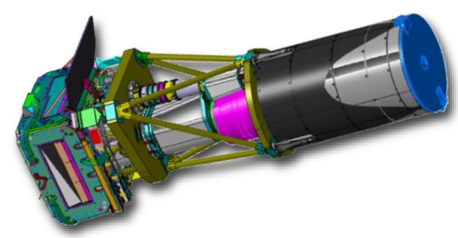
CoRoT-7 b

The discovery of the first transiting Earth-like planet by the CoRoT satellite



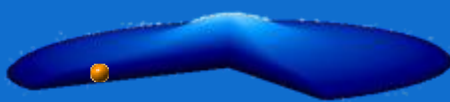
Manne Siegbahn Memorial Lecture 2010 – Stockholm

D. Rouan, Observatoire de Paris

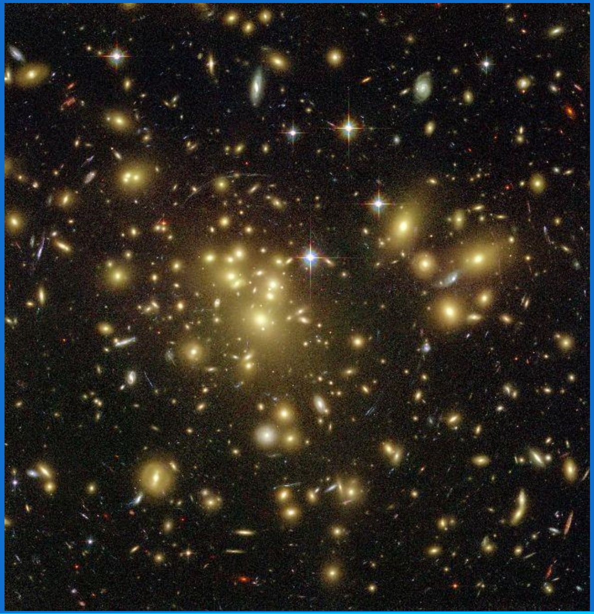
1- Exoplanets hunting

Other planetary systems ?

- The sun : a star among 100 billions in the Milky Way



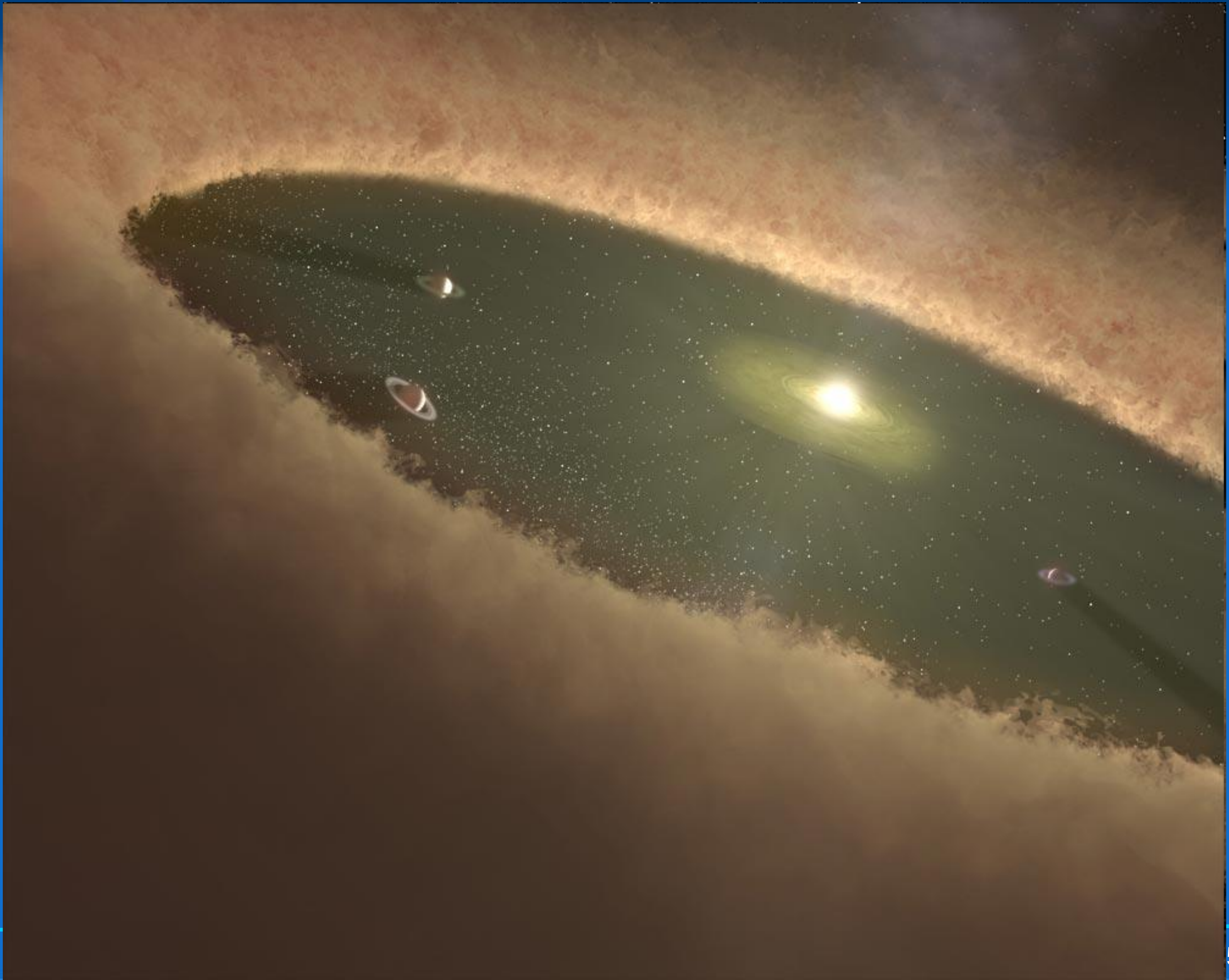
- The Milky Way : one galaxy among 100 billions in the *accessible* Universe
- The sun would be unique among 10^{22} stars ?



Other planetary systems ?

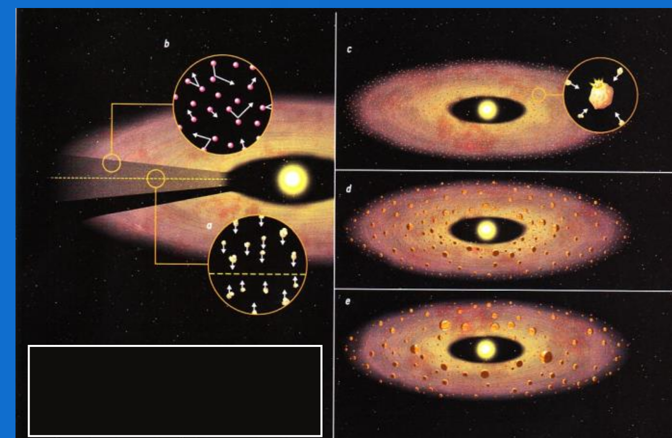
- Astronomers are convinced since a long time that the solar system with its 8 planets and its « small bodies » (asteroïds, moons, satellites), is not unique in the Universe.

- However, it's only since 1995 that they got a proof, with the established discovery of the first extrasolar planet by M. Mayor & D. Queloz : 51 Peg B



Why detecting other planetary systems ?

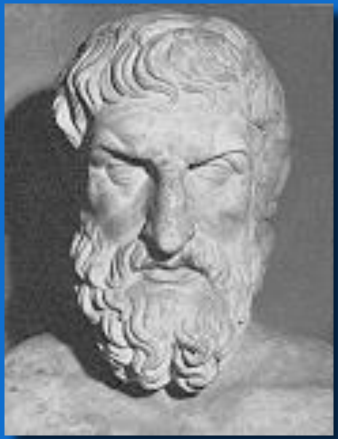
- To understand in details how the star/planets system forms :
  - under which necessary conditions ?
  - what is responsible of the observed broad variety ?



- To predict the evolution of our own system and of each of its individual planets
  - Migration of planets from outside to the interior
  - Planets *ejected* by tidal interaction with other planets
  - Planets loosing their atmosphère (Mars) or becoming hot (Venus)

Why detecting other planetary systems ?

- Detecting other islands of life in the Universe ?
- An ancient and fundamental question
  - « Other worlds, with plants and other living being, some similar and other different from ours must exist » (Epicurus, 300 B.C)



- A question accessible to anyone, that has resonance in any of us
- A question to which science pretends to bring a first element of answer in a rather near future

Detecting directly a planet ?

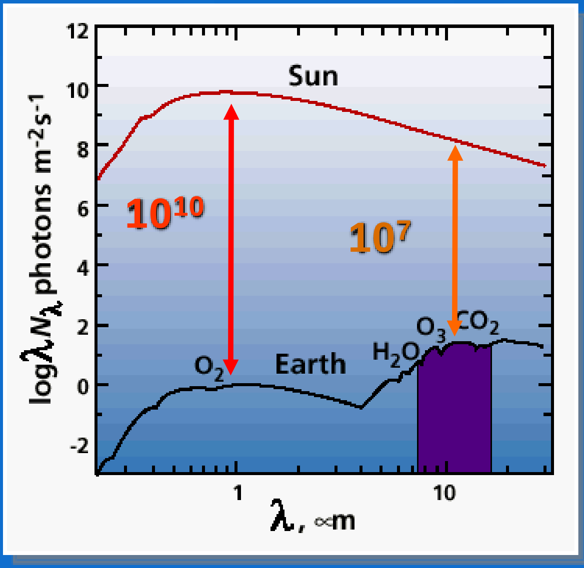
- An exoplanet is difficult to detect directly because :

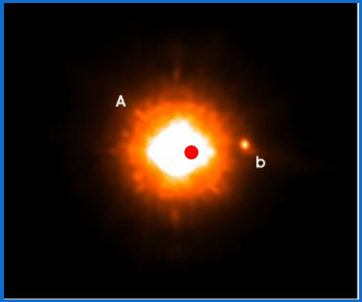
- It is much smaller than the star it is obiting

- It is not self-luminous : it just reflects the light of the star.

  ➜ It's much less bright than the star

- It's very close from the star that dazzles the observer





Detecting dire[...]y a planet ?

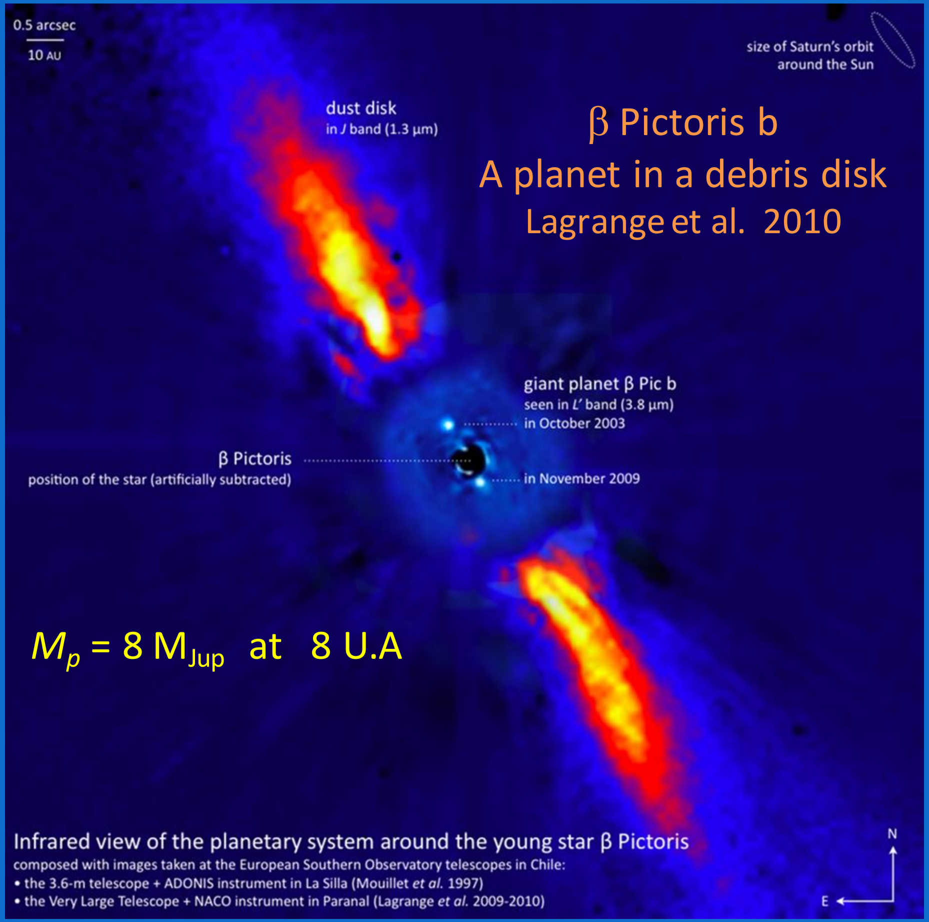
Direct detection of a planet is AWFULLY difficult !!! Thus indirect methods have been the most productive until now

Detecting directly a planet !

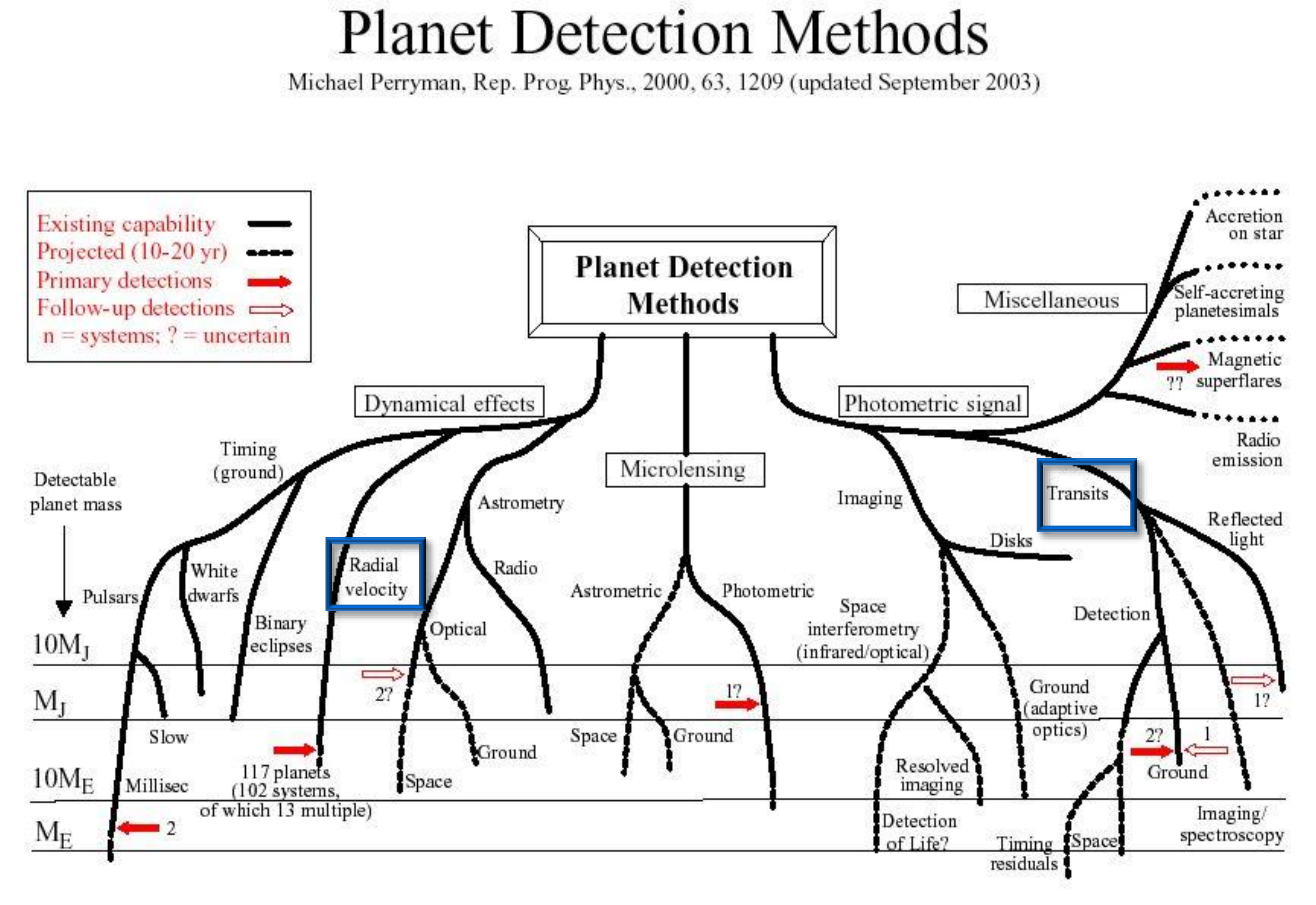
- Indirect detection is the rule for the 490 exoplanets that have been found today

- However, in very few cases corresponding to especially favourable situations, direct detection has been possible :

  Beta Pictoris B : a planet on a 8 AU orbit (≈ Saturn) around a young star.



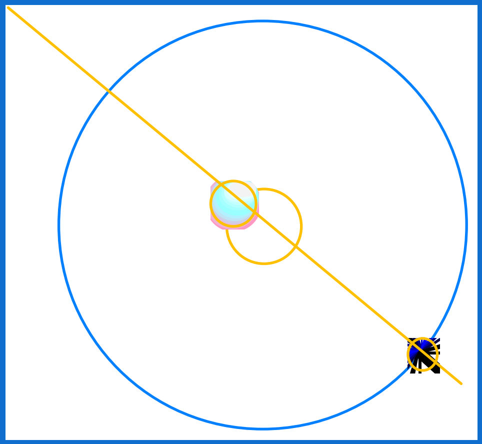
The tree of planet detection methods



The reflex motion

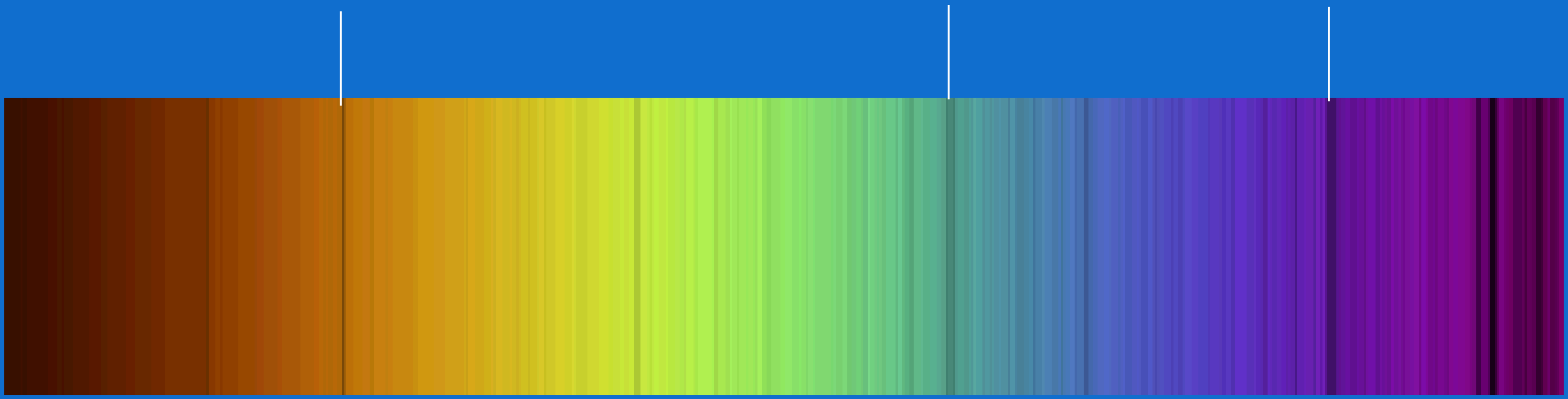
- The center of mass of the star-planet system being fixed, the star travels also on a circular orbit, of very small radius.

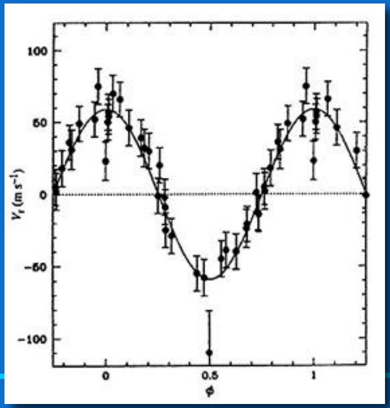
- The radial velocity of the star on this orbit is measurable thank to Doppler effect



Radial velocity measurements

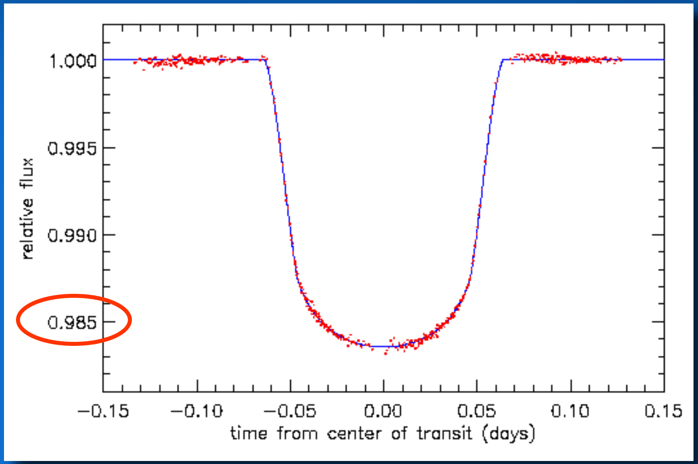
- Using a high resolution spectrograph, one measures the tiny change in wavelength on a large number of spectral lines





Detection of transits

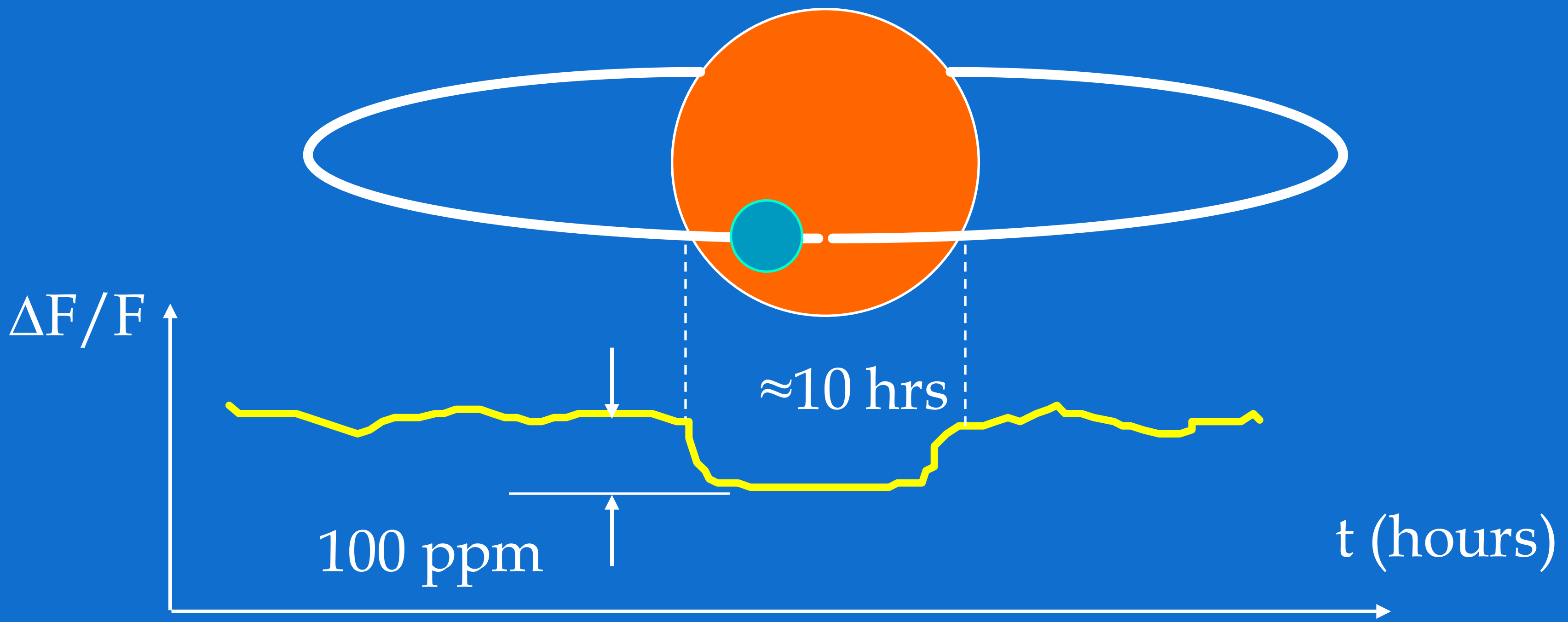
- One looks for events (transits) where the planet travels *between the star* and the observer ➜ small decrease of star brightness



Transit of a planet

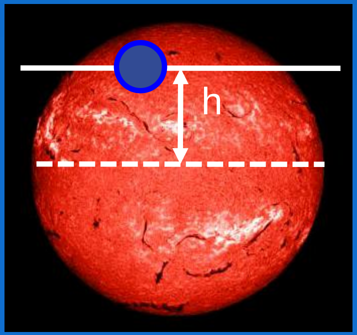
- The chance to be in favourable case (observer in the orbital plane) = 0.5% for the Earth vs Sun

- Consequence: one must monitor a large number of stars during long periods

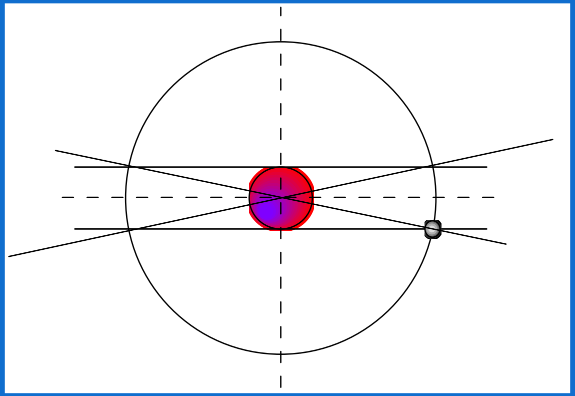


Transit : few basic relations

- Signal ≈ $(R_p/R_*)^2$ (+ limb darkening effect)
  Jupiter / Soleil = 1% ; Earth/Sun : 0.01 %



- Probability for the observer to be in the orbital plane
  $p = R_*/a$
  Earth / Sun p = 0.5%
  51PegB p = 10%



- Transit duration :
  For an impact parameter h
  $\tau = 14\ h\ a^{1/2} M_*^{-1/2} R_* (1-h^2)^{1/2}$
  Earth: 14h ; Jupiter : 31h ; 51PegB : 3h

- Cumulated Signal : $N \tau \propto a^{-1}$: Favour planets w small orbit

Detection of transits : a specially rich information

- Mesure of planet's size

  If measure of the mass ⇦ density and thus clues on the structure
- Impact parameter ⇦ Inclination of the orbit
- Secondary transit ⇦ albedo and temperature
- Photometric variations during the transit ⇦ stellar spots
- Rössiter effect ⇦ rotation axis of the star vs orbital plane
- Variations in periodicity ⇦ other planets or satellites
- Spectroscopy of transits : absorption or emission lines ⇦ composition

The CoRoT satellite

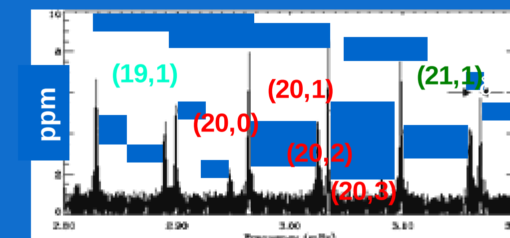
COROT : a European project

- *CoRoT : Convection Rotation Transit*
- France : CNES main contractor
  - Alcatel Alenia Space
  - Institutes : LESIA (Observatoire de Paris), LAM (Marseille), IAS (Orsay)
- Other partners : Austria, Spain, Germany, Belgium, ESA, Brazil
- Launched on 27 December 2006
- Mission recently extended for 2 more years

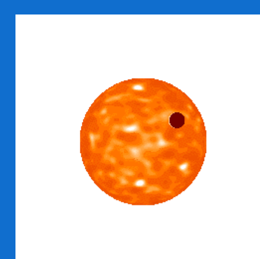
CoRoT: a photometric satellite

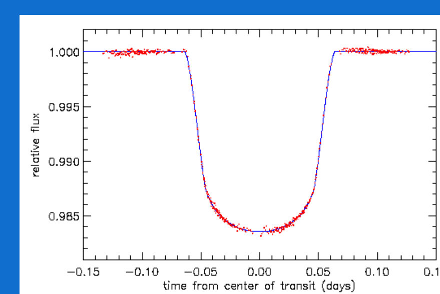
- Principle: monitor continuously the flux of thousands of stars during 10 cycles of 5 months each
- Two programmes conducted in parallel :

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



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

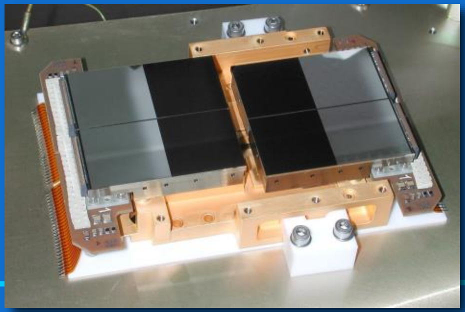


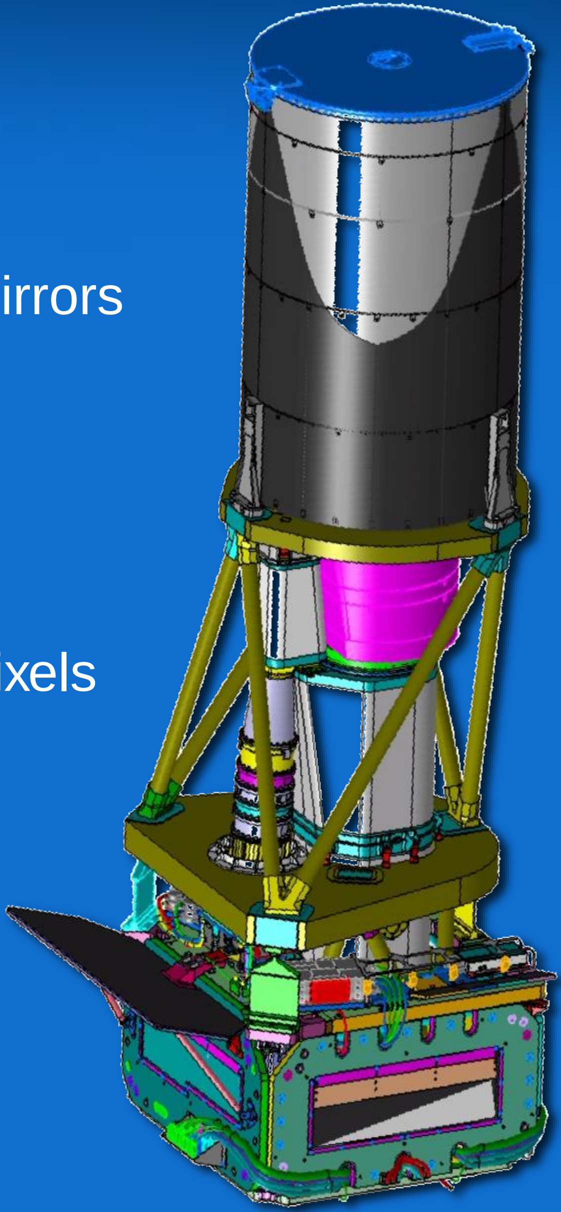


The CoRoT Instrument

- Télescope
  - Pupil diameter : 27 cm
  - Afocal telescope : 2 parabolic mirrors
  - Long sunscreen

- Wide field camera
  - Dioptric objective w 6 lenses
  - Focal plane : 4 CCD of 2048^2 pixels
    - – 2 CCD astero-sismology
    - – 2 CCD exoplanets
  - Exoplanet field : $3.45(°)^2$

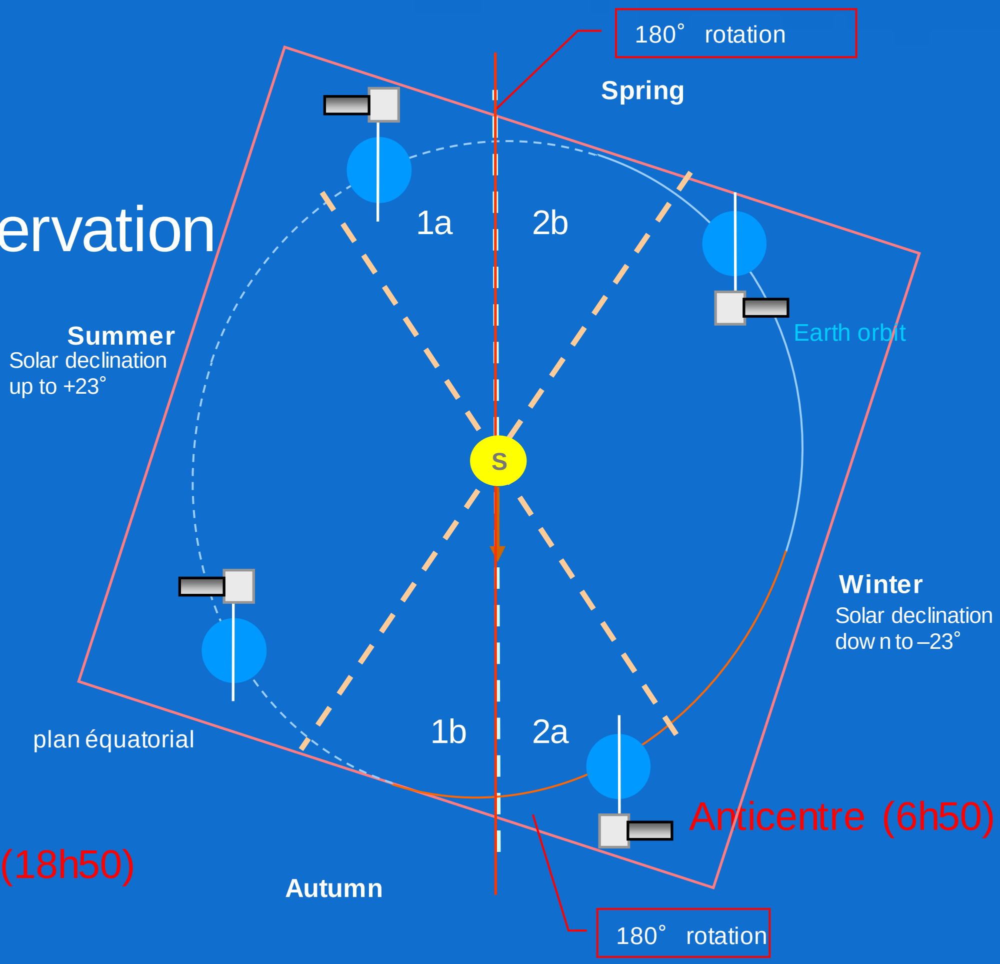




Observing strategy

- Polar orbit
- Sun *in the back* ➜

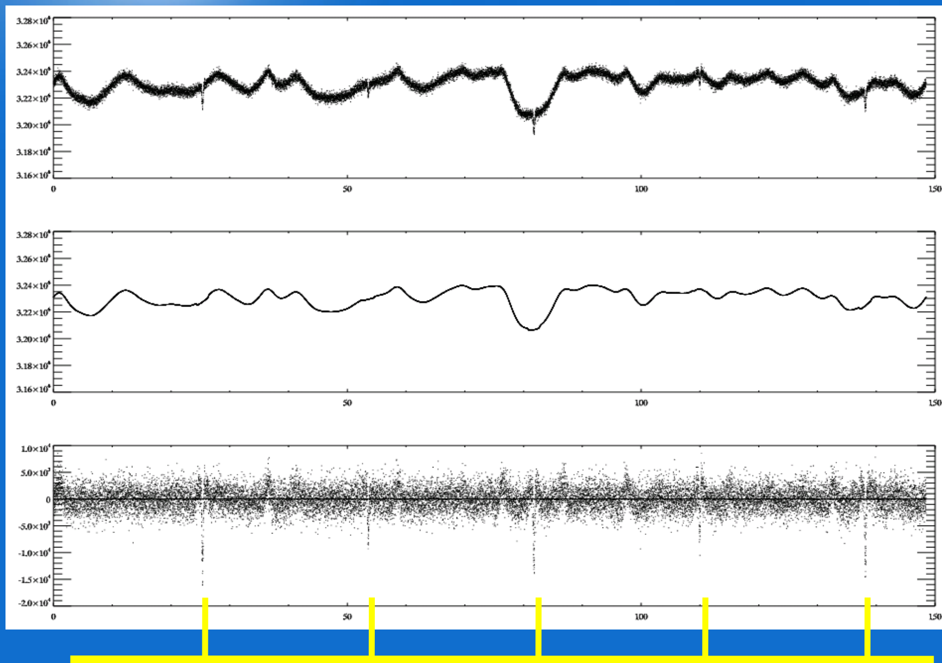
  Flip each semester
- 150 days of continus observation of each field
- 10 fields



Launch

With a good old faithful Soyuz

Processing a light curve



Original

Low frequencies : stellar fluctuations

High frequencies : transits

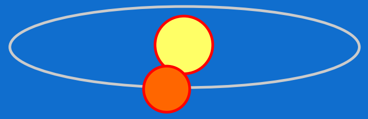
- Detection of a planet candidate : at least three transit-like periodic events

  ➜ orbital périods T < 50 days

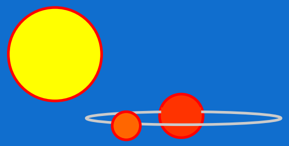
Beware of *false positives*

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

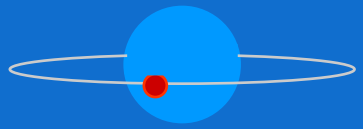
- The star is a Grazing Eclipsing Binary (GEB)



- Eclipsing Binary in the Background (BEB)



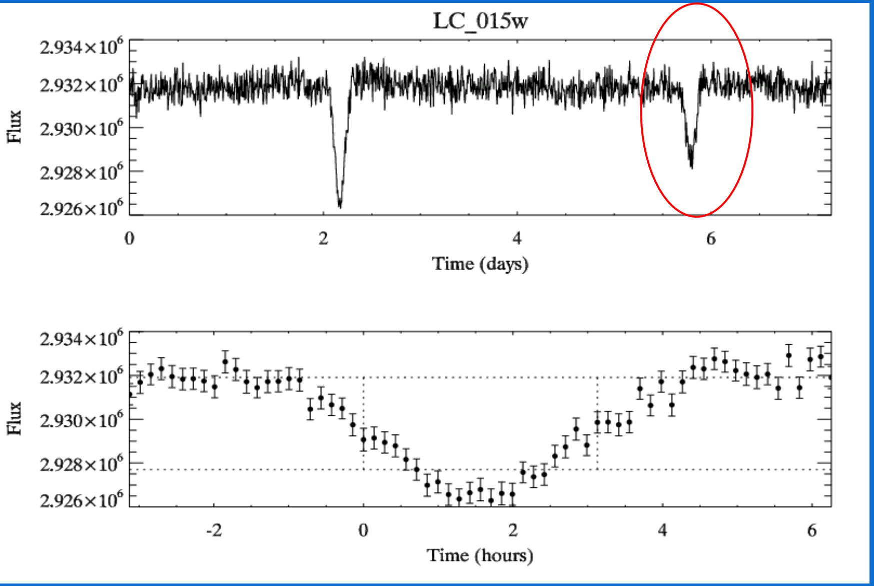
- Eclipsing Binary in a dwarf/giant system



- FOLLOW-UP FROM THE GROUND IS MANDATORY !

How identifying a liar ?

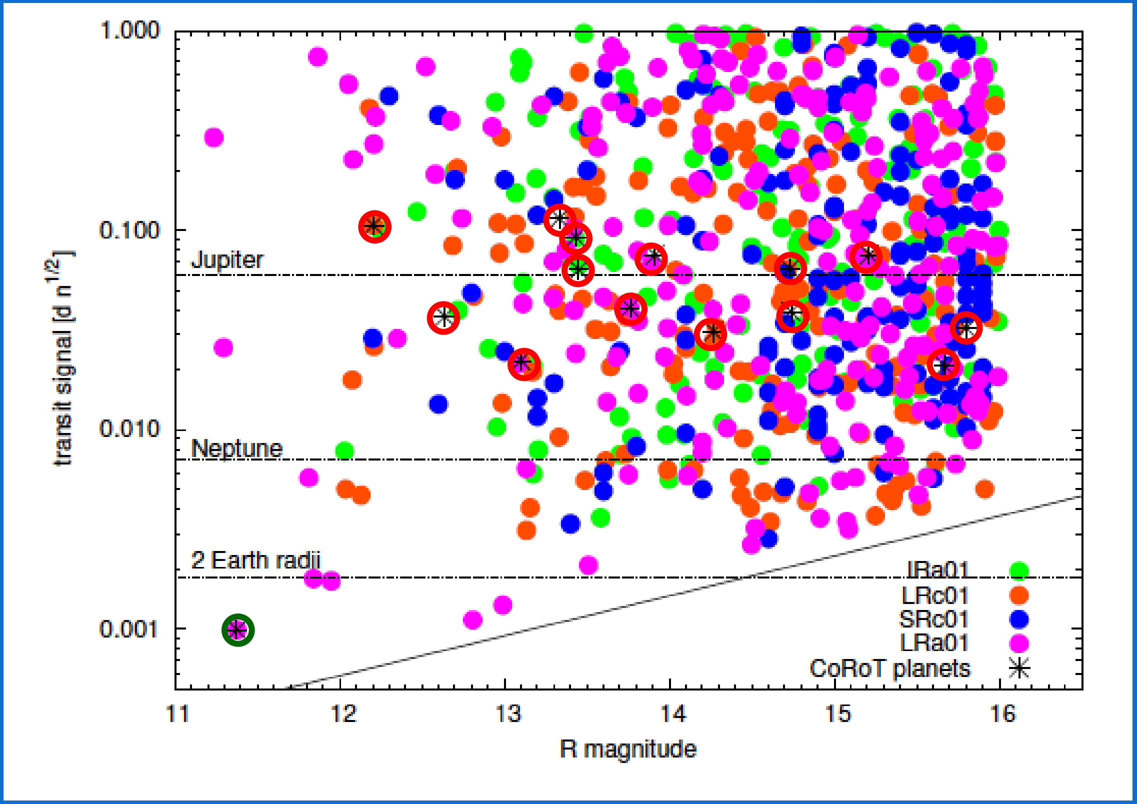
- Transit : V-shape and secondary eclipse



- Radial Velocity ➜ mass of star or of a planet
- Spectroscopy ➜ identify giant stars or blend (binary)
- ON/OFF Photometry of nearby stars ➜ background binaries
- CoRoT Coulours of the transit ➜ binary system

CoRoT does detect planets !

- 17 planets up to now (14 published)

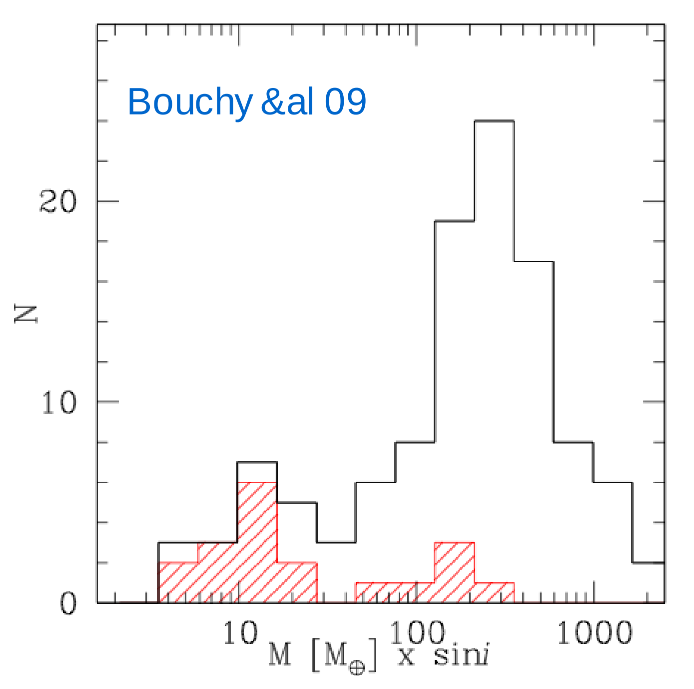


- among which one of special interest …

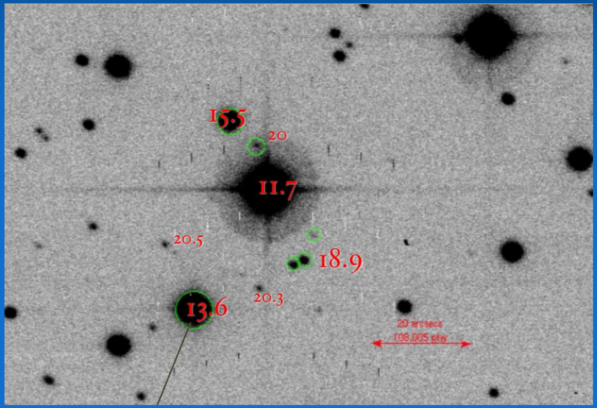
CoRoT-7b:
an Earth's cousin

Short period planets:

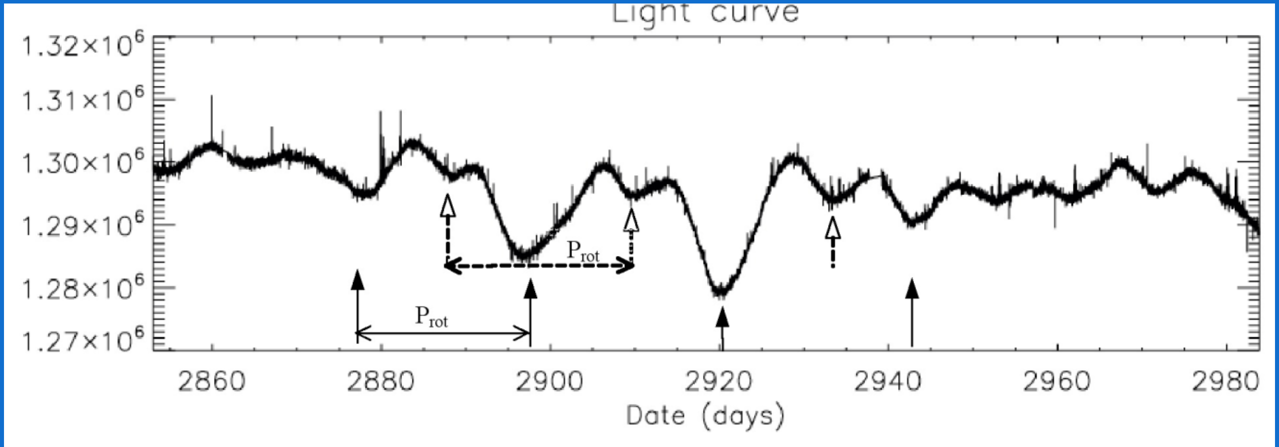
- 2006: first Super Earth detected (gravitational lensing)
  - Beaulieu et al. Nature 06
- Recent results from Radial Velocity point to a very significant population of Super-Earth: e.g.Mayor et al. 09
- Today: 55 planet w M < 0.1 M_{Jup}
  - An important component : 30 % of all solar type stars may harbour one hot SE
- Size needed !
  - to derive the structure
- One major goal of CoRoT
  - detect transits of Super-Earth
  - performances allow it
  - And indeed a first case !



The star CoRoT-7

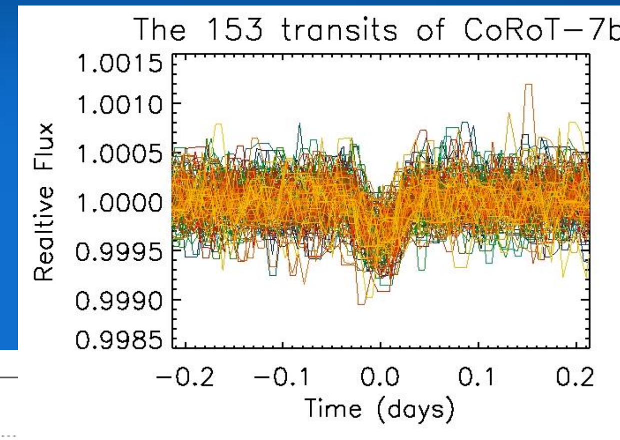


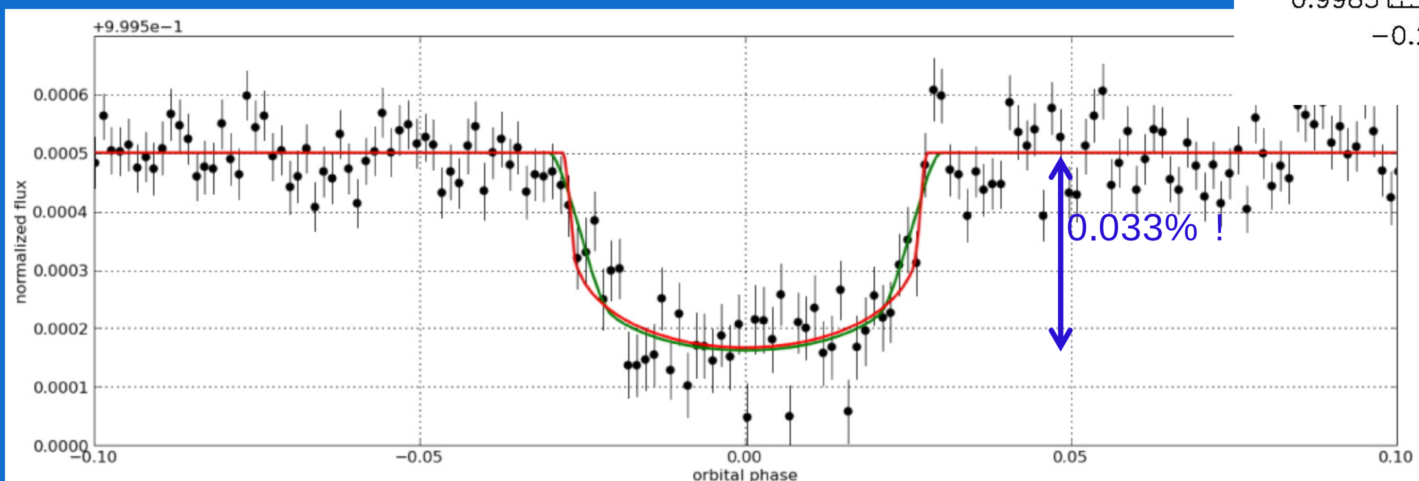
- Spectrum ➜ type
- Parameters :
  - G9V star - mV = 11.7
  - Teff = 5250 K : quasi-solar
  - Distance = 130 pc ± 30
  - age ≈ 1.2 Gyr
- Very active : emission feature in H and K Ca lines, 2% variability !



- Spots clearly seen crossing the disk because of rotation
  ➜ rotation period = 23 days

The folded light curve





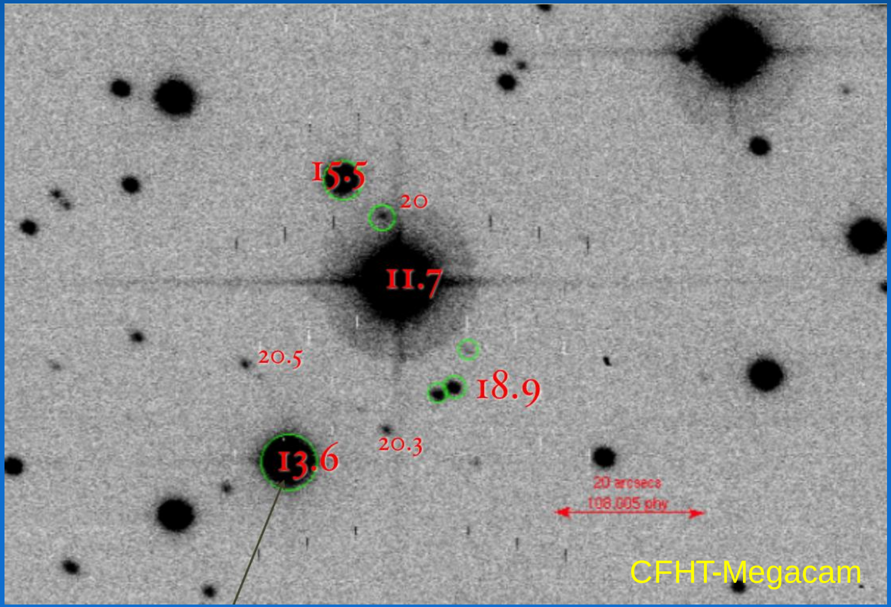
- Transits first detected by quick-look analysis (« alarm » mode)
- 153 transits, all ~ seen when superimposed
- Extremely short period : P= 0.8536 days

  ➜ very small transit depth : $\Delta F/F = 0.033\%$

A vigorous follow-up programme

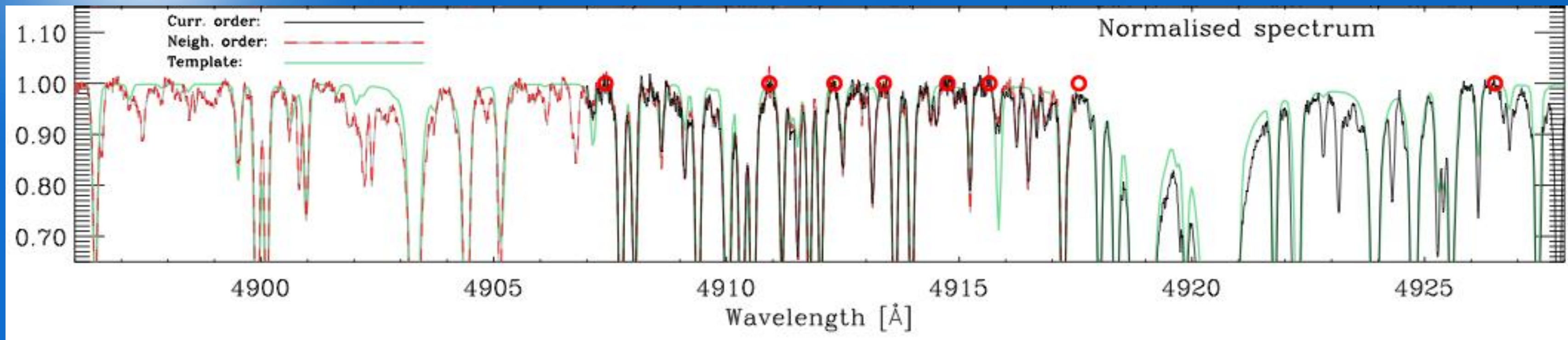
- Such a small transit signal
  - IF A PLANETARY ONE -
  means a very small planet :
  $R_{pl} = 1.7\ R_{earth}$

- A small planet or a usual case of false positive, such as BEB, GEB or giant planet in a triple system ?

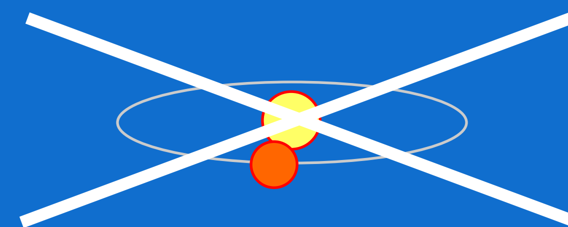


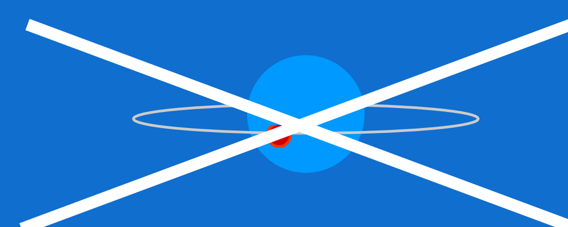
- ➜ A vigorous Follow-up programme from the ground, using several of the top-level instruments in the world was conducted

Follow-up 1 : Spectrum

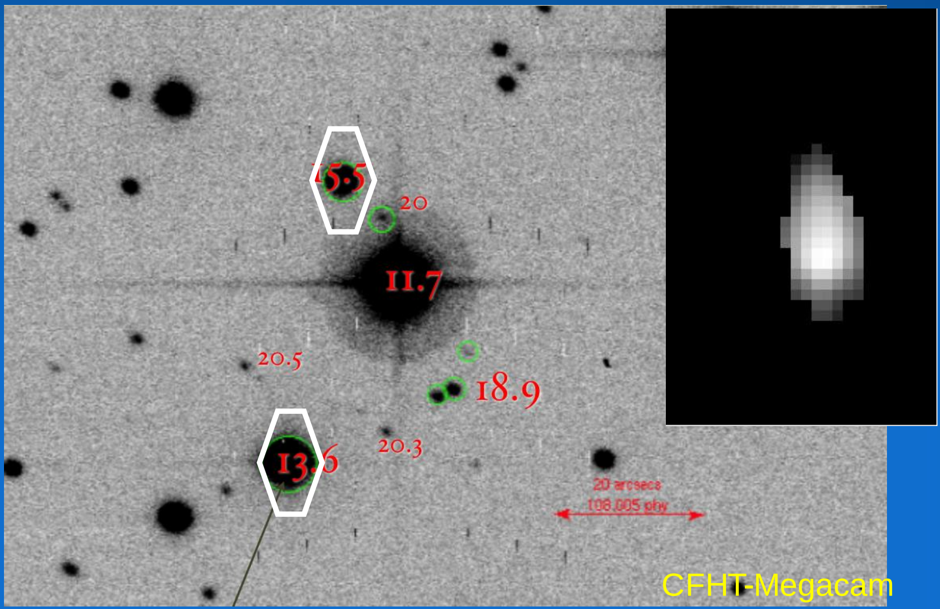


- High resolution spectra
- ➜ a unique star of type G9V
- Cannot be a blend
- Excludes a Grazing Eclipsing Binary
- Excludes a giant star eclipsed by a dwarf star or a giant planet

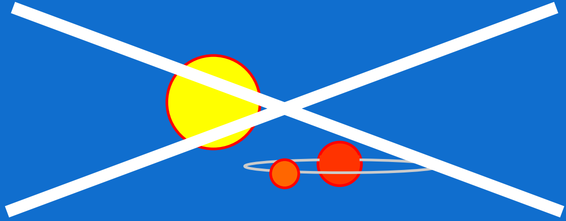




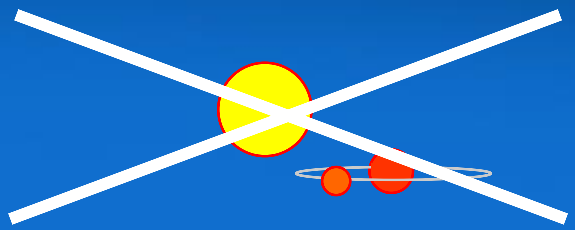
Follow-up 2 : ON/OFF Photometry



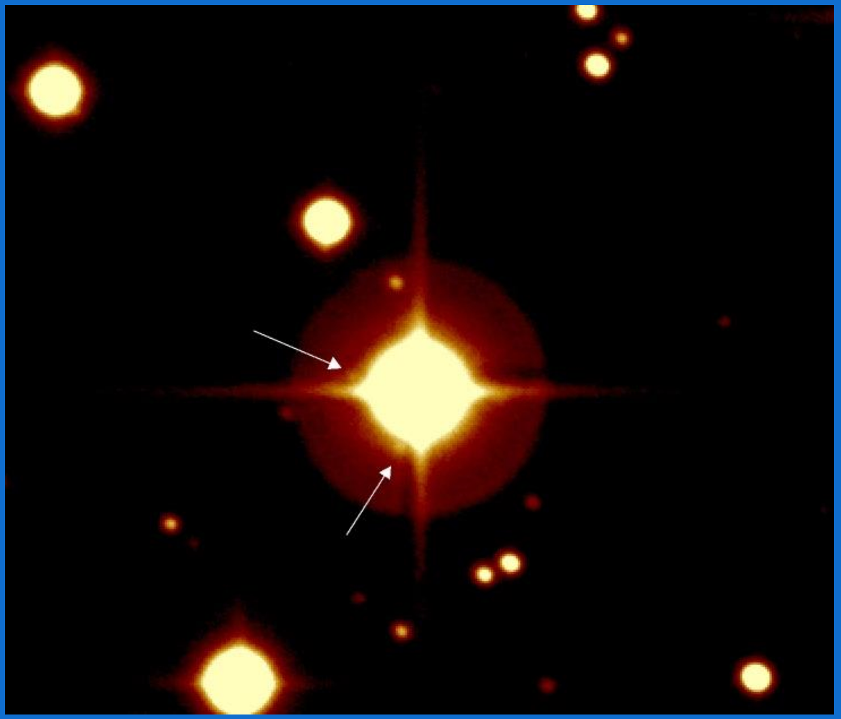
- ON/OFF CCD photometry on nearby stars
- PSF + Corot mask ➜ light in corot-aperture :
  - 99.63 % from Corot-7b
  - 0.24 % V=15.5 ✷ 17" NE
  - <0.1% V=13.6 ✷ 30"SE
- Only those 2 stars could produce false alarm
- ON/OFF photometry :
  - NO Δmag > alarm
- BEB at distance 8 to 30 arcsec excluded



Follow-up 3 : Good seeing Imaging

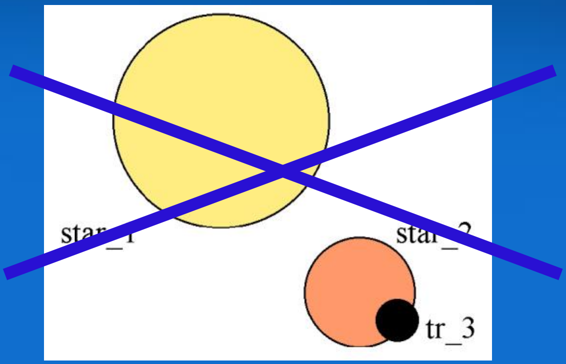


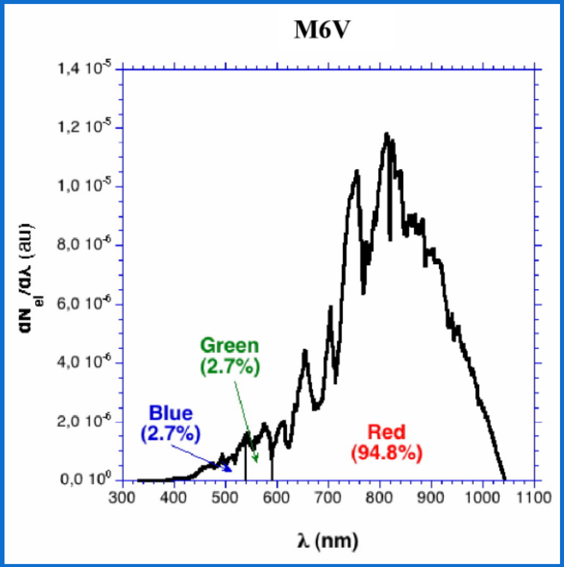
- Good angular resolution images in a very good site (CFHT Hawaii)
  - sub-pixel recentering
  - median of the cube
- Two faint stars detected @ 4.5 & 5.5 arcsec
- Magnitude estimate (fake stars added) : Δm = 10
  - too faint to cause a 3.5 10^{-4} $\Delta F/F$
- BEB at distance 4 to 8 arcsec excluded

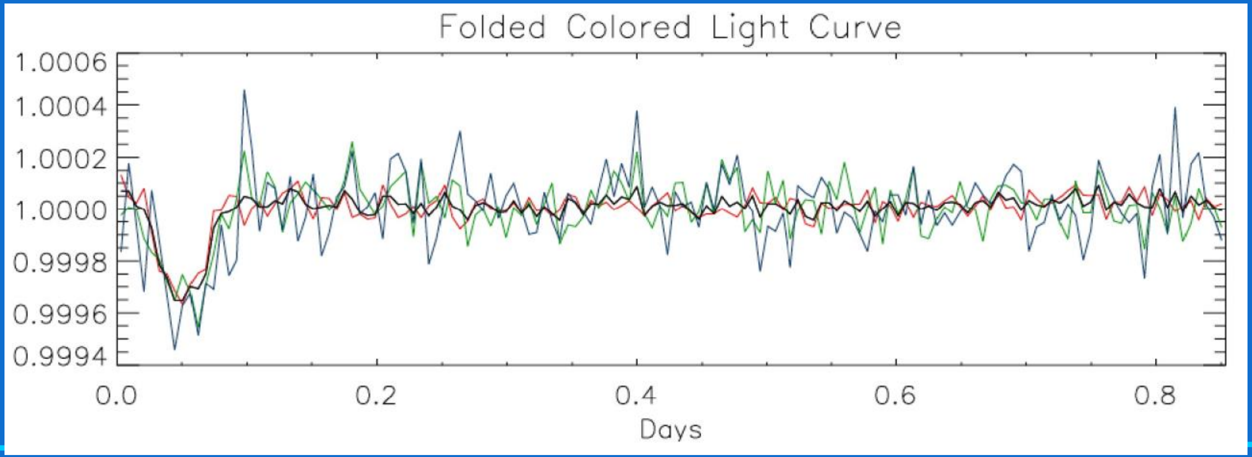


Follow-up 3 : CoRoT colors

- Triple system with a Jupiter transiting the second star ?
- CoRoT Colors : 3 Light Curves
  - *Blue, Green, Red*
  - transit is achromatic !
- Eliminate a triple system because star 2, and thus the transit signal, should be red





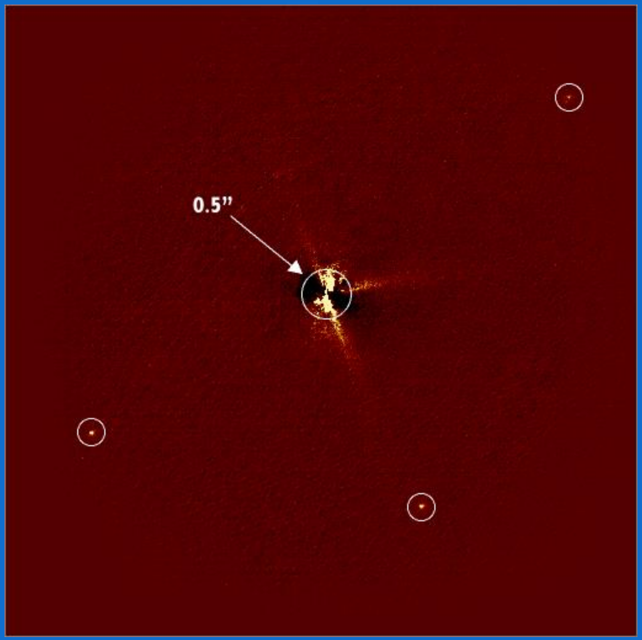


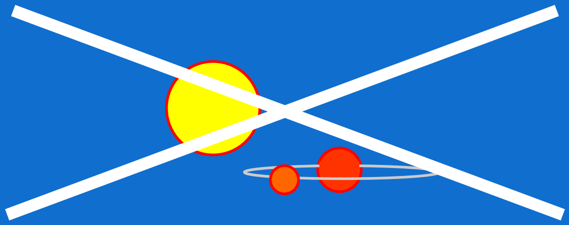
Follow-up 4 : Adaptive Optics Imaging

- High angular resolution image in near-IR with NACO-VLT
  - Adaptive optics + differential imaging by rotation of the camera on the sky

- Three stars detected
  - all at angular distance > 4”
  - Magnitude = 18.4 - 18.7
  - too faint to be BEB false positive

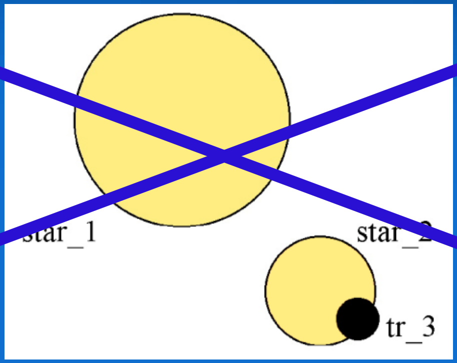
- BEB between 0.5” to 4” excluded

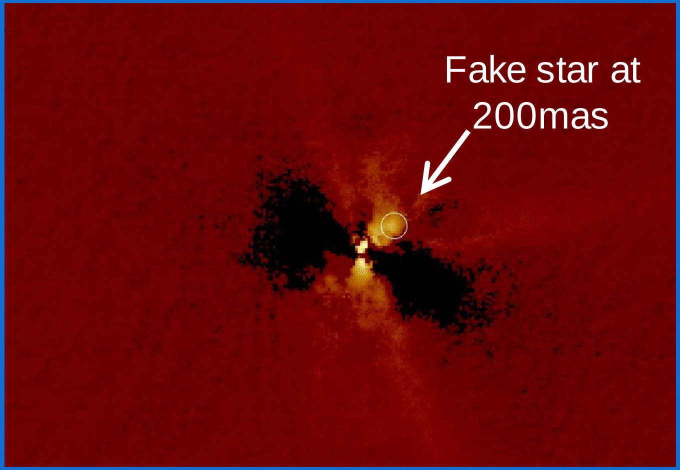




Follow-up 4b: Adaptive Optics Imaging

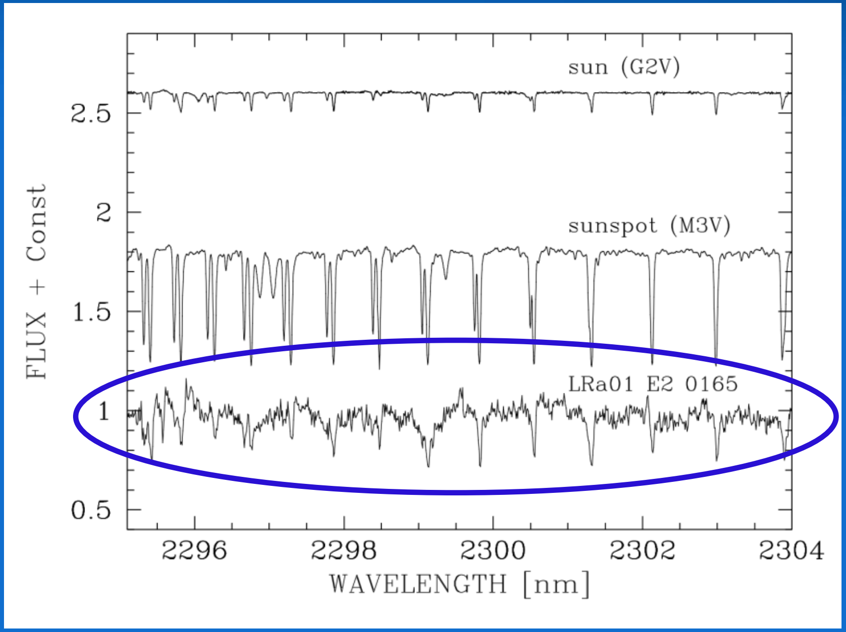
- Jupiter transiting a close background star of same color as Corot-7 ?
  - Would not be detected in Corot colors
  - the star must be 3.5 10^{-2} fainter
- High angular resolution image with NACO-VLT
  - add a fake faint star at 0.2" and 0.3"
  - do the same processing as before
  - a star with $\Delta m = 5$ would be detected at 300 mas and likely at 200 mas
- Probability to have a star of mag 16.5 and same color, w a transiting Jupiter within 0.25" < 2 10^{-4}



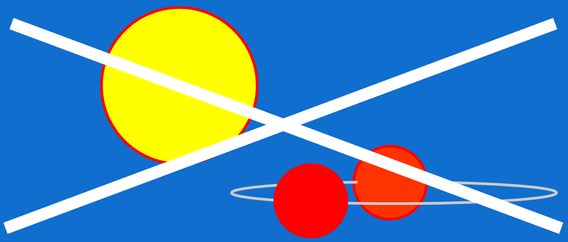


Follow-up 5 : IR spectra

- Triple system with 2 eclipsing low mass stars?
- IR spectra (CRIRES-VLT) :
  - At 2 µm : strong CO overtone lines in spectra of K and M stars
- Result:
  - No K or M stars at the distance of Corot-Exo7 within 0.3”



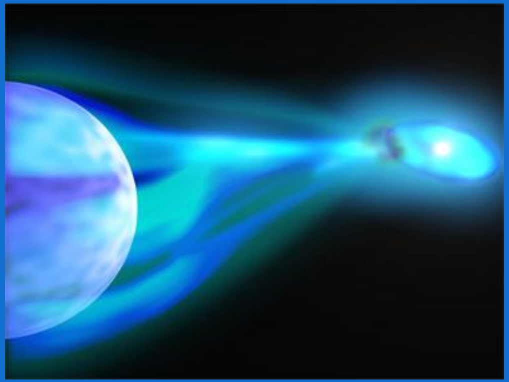
- Eclipsing binary system of M stars orbiting Corot-Exo7b excluded



Follow-up 6 : X-ray activity

- If close binary (P=0.85 days) ➜ Strong X-ray emitter

  e.g. : YY Gem with Period = 0.81 days



- ROSAT satellite « all sky survey »

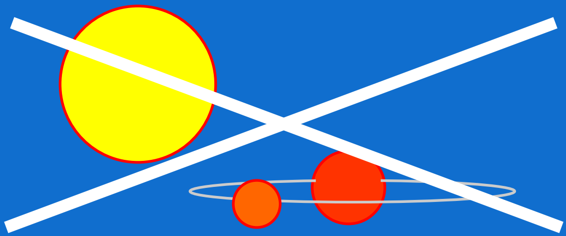
  E = 0.1 - 2 keV

  region of Corot-Exo7b

- Results:

  NO X-ray binary out to 250 ± 100 pc

- Late M binary system orbiting Corot-7b excluded



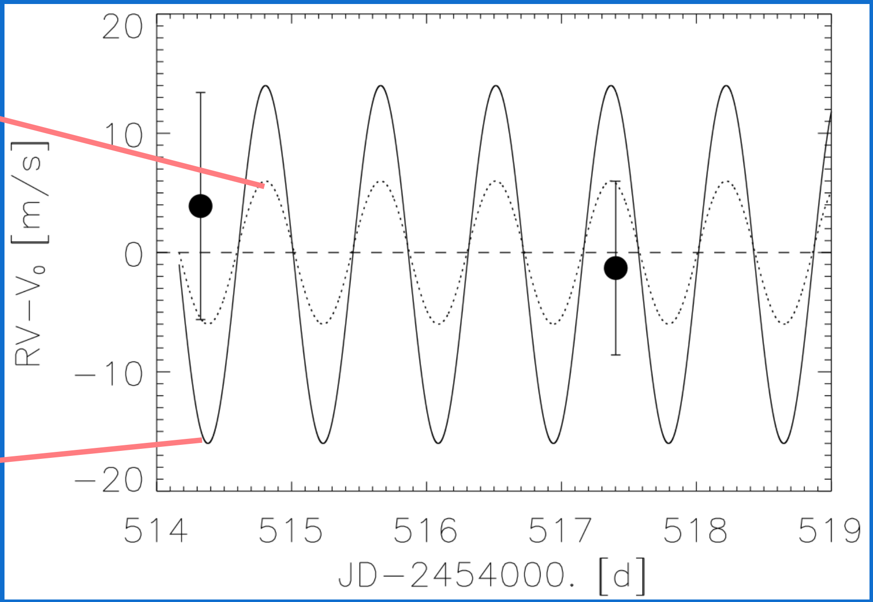
Follow-up 7: Radial Velocity

- Velocimetry with the spectrograph SOPHIE (Haute Provence)
  - 2 points measured
  - excludes a planet of mass > 21 $M_\oplus$ with 95% confidence level

➜ NO grazing Jupiter or white dwarf (excluded by timing anyway)

10 $M_\oplus$

21 $M_\oplus$



All *known* cases of false positives practically eliminated with a high level of confidence

(risk of a background blend = 8 10^{-4})

➜ with a fairly high probability

the transit should be due to a

Super Earth planet

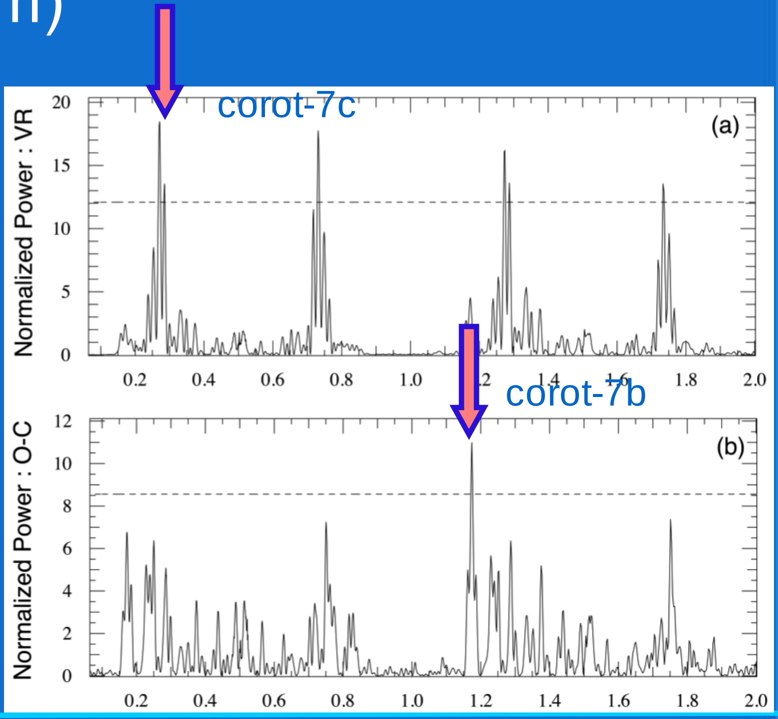
of radius 1.7 $R_{\oplus}$

on a very close orbit

Léger, Rouan, Schneider et al., A&A, 2009

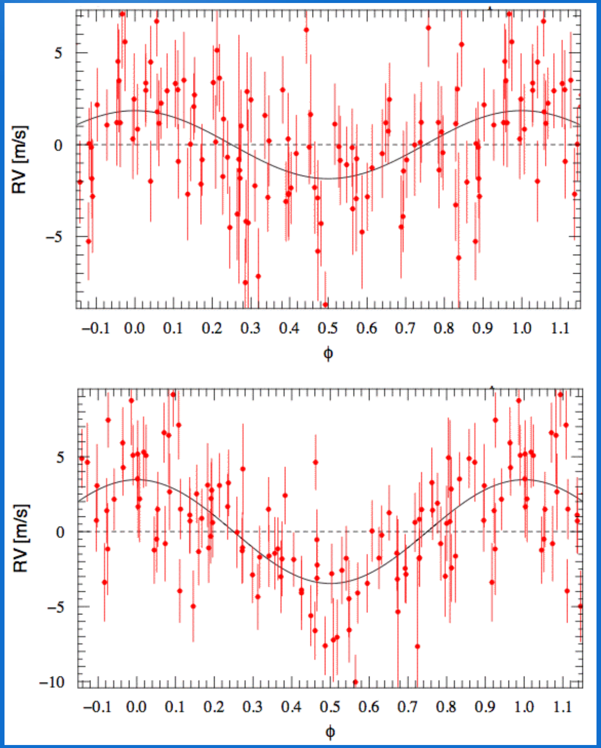
The real « Plus » :
Radial Velocity with HARPS

- 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 !



Radial Velocity with HARPS

- Finally a *two Super-Earth* solution is found



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

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

Parameters	Adopted solution
Period [days]	$0.853585 \pm 2.4 \cdot 10^{-5}$ (‡)
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 !

Corot-7b characteristics

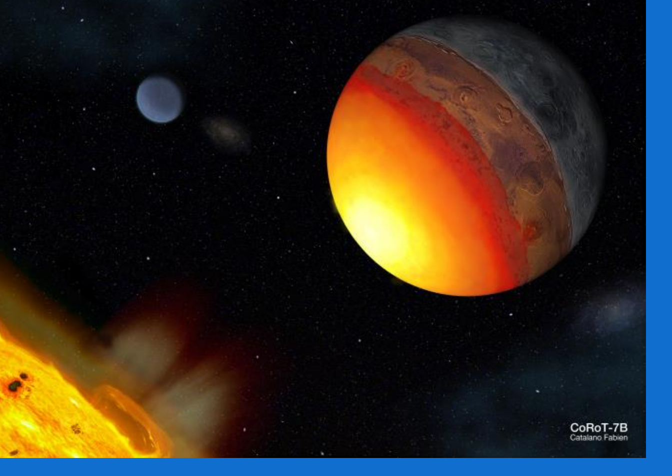
- A big sister of the Earth :
  - $M = 4.8 - 6\ M_\oplus$
  - $R = 1.6 – 1.7\ R_\oplus$
  - Deserves the Super-Earth denomination

- A very different *ecologic* environment
  - Period: P = 0.85 d ➜ one year = 20.5 h !
  - Orbit radius : a = 0.017 AU = 4.5 stellar radius !

  ➜ A sun of 28° in the sky !

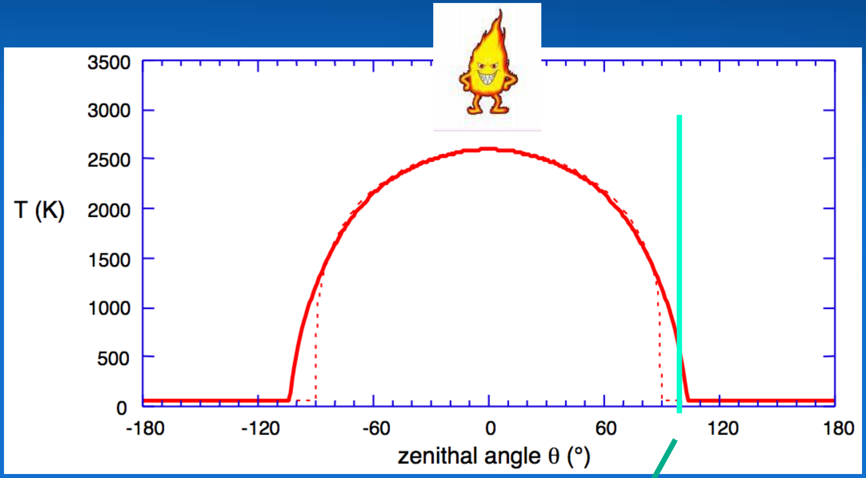
Nature of Corot-7b ?

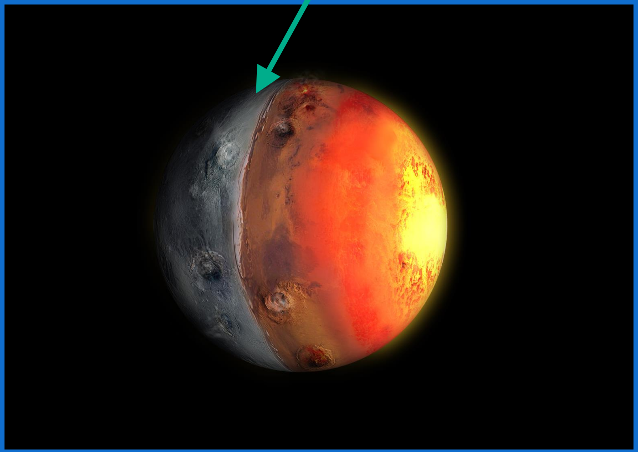
- First solid evidence for a rocky planet !
  - A lot of exciting physics (Léger et al. Submitted)
- Tidal forces :
  - Must be phase-locked (t$_{synch}$< 100 yrs) :
    keep one face towards the star (as the Moon vs Earth)
  - Moderately elongated under
    tidal forces < 150 km
  - Tidal heating could be extremely
    efficient if *excentricity is ≠ 0*
    could be *analog to Io* ➜ *volcanism ?*



Nature of Corot-7b ?

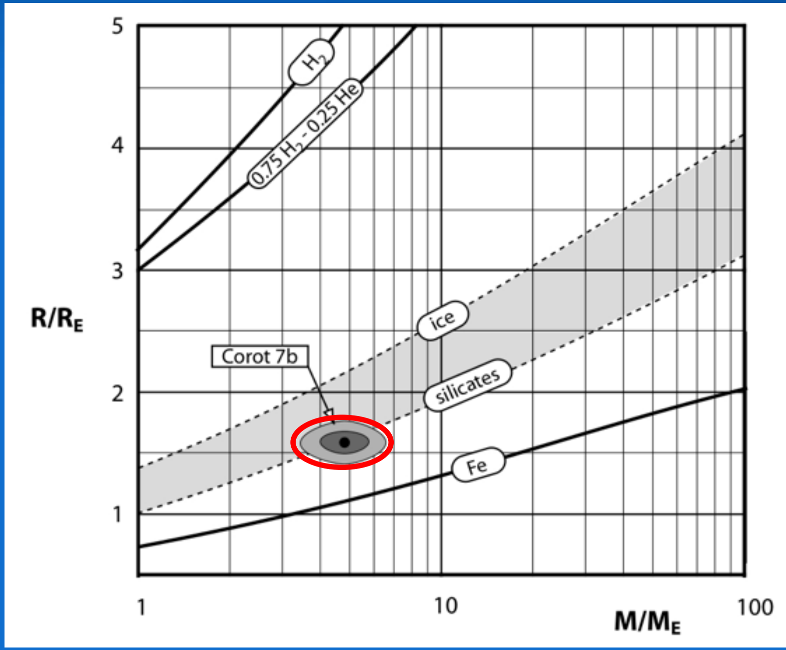
- Temperature
  - dark side : 50K pretty cold !
    geothermal origin
  - dayside :1800-2600 K : pretty hot !
    no heat redistribution by atmosphere or ground
  - Thus… a *temperate* region of 90 km width only (270-370 K)
    - life is however not possible : no water !

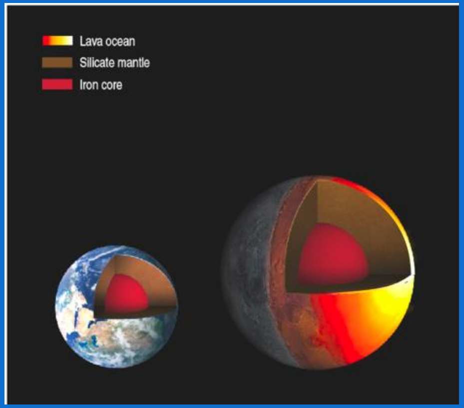




Nature of Corot-7b ?

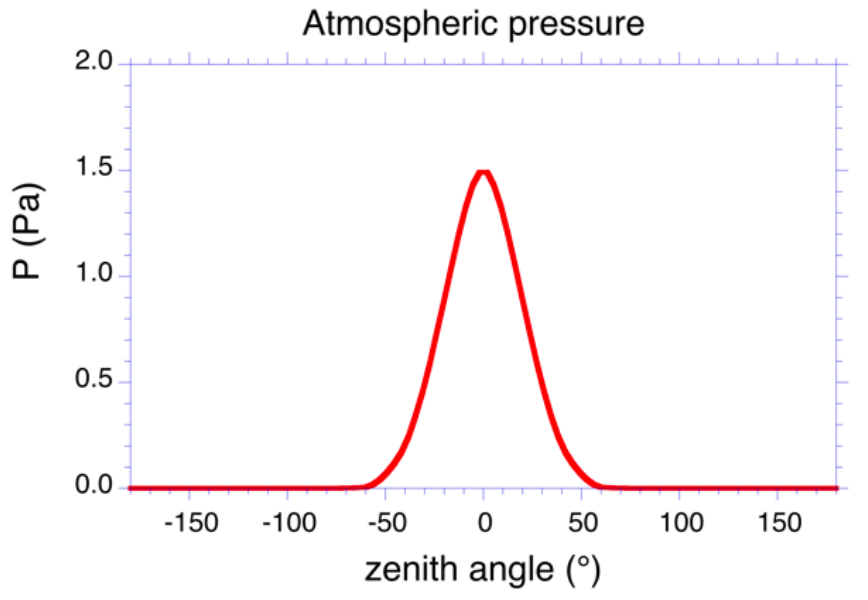
- Structure
  - First time density of a SE measured
  - 5.5 – 7 $g.cm^{-3}$ (~Earth) ➜ rocky
    Most probably silicates mantle
    compatible w 20% of water
  - Likeky migrated from a wider orbit
    core of a Neptune
    or a true rocky telluric
  - surface : *ocean* of liquid rock
    up to a latitude of = 40°
    refractory oxydes: CaO, Al_2O_3
  - continent or frost H_2O, CO_2 elsewhere



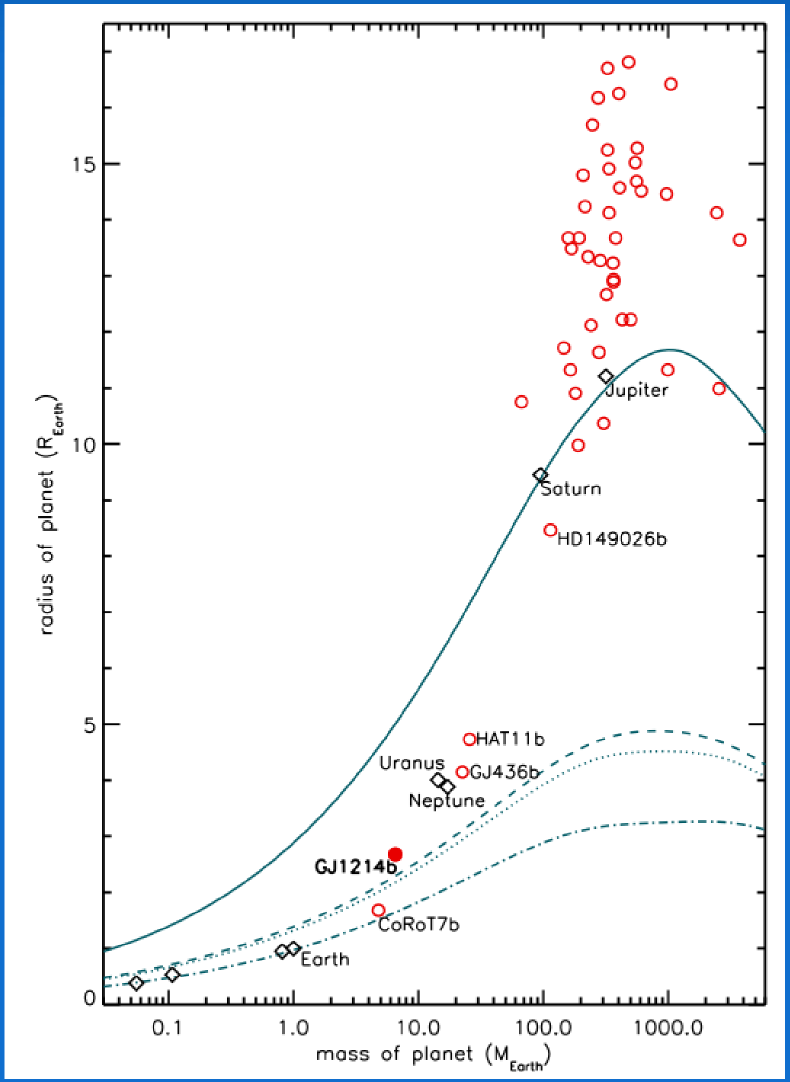


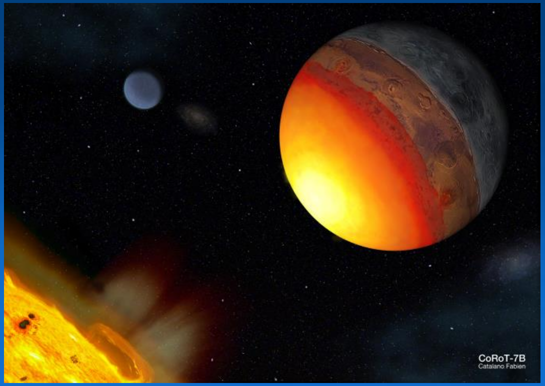
Nature of Corot-7b ?

- Atmosphere
  - 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



Telluric or icy giant ?





Corot-7b :

A planet whose mass and size make it a cousin of Earth

Orbiting a star cousin of our Sun

➔ A solid milestone on the pathway towards habitable planets

Thanks extended to both CoRoT and HARPS teams


Thank you for your attention