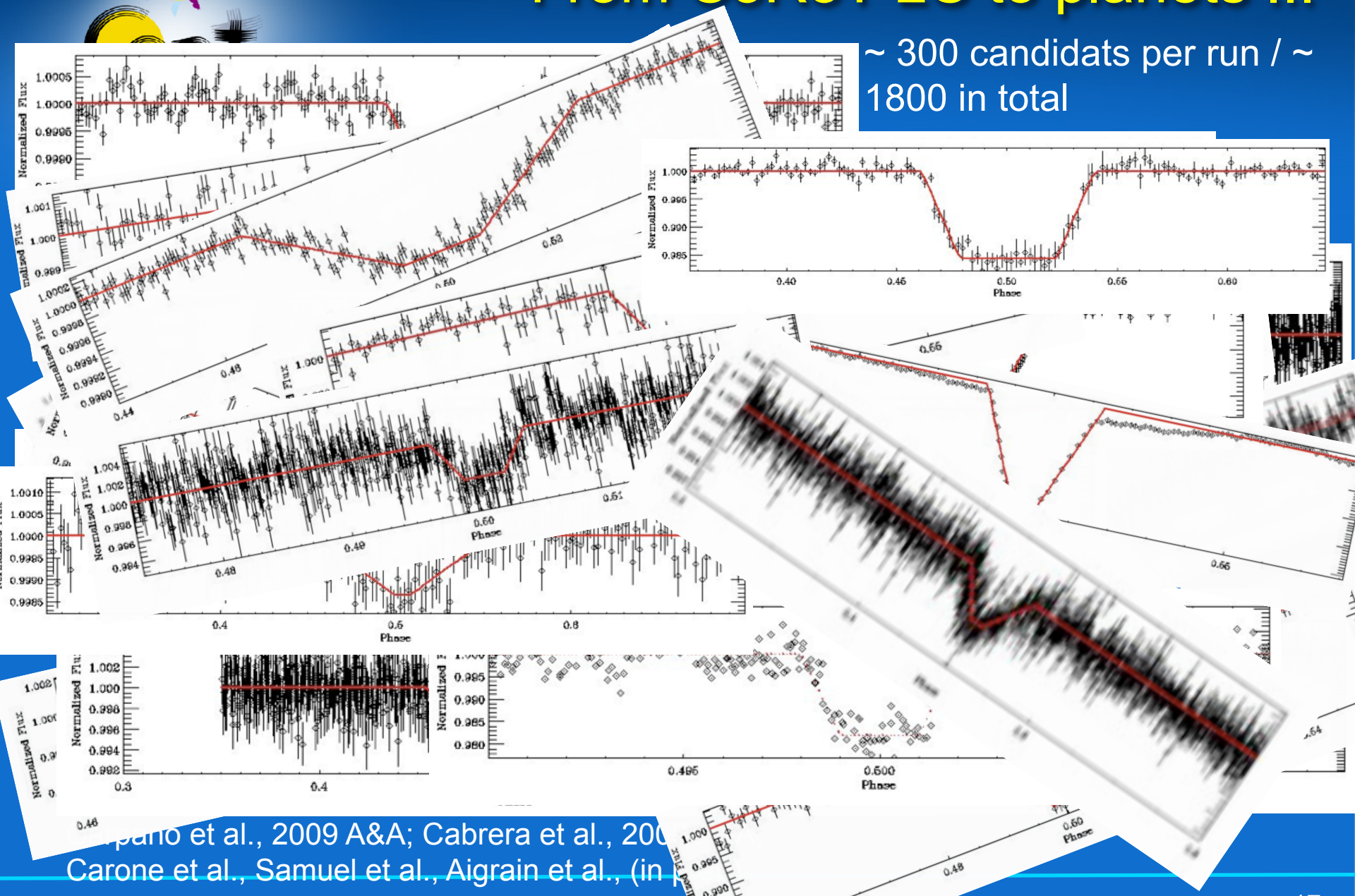
CoRoT Light Curves

- 17 runs : 1400 days, 150 000 stars
  ~ 90 000 Light Curves (LC) > 60 days
  ~ 60 000 LC in Short Runs



From CoRoT LC to planets ...

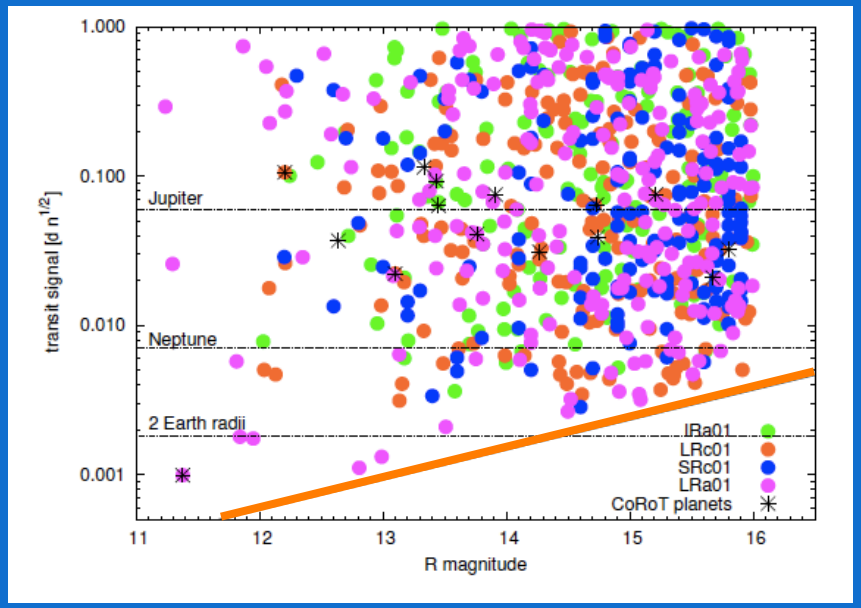
~ 300 candidats per run / ~ 1800 in total



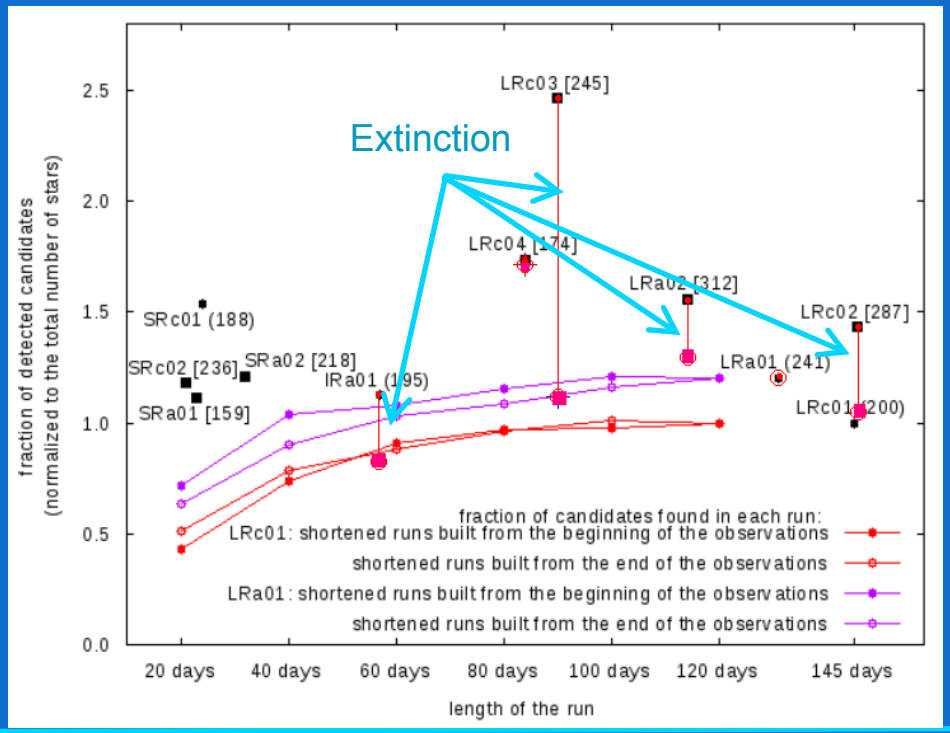
...pano et al., 2009 A&A; Cabrera et al., 200...
Carone et al., Samuel et al., Aigrain et al., (in p...

Detection : performances

- CoRoT team has analyzed ≈ 10^5 stars and confirmed (so far) 20 substellar objects : 18 transiting planets and 2 brown dwarves
  - All in long runs
  - 200-300 detections of periodic events / run : 2-3 %
  - 1-4 detections of planets / run : 0.5 - 2% of periodic cases
- The dispersion in yields is likely due to extinction variations

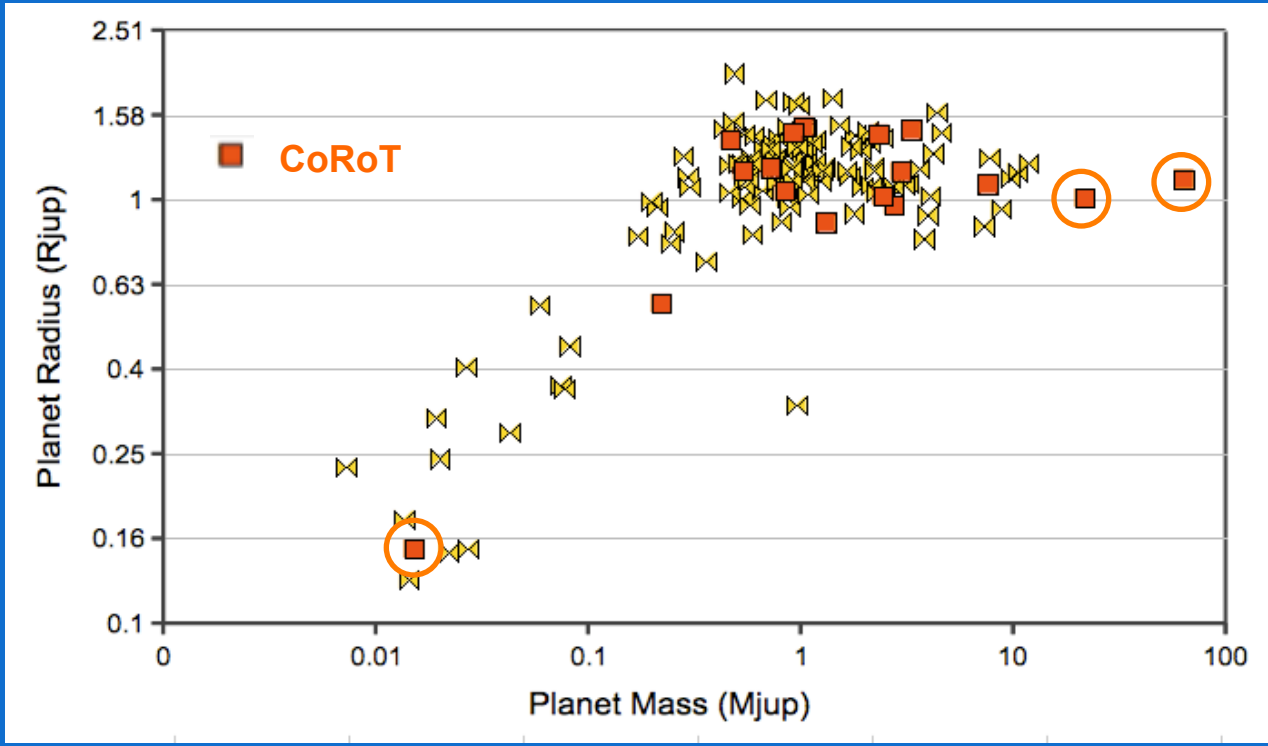


Cabrera et al., 2009 A&A 506, 501 + priv. com.



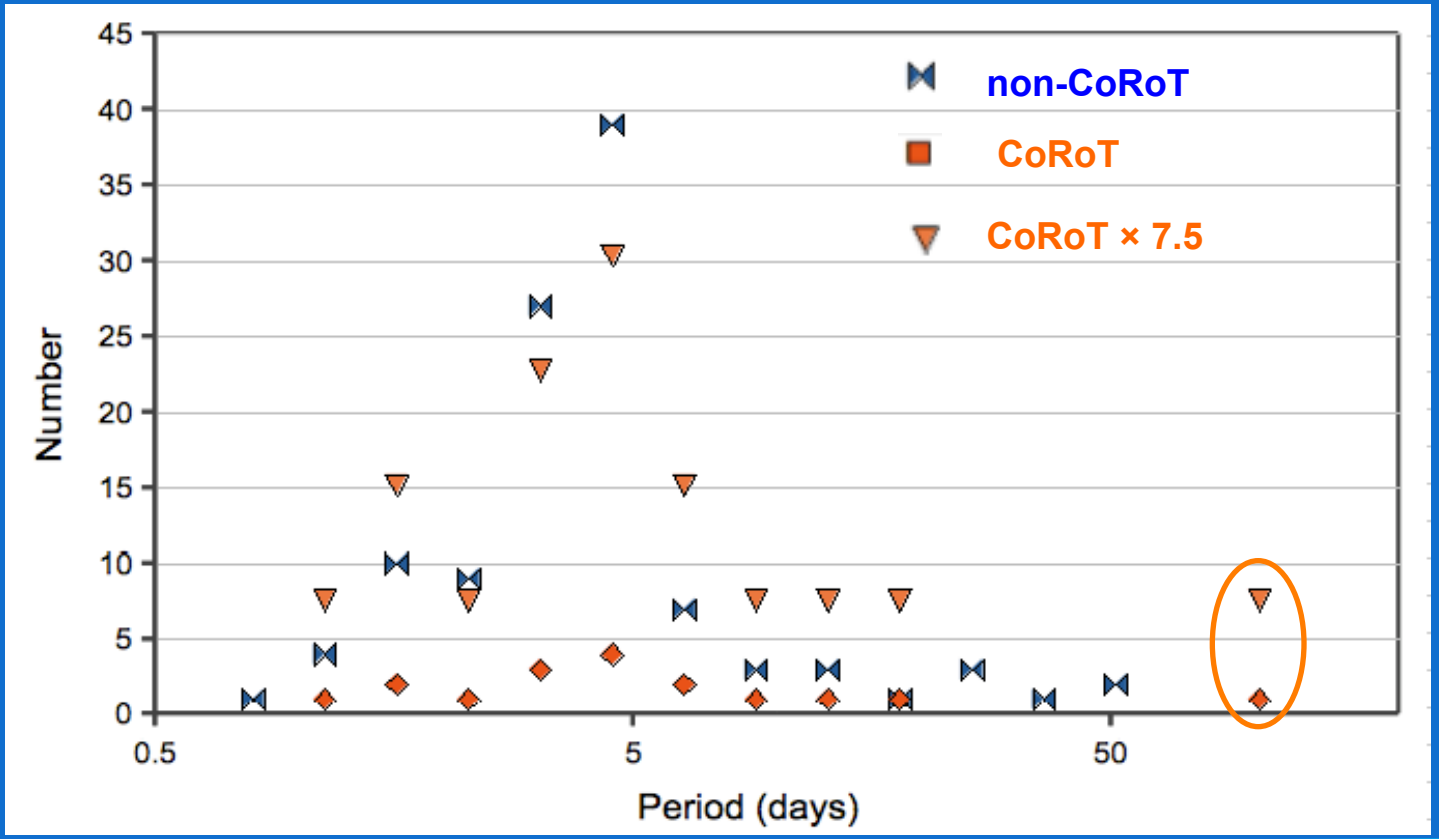
CoRoT planets on the R vs M diagram

- Corot covers well the whole range
  - Densities from 0.21 to 55 g cm^{-3}
- Corot extended towards both extremes :
  - Corot-15b : 65 M_{Jup} and Corot-7b : .015 M_{jup}
- 2 brown dwarves
  - Corot-15b and Corot-3b



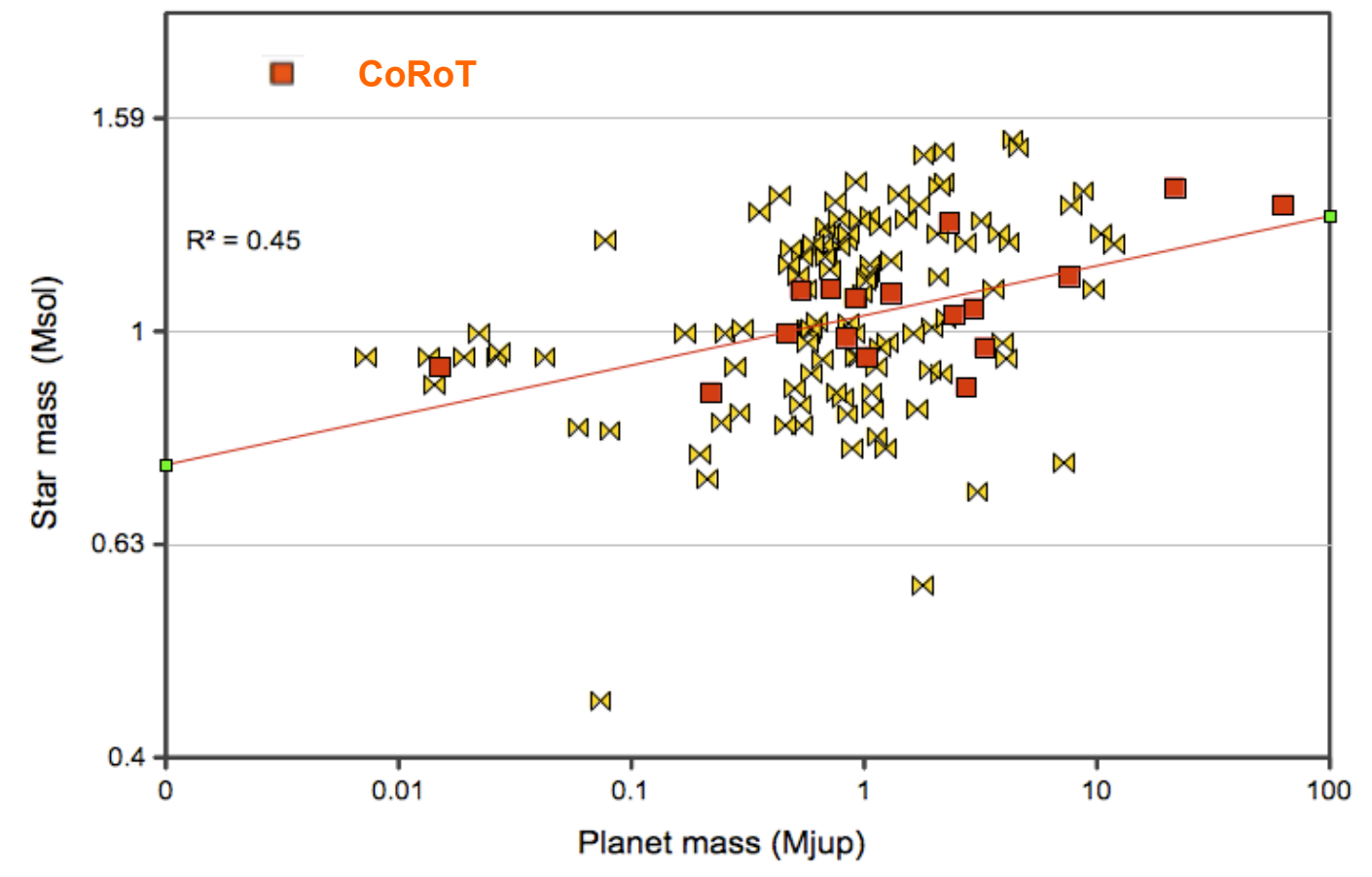
Periods of transiting systems

- CoRoT appears to be unbiased with respect to orbital period values
  - three medium periods : 9 - 13 days
  - one long period : 95 days



Massive companions for massive stars ?

- CoRoT sample supports an already mentionned (and expected) trend

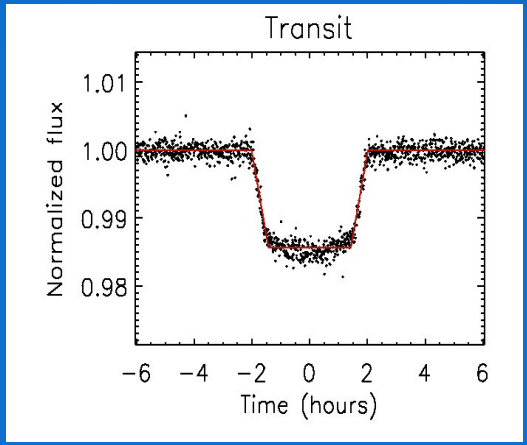


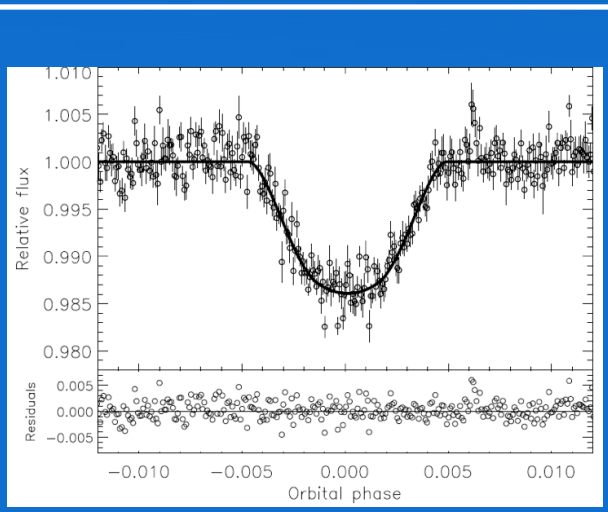
Highlights

“Long period” systems

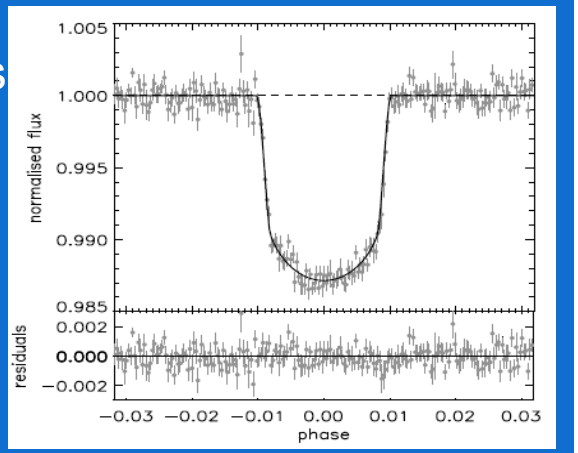
Aigrain et al.,2008 A&A ;
Moutou et al., 2008 A&A
Fridlund et al., 2010 A&A

CoRoT-4b: 7 transits
Period = 9.2 days
M_p= 0.72 M_{jup}
R_p = 1.19 R_{Jup}
ρ= 0.525 g/cm^3



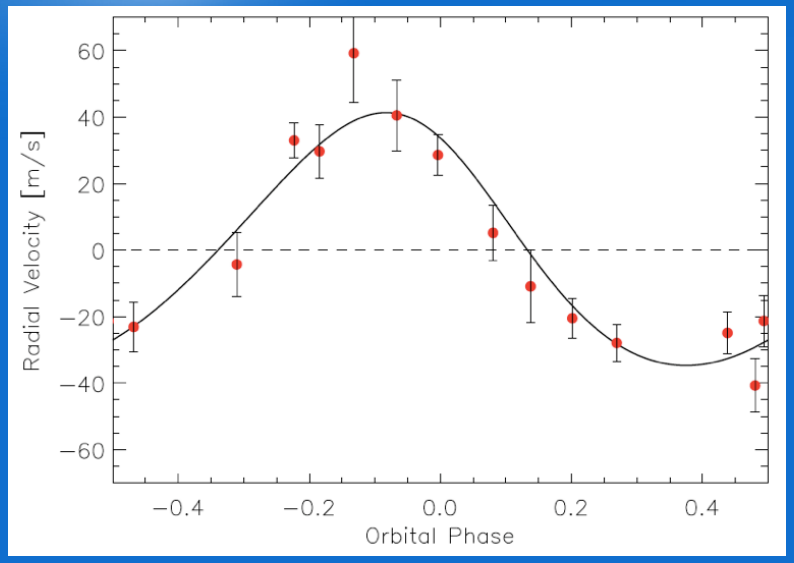


CoRoT-6b: 15 transits
Period = 8.88 days
M_p= 2.96 M_{jup}
R_p = 1.16 R_{Jup}
ρ= 2.32 g/cm^3
[Fe/H] = -0.20



CoRoT-10b : 15 transits
Period = 13.24 days
M_p= 2.75 M_{jup}
R_p = 0.97 R_{Jup}
e = 0.53
ρ= 3.7 g/cm^3
K1V [Fe/H] = 0.26

The “very long period” system Corot-9b : a Mercury-like orbit



Period = 95.27 days

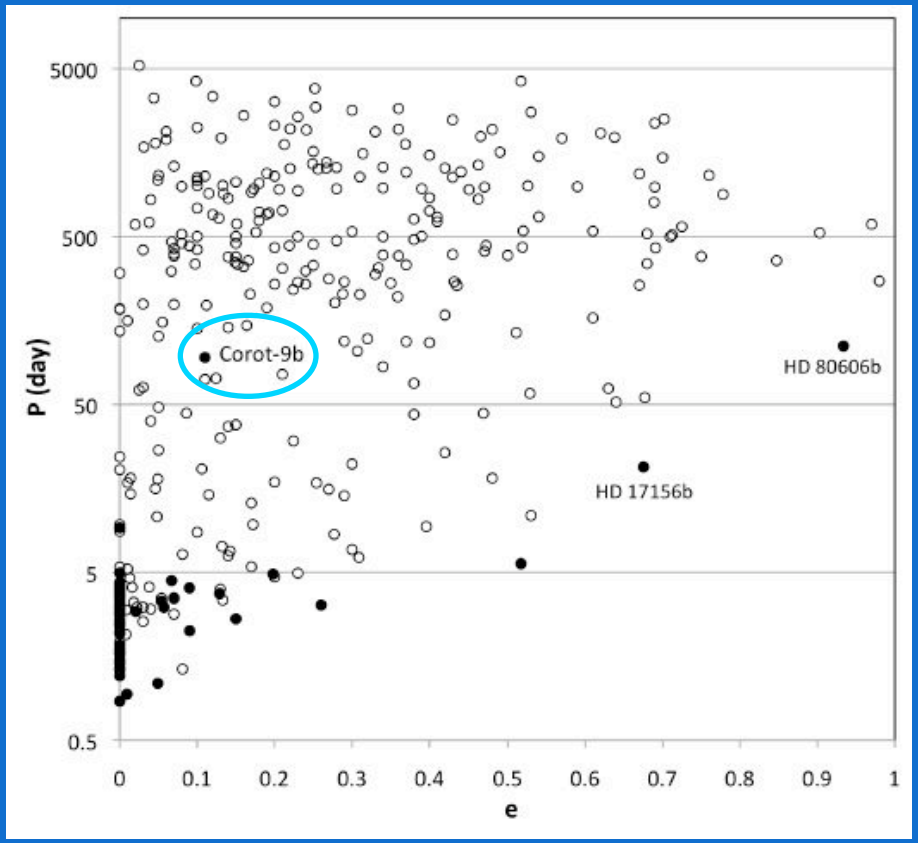
M_p= 0.84 ± 0.07 M_{jup}

R_p = 1.05 ± 0.04 R_{Jup}

ρ= 0.525 ± 0.15 g/cm^3

Will soon be re-observed

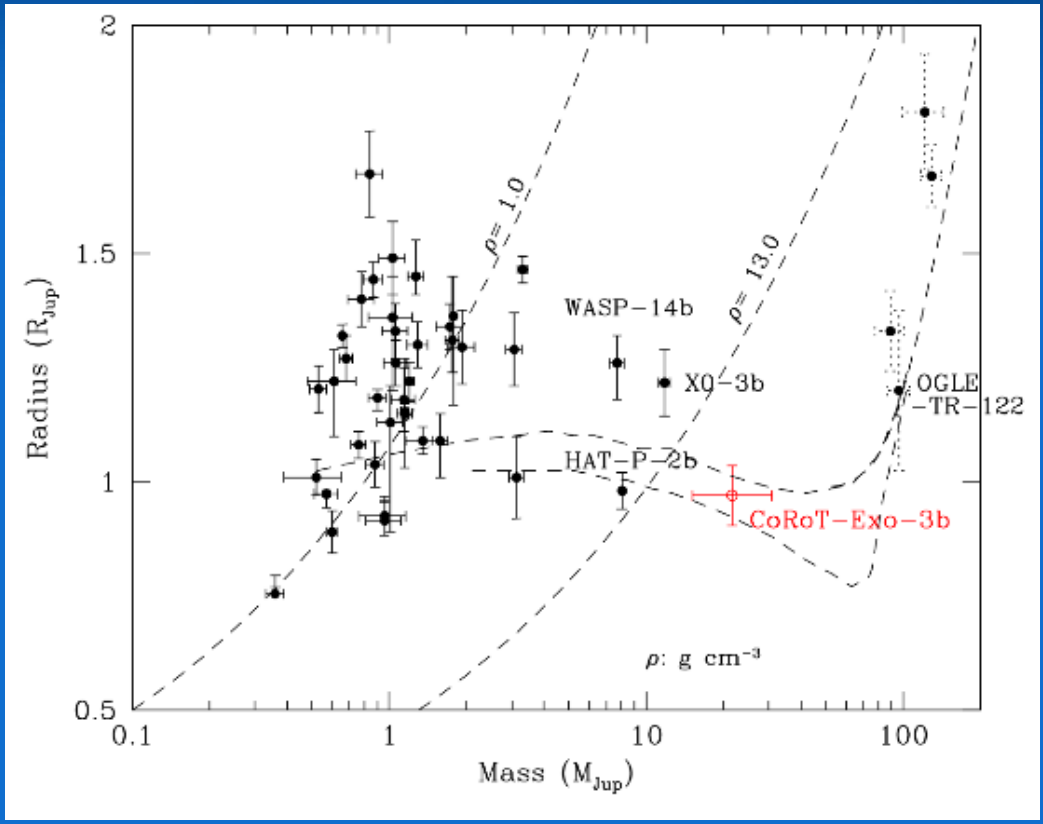
Deeg et al., Nature 2010



At the extreme of the mass function

CoRoT-3b :
34 transits

F3V - vsini = 17 km/s
Period = 4.26 days
M_p= 21.6 ± 1.00 M_{jup}
R_p = 1.01 ± 0.07 R_{Jup}
ρ= 26.4 ± 5.6 g/cm^3



Deleuil et al., 2008 A&A 491, 889

- Super-planet or brown dwarf ?
- Definition of a planet ?
- An exceptional object or just one member of a new class ?

CoRoT-15b : a bona fide Brown Dwarf

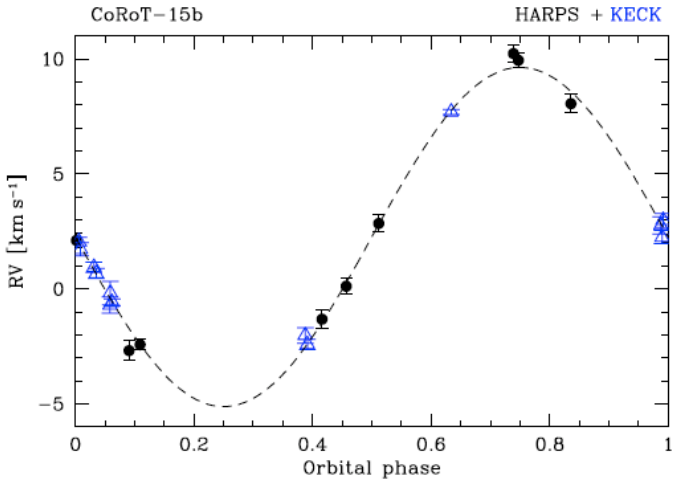
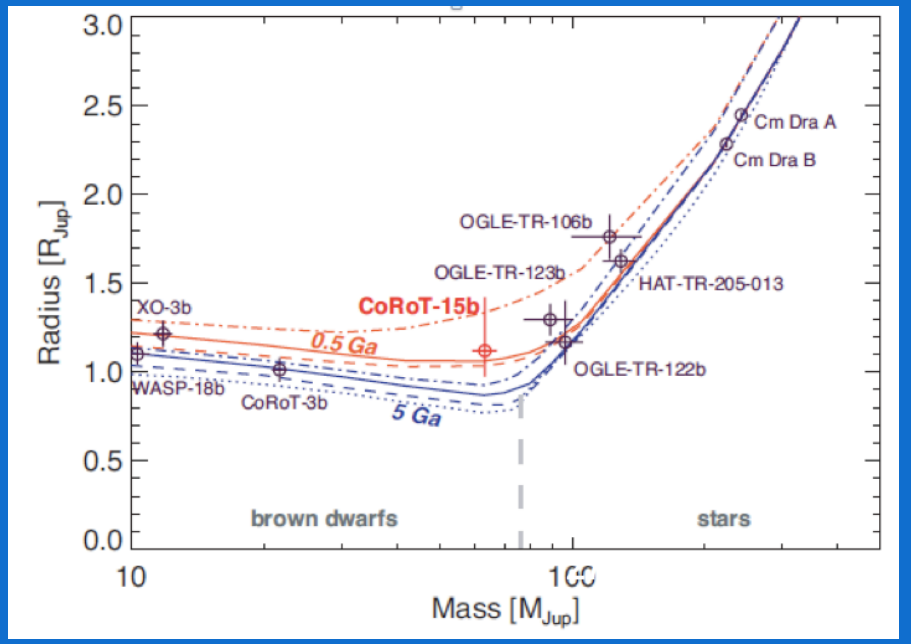


Fig. 3. Phase-folded radial velocity measurements of CoRoT-15 with HARPS (dark circle) and HIRES (open triangle)

Bouchy et al., 2010



CoRoT-15b :
34 transits
F7V vsini = 19.0 km/s
Period = 3.06 days
M_p= 63.3 ± 4.10 M_{jup}
R_p = 1.12 ± 0.3 R_{Jup}
ρ= 59.0 g/cm^3

CoRoT-8b : a Neptune-like planet

- CoRoT-8b

49 transits

Period = 6.21 days

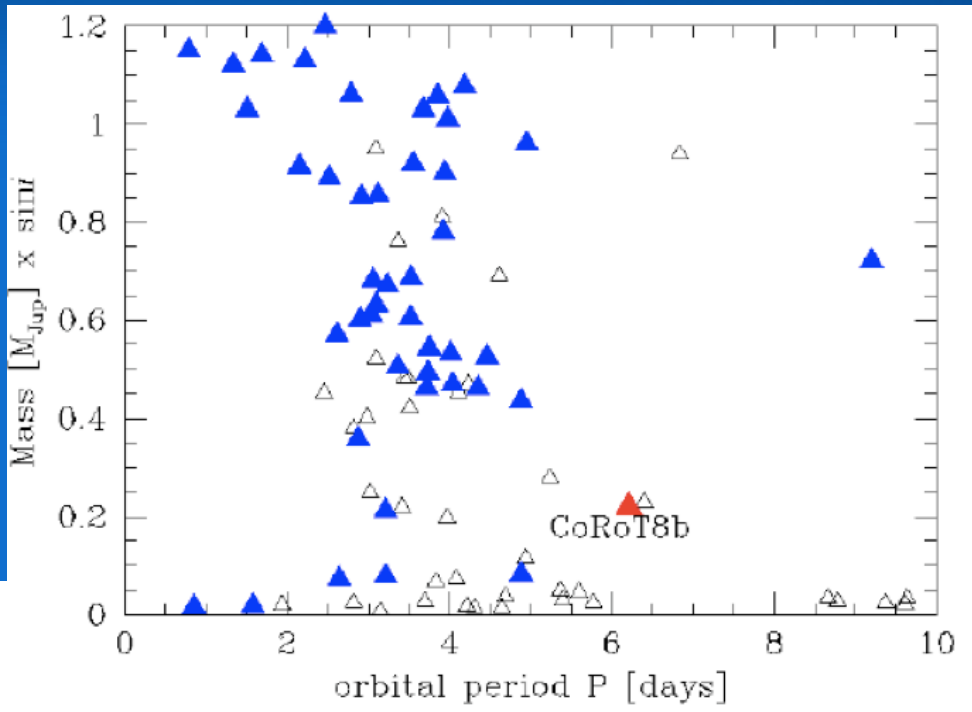
M_p= 0.22 ± 0.03 M_{jup}

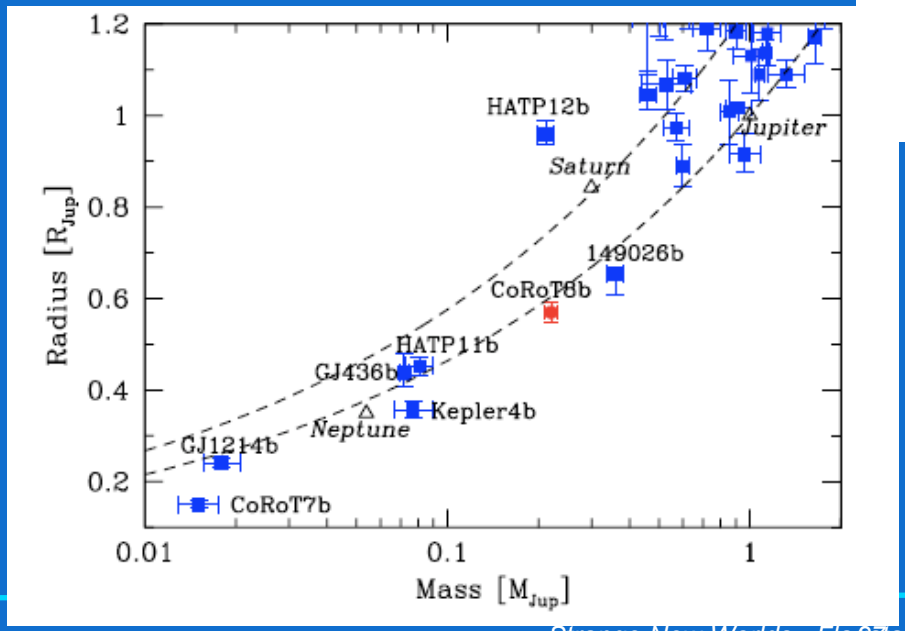
R_p = 0.57 ± 0.02 R_{Jup}

ρ= 1.6 ± 0.10 g/cm^3

[Fe/H] = 0.30 ± 0.10

Bordé et al., 2011 A&A



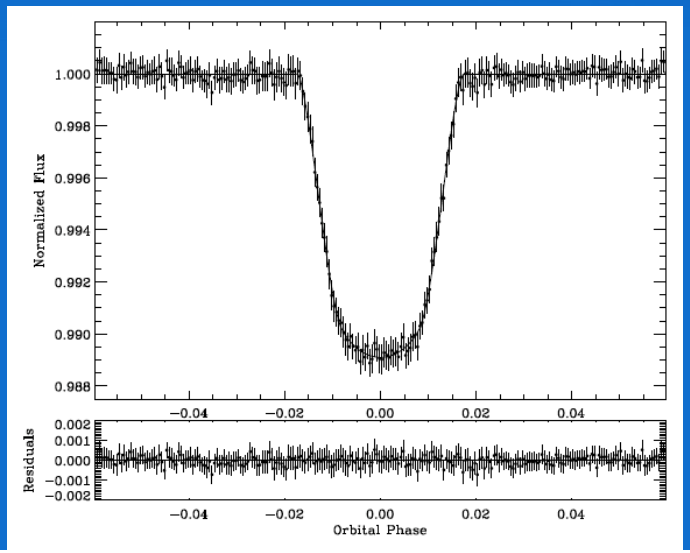


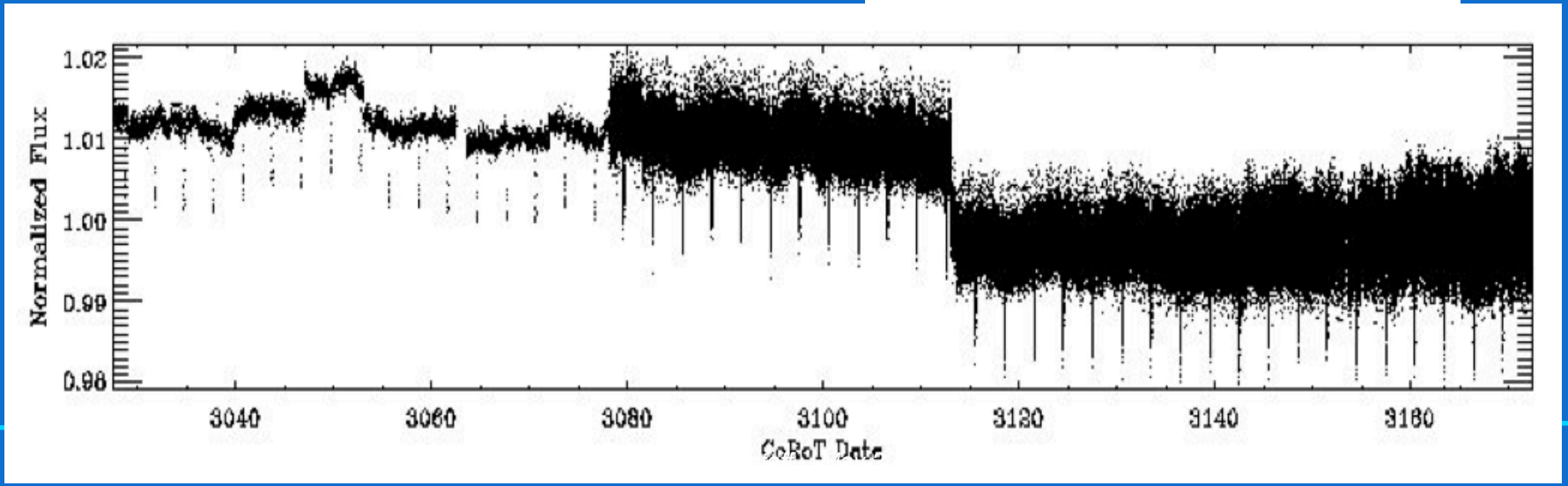
CoRoT-11b : a bloated planet around a fast rotator

- CoRoT-11b

F7V - vsini = 40km/s
49 transits
Period = 2.99 days
M_p= 2.33 ± 0.34 M_{jup}
R_p = 1.43 ± 0.03 R_{Jup}
ρ= 0.99 ± 0.15 g/cm^3
[Fe/H] = -0.03 ± 0.08

Gandolfi et al., 2011 A&A

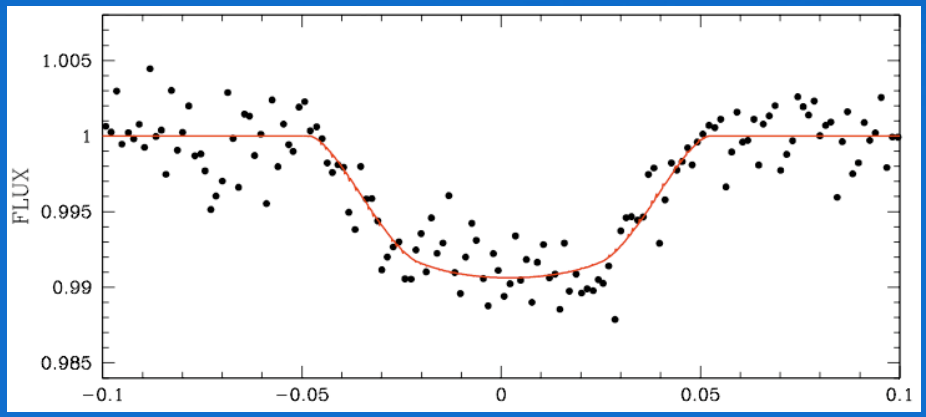


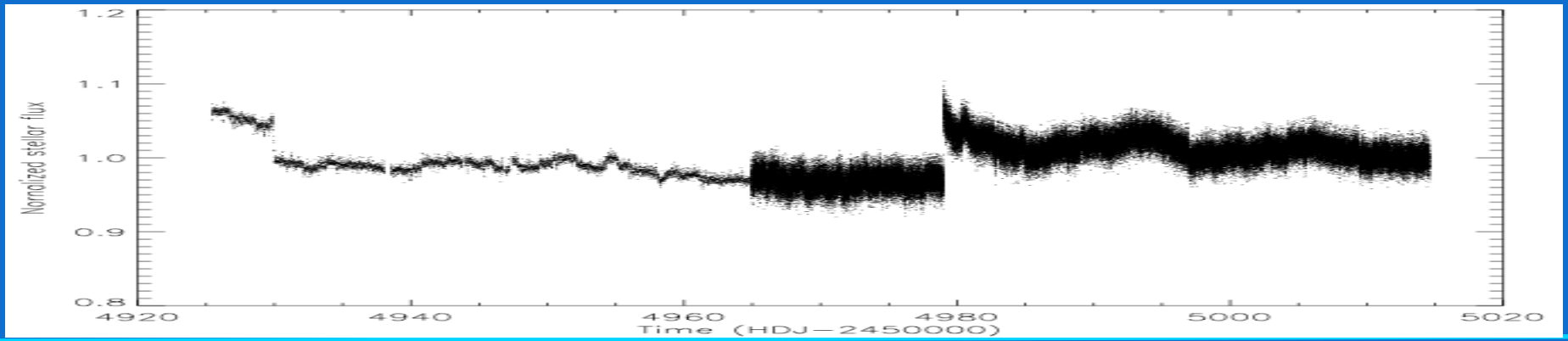


CoRoT-16b : hot, despite excentric Jupiter !

- CoRoT-16b
  G5V
  16 transits
  Period = 5.35 days
  M_p= .535 ± 0.084 M_{jup}
  R_p = 1.17 ± 0.15 R_{Jup}
  ρ= 0.44 ± 0.17 g/cm^3
  [Fe/H] = -0.03 ± 0.08
  e = 0.33 ± 0.1 =>
  interaction w another planet ?

Ollivier et al., A&A submitted





CoRoT-17b : an old Jupiter

- CoRoT-17b
  G2V – age: 11± 1 Gyr ➜
  one of the oldest

Soon to be engulfed by its mother star becoming a giant ?

49 transits

Period = 3.77 days

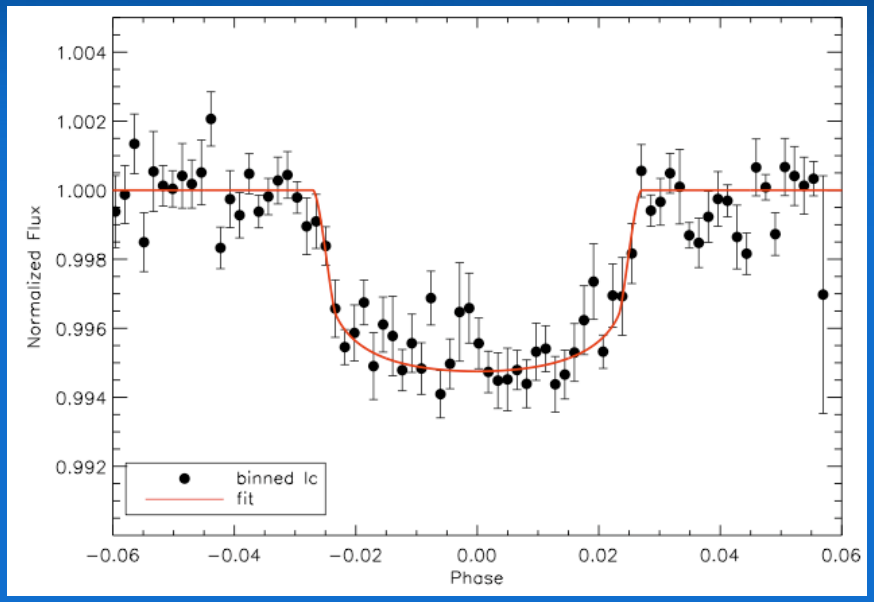
M_p= 2.43 ± 0.3 M_{jup}

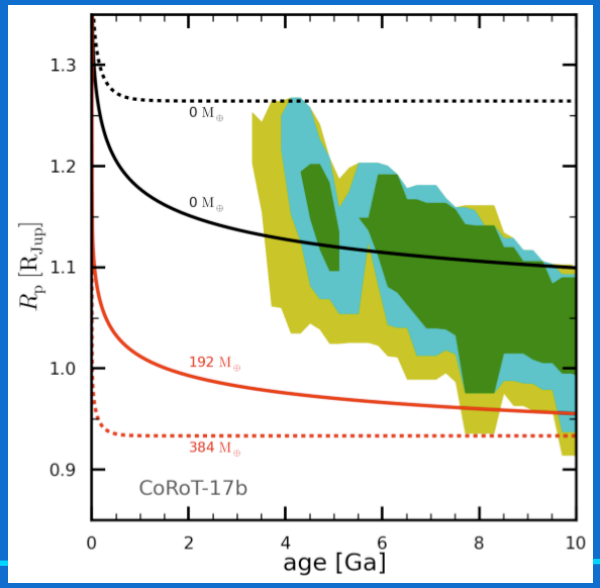
R_p = 1.02 ± 0.07 R_{Jup}

ρ= 2.82 ± 0.38 g/cm^3

[Fe/H] = -0. ± 0.

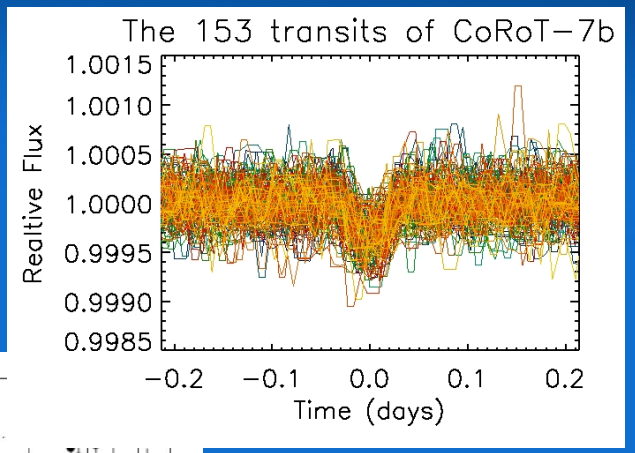
Csizmadia et al., A&A accepted

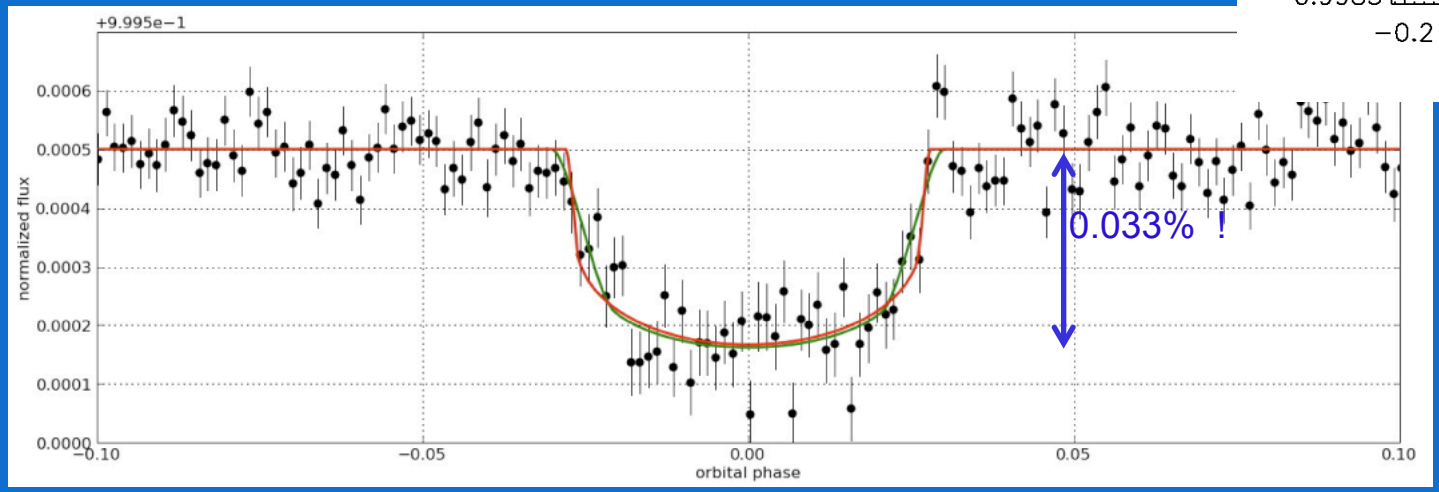




Corot-7b: the first hot super-earth

The folded light curve

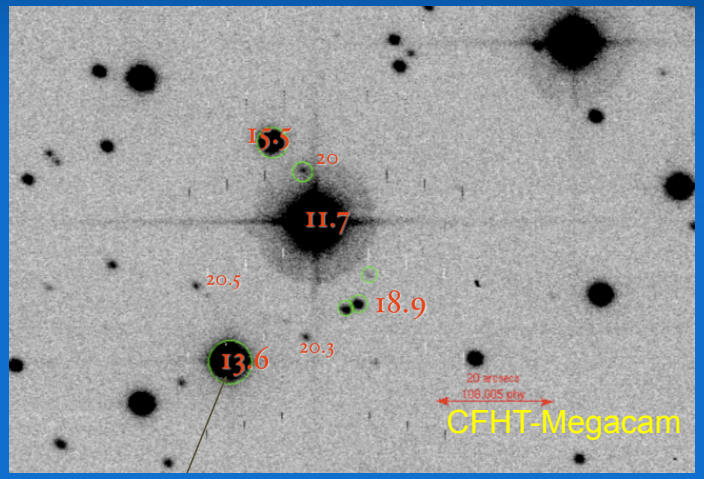




- Transits first detected by quick-look analysis (« alarm » mode)
- 153 transits, all ~ seen when superimposed
- Extremely short period : P= 0.8536 days

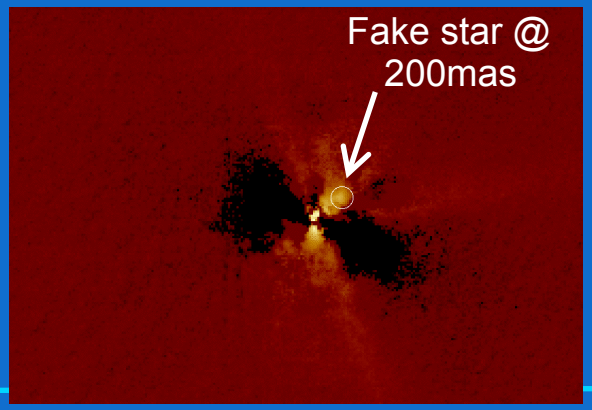
➜ very small transit depth : ΔF/F = 0.033%

A vigorous follow-up programme



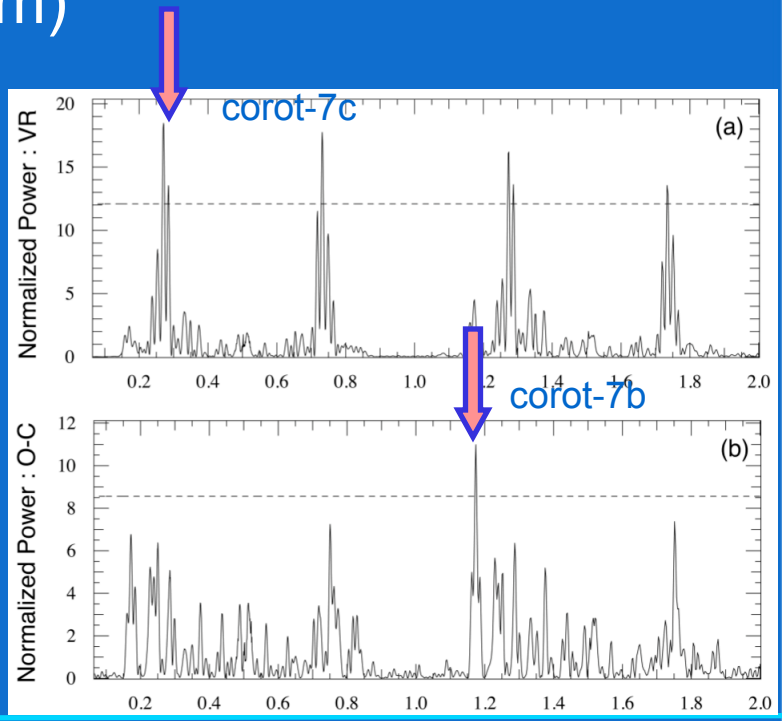
- Such a small transit signal
  - IF A PLANETARY ONE -
  means a very small planet :
  $R_{pl} = 1.7\ R_{earth}$

- ➜ A vigorous Follow-up programme from the ground, using top-level instruments in the world was conducted:
  - ON/OFF photometry (BEB) : CFHT, Canarias
  - IR spectra (CO bands of a M binary) : VLT / CRIRES
  - Adaptive Optics (closest BEB) : VLT / NACO
  - CoRoT color (triple system) : Corot LC
  - X-ray survey (close M binary) : ROSAT
  - Radial velocity : SOPHIE, HARPS



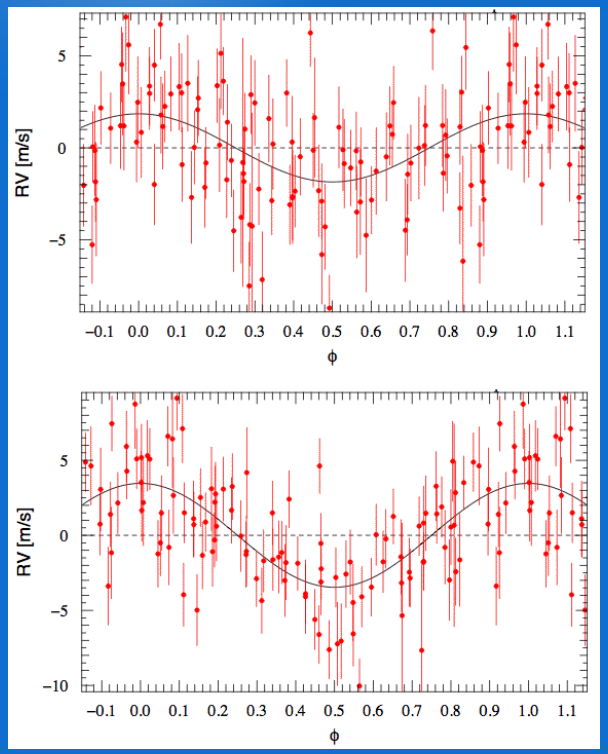
Radial Velocity with HARPS

- HARPS Velocimetry (Queloz, et al. A&A 2009) :
  - 106 measurements (70h) during 4 months
- Difficulty : strong variablity of the star affects the analysis
  - obvious correlation w rotation (23 days)
- Scargle analysis (≈ Fourier Transform)
  - after filtering of rotation (3 harmonics)
  - first peak : 3.7 days
  - Substracted ➜ 2nd peak at 0.85 days
  - Phase of 0.85 d peak agrees w transit
  - Clear confirmation of Corot-7b
  - And discovery of ***a second planet !***



2 (3?) small planets !

- A *two Super-Earth* solution was found



Corot-7b
M = 4.8 ± 0.8 $M_\oplus$
P = 0.853 days
a = 0.017 AU
R = 1.68 ± 0.1 $R_\oplus$

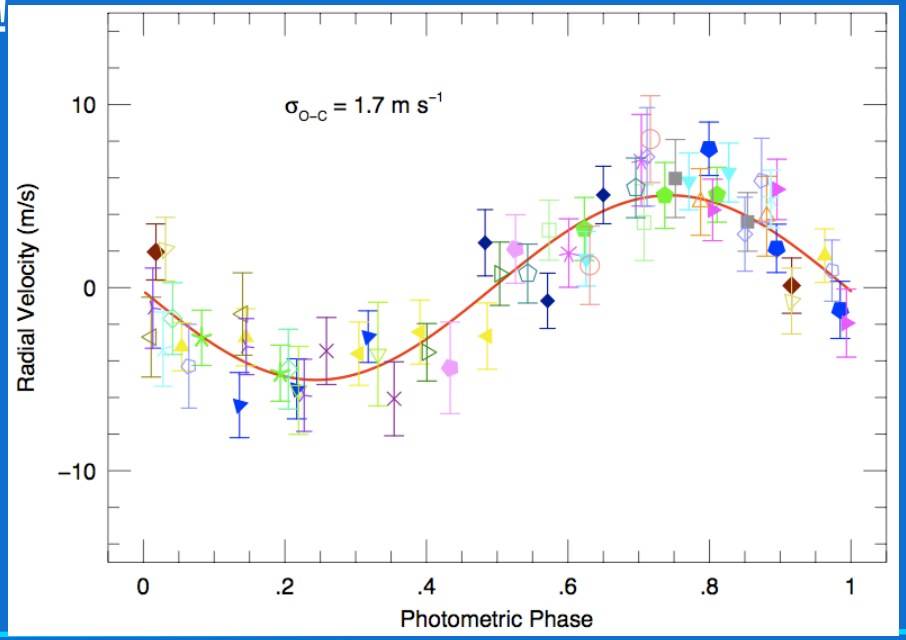
Corot-7c
M = 8.4 ± 0.9 $M_\oplus$
P = 3.70 days
a = 0.046 AU

Parameters	Adopted solution
Period [days]	0.853585±2.4 · 10^{-5} (‡)
T_{tr} [JD]	2454446.731 0.003 (‡)
T_0 [JD]	
K [m s^{-1}]	3.5 ± 0.6
e	0
ω [deg]	180
m [$M_\oplus$]	4.8 ± 0.8
a [AU]	0.017
Period [days]	3.698 ± 0.003
T_0 [JD]	2454445.0 ± 0.7
K [m s^{-1}]	4.0±0.5
e	0
ω [deg]	180
m [$M_\oplus$]	8.4 ± 0.9
a [AU]	0.046

- First case of a system with 2 Super-Earths, one in transit
- A third planet is suspected ➜ a very compact system !

Mass of Corot-7b ? No more controversial

- Reanalyzing the RV data set
  - Several assessments : 2.3 – 8 $M_\oplus$: who can we trust ?
    - Important consequence on density and thus structure
  - Léger et al. 2011 take the median value : 6.9 ± 1.2 $M_\oplus$
  - A smart idea from Artie Hatzes : only keep radial velocity data on nights where multiple measurements were made ➜ effectively removes the activity !
    (Hatzes et al, submitted)



  - M = 7.3 ± 1.4 $M_\oplus$
    ➜ ρ = 10.1 ± 2.7 g cm^{-3} as Kepler-10b : a twin on many aspects.
  - And now 55 Cnc e !

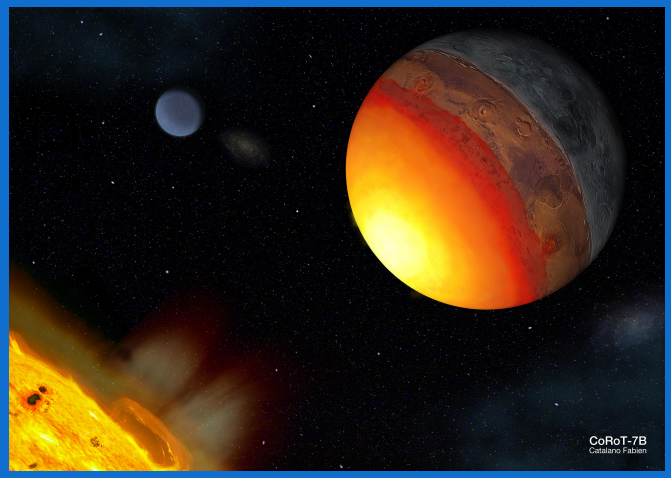
Corot-7b characteristics today

- A big sister of the Earth :
  - M = 7.3 $M_{\oplus}$ (Hatzes et al., 2011)
  - R = 1.7 $R_{\oplus}$ (Brunnt et al., 2010)
  - Deserves the Super-Earth denomination

- A very different *ecologic* environment
  - Period: P = 0.85 d ➜ one year = 20.5 h !
  - Orbit radius : a = 0.017 AU = 3.6 stellar radius !
  - ➜ A sun of 30° in the sky !
- A *Strange New World* without any doubt !

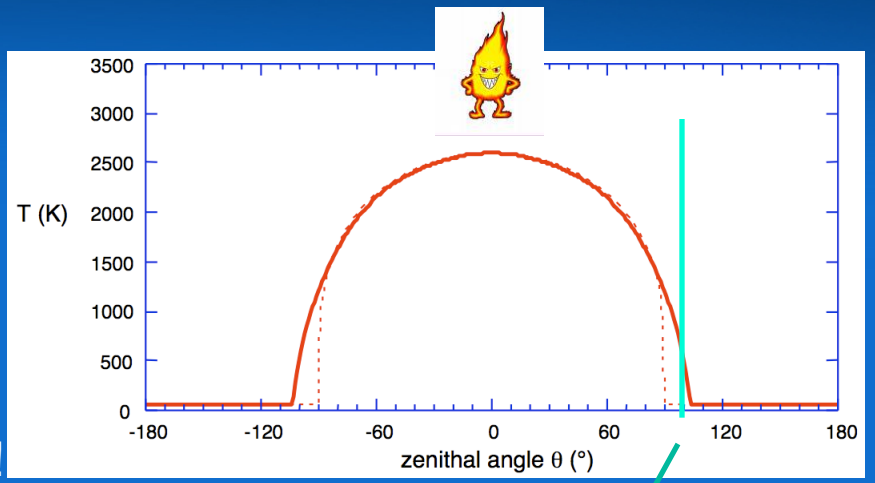
Nature of Corot-7b ?

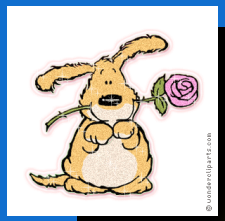
- The first solid evidence for a rocky planet !
  - A lot of exciting physics (Léger et al. Icarus in press)
- Tidal forces :
  - Must be phase-locked (t_{synch}< 1 Myr) : keeps one face towards the star
  - Moderately elongated under tidal forces < 150 km
  - Tidal heating could be extremely efficient if *excentricity is ≠ 0*, but model predict $e < 10^{-4}$

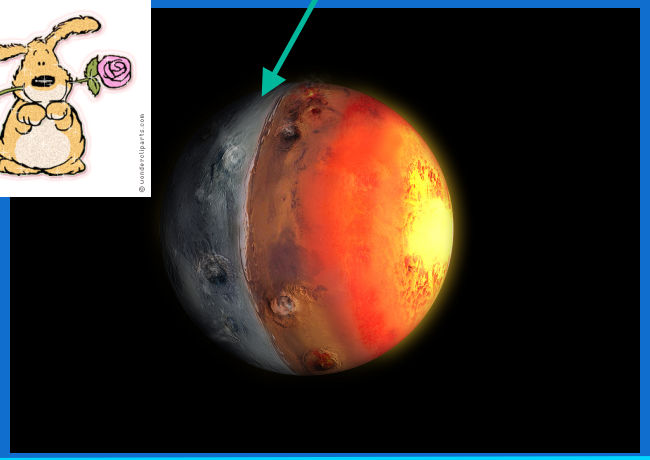


Nature of Corot-7b ?

- Temperature
  - dark side : 50K pretty cold !
    geothermal origin
  - dayside :1800-2600 K : pretty hot !
    no heat redistribution by atmosphere nor ground
  - Thus, between the two… a *temperate* region of 90 km width only (270-370 K)
    - life in this niche ?
      impossible : no water !







Nature of Corot-7b ?

- Structure / composition
  - First time density of a SE measured
  - 10 g.cm^{-3} (≥ Earth) ➜ rocky

    Most probably a « dry Earth » :
    silicates mantle & iron core
  - Likeky migrated from a wider orbit

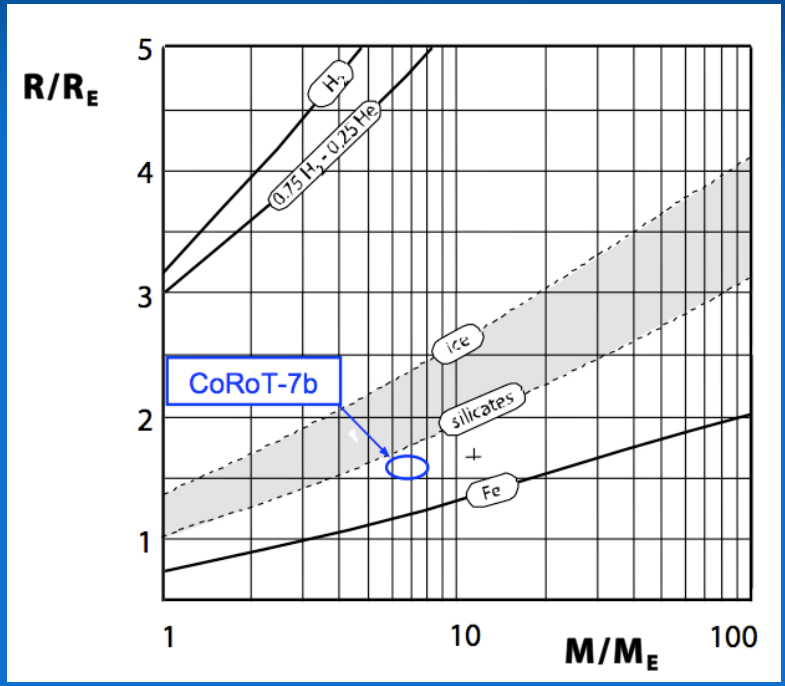
    core of a Neptune stripped by wind

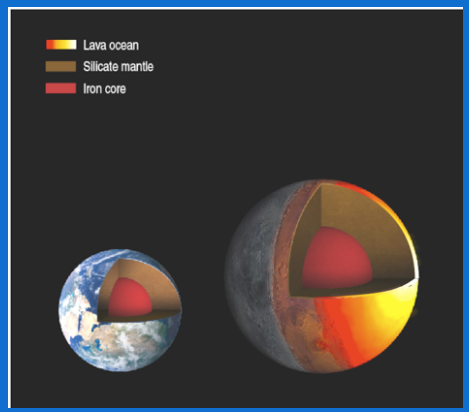
    or a true rocky telluric

    In-situ formation from boulders not excluded
  - Surface :
    - *Lava ocean* of liquid rock of 45 km depth,

      up to a latitude of = 45 - 50°

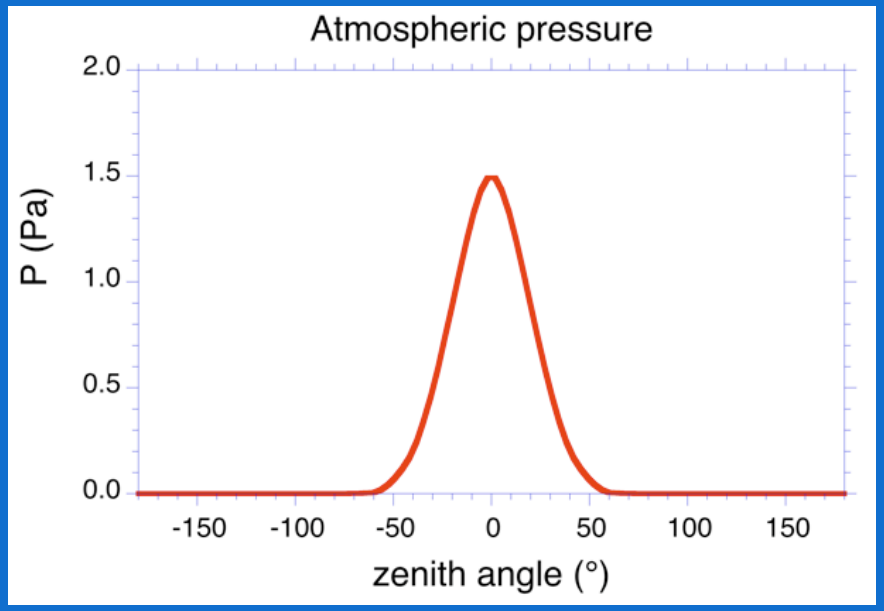
      refractory oxydes: CaO (13%), Al_2O_3 (87%)
    - continent or frost H_2O, CO_2 elsewhere





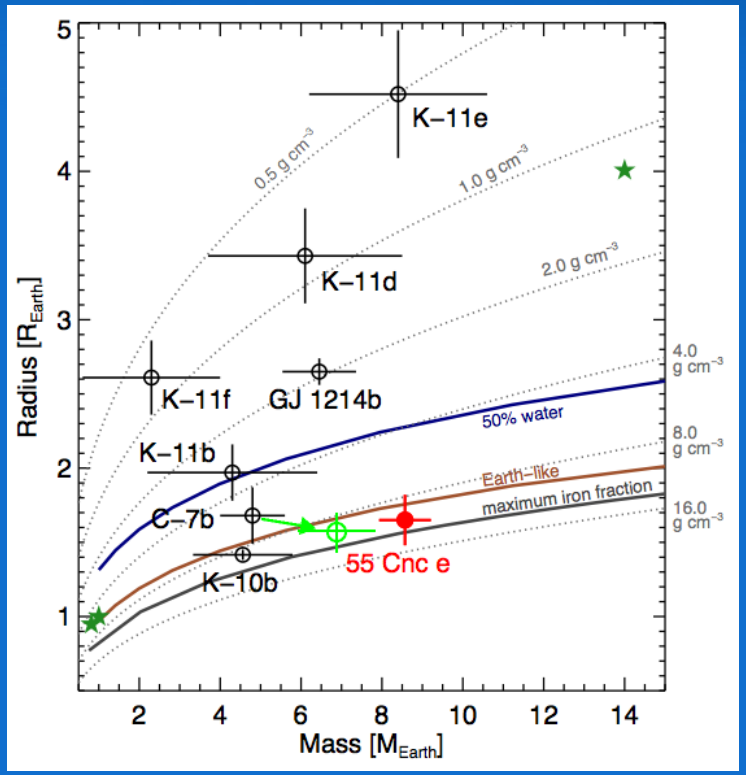
Nature of Corot-7b ?

- Atmosphere
  - Stellar wind +UV: escape of all volatiles within 0.1 to 1 Gyr (< age of the system)
  - composition : vaporised silicates
    - Should be extremely tenuous : P = 5-0.05 10^{-5} bar



A new class of *Lava-Ocean* planets

- The 2 other members :
  - Kepler-10b (Bathala et al 2011): a quasi twin
  - 55 Cnc e (Winn et al. 2011)
- All three found in a narrow domain of period, radius and mass
- All three around a solar-like host star
- A density somewhat larger than Earth
- A good alignment on a unique silicate+iron theoretical [M / R] curve (Valencia et al 2006)
- All three must be spin-orbit synchronized
  - a star facing side extremely hot ➜ lava ocean of melted rocks
  - a dark side extremely cold
  - secondary eclipse in the infrared should be detectable
- Atmosphere must have been expelled by stellar wind



Second CoRoT Symposium

Marseille 13-17 June 2011

http://symposiumcorot2011.oamp.fr

4 new CoRoT planets will be announced !

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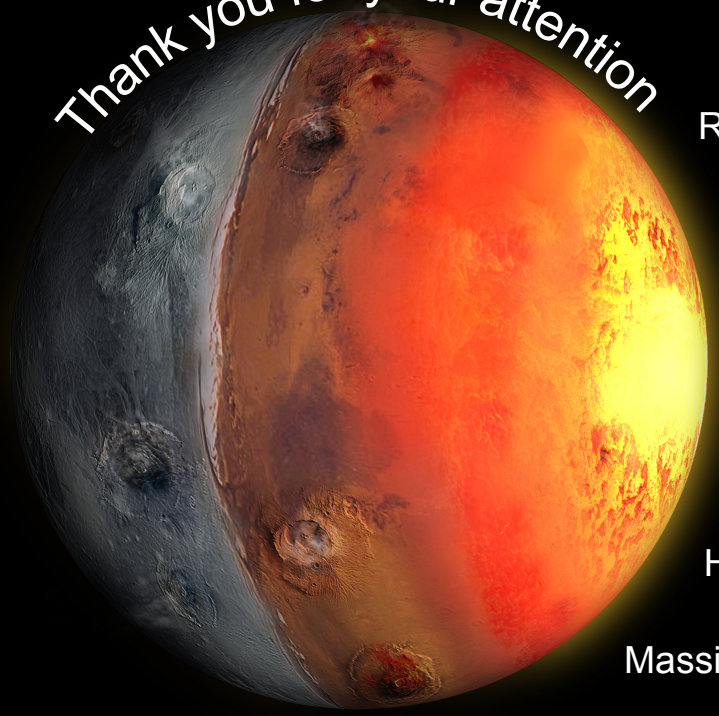
Destination...Le Monde - Toute reproduction interdite

Thank you for your attention



Rocky Corot-7b

Brown dwarves

Long period planet

Old Jupiter

Hot, yet excentric Jupiter

Massive very hot Jupiter