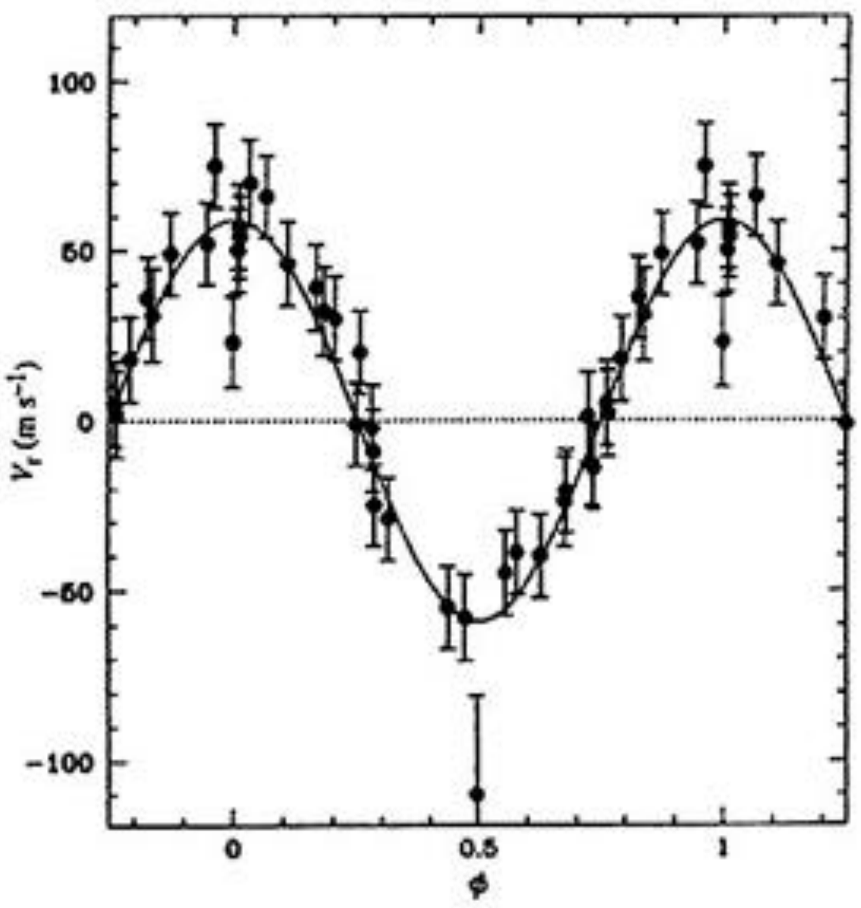
Studying extrasolar planets with CoRoT

Eike Guenther

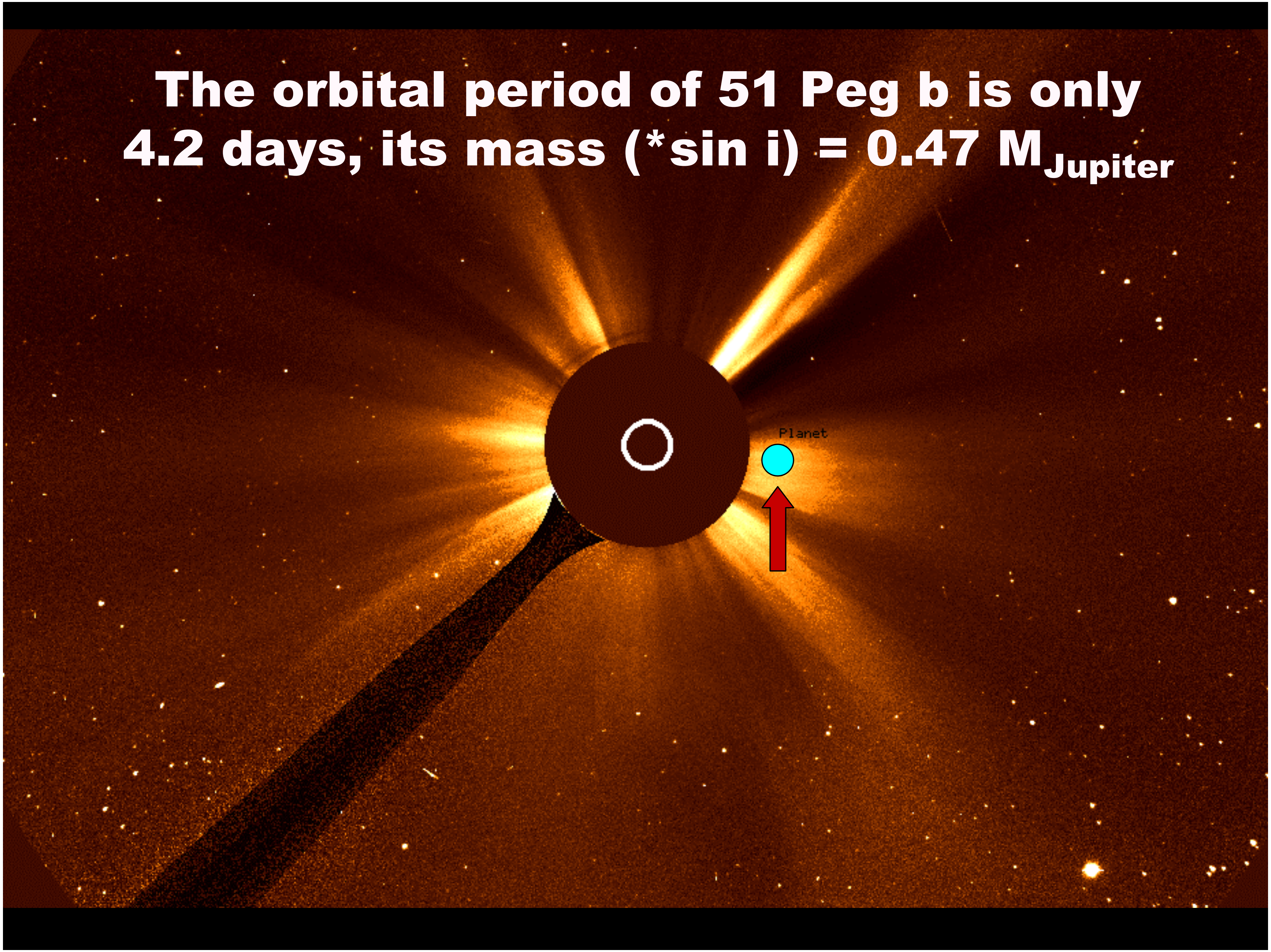
Thüringer Landessternwarte Tautenburg

Jean-Baptiste Camille Corot
(16- Julie 1796 - 22. Februar 1875)

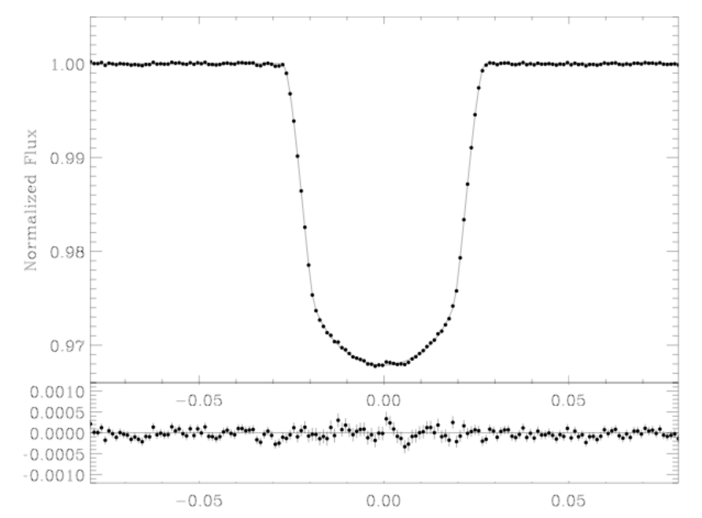
In 1995 Michel Mayor und Didier Queloz discovered the first extrasolar planet orbiting a solar-like star by measuring precisely the radial-velocity variations: 51 Peg b

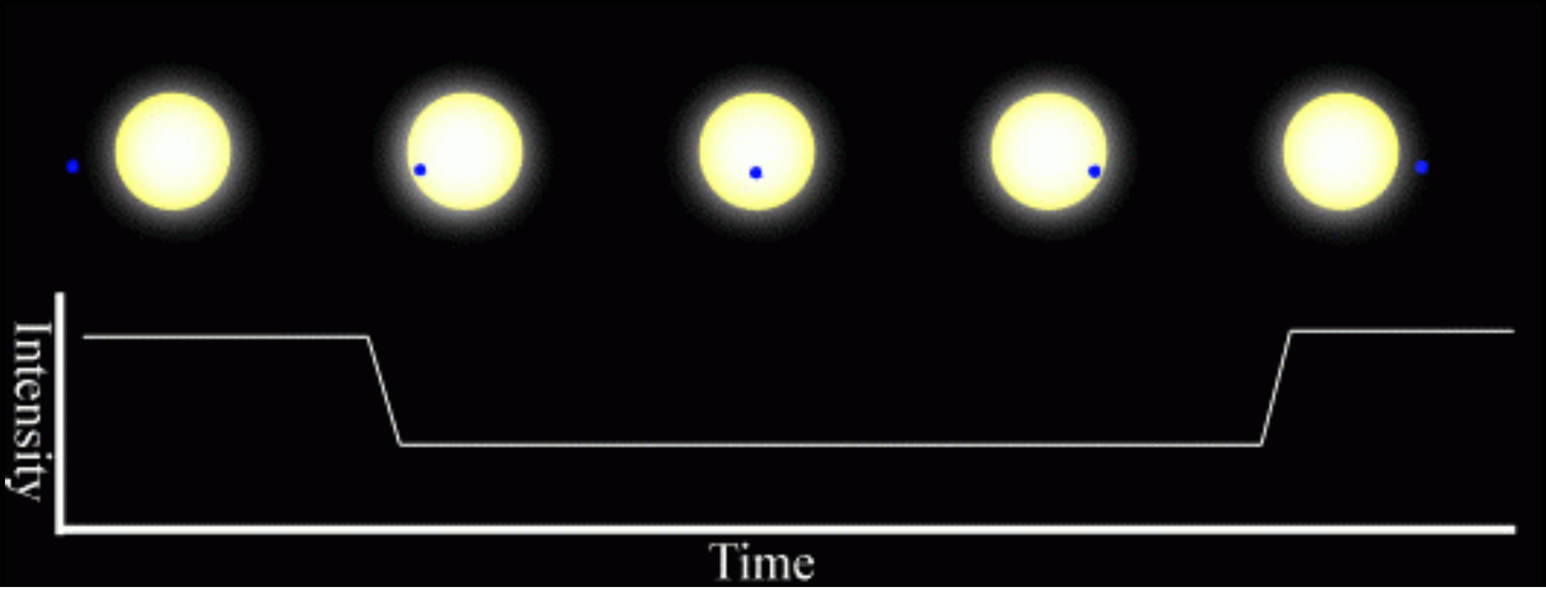


The orbital period of 51 Peg b is only 4.2 days, its mass (*sin i) = 0.47 $M_{Jupiter}$



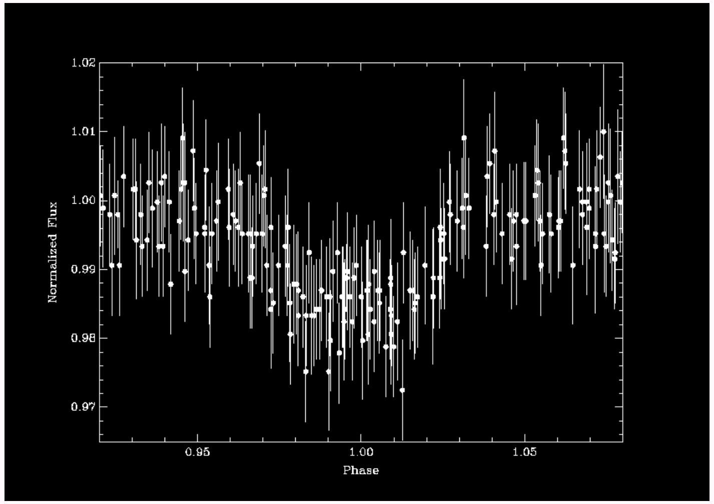
At that time CoRoT was already in the planning stage. The discovery of 51 Peg b meant that it would be possible to detect transiting planets. The observation of a transit gives us the radius of a planet.

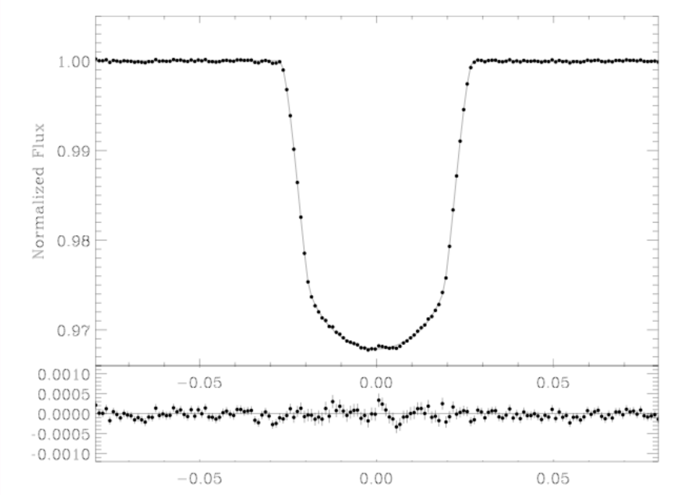




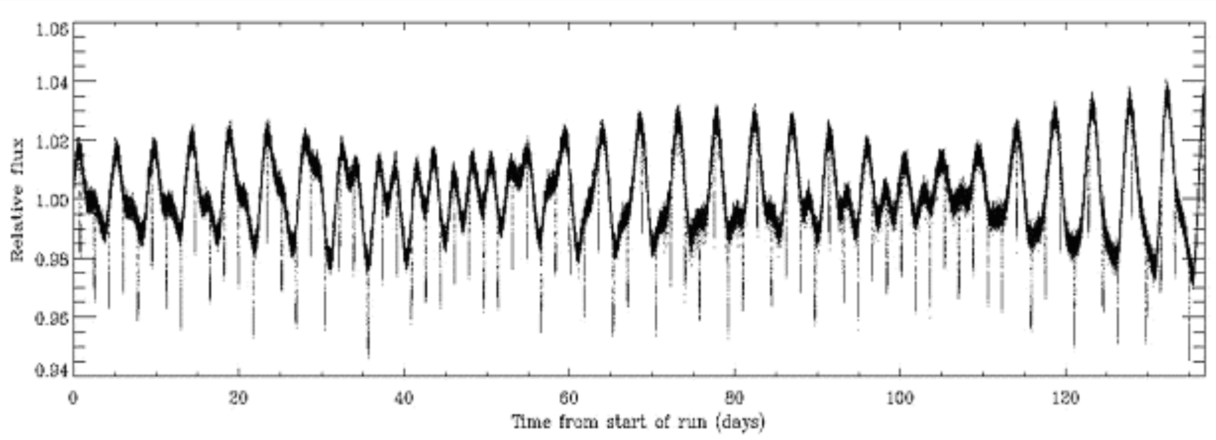
What is the advantage of space-based observations for the detection of transiting planets?

- **Much higher photometric accuracy (terrestrial planets instead of hot Jupiters)**





- **Continuous light-curves without gaps (active stars, planets of long orbital period, more transits are observed)**



Scientific Objectives of CoRoT

(Convection, Rotation et Transites planétaires)

- 1.) Detecting oscillations of solar like stars.
- 2.) Detecting transiting gaseous planets.
- 3.) Derive radius, mass, density of gaseous planets to obtain mass-radius relation.
- 4.) Determine frequency of short-period massive planets.
- 5.) Mission has fair chance to detect even a rocky planet.

Time-table

Launch: 27.12.2006

First image: 18.01.2007

First scientific observations: 05.02.2007

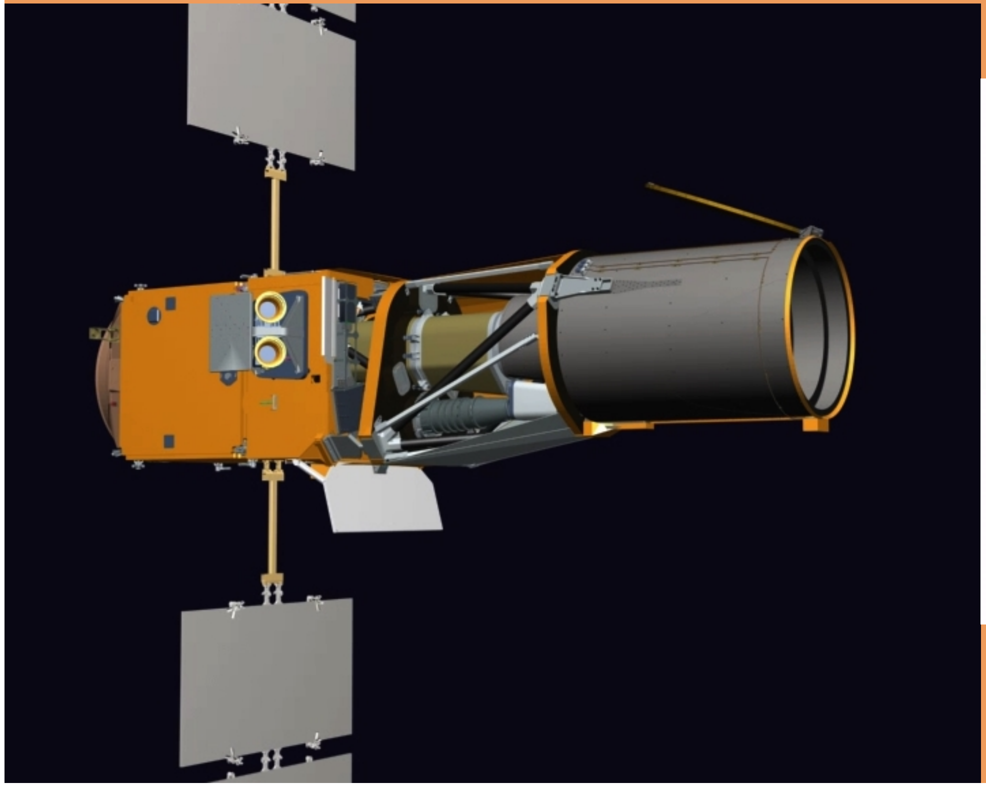
First discovery published: 04.01.2008

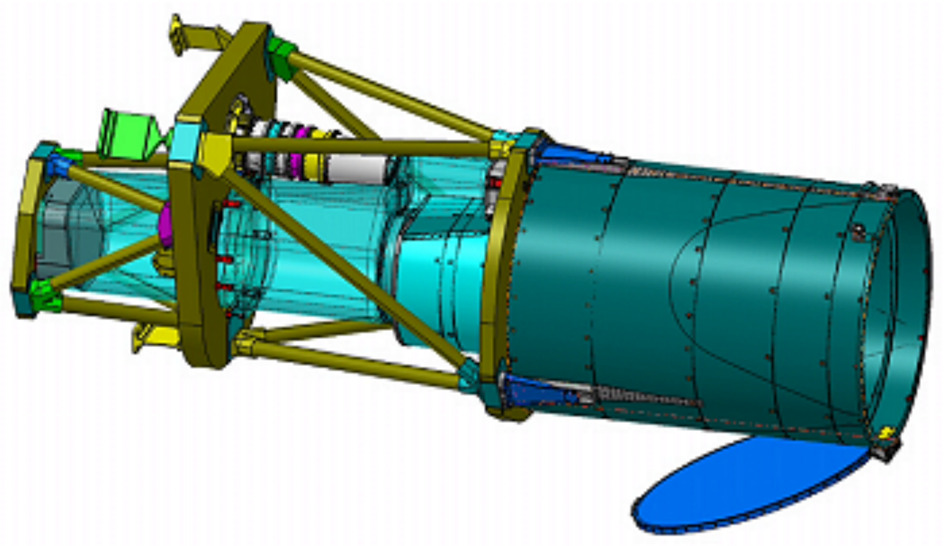
Planed lifetime: 3 years, but mission continued until 02.11.2012

The CoRoT satellite

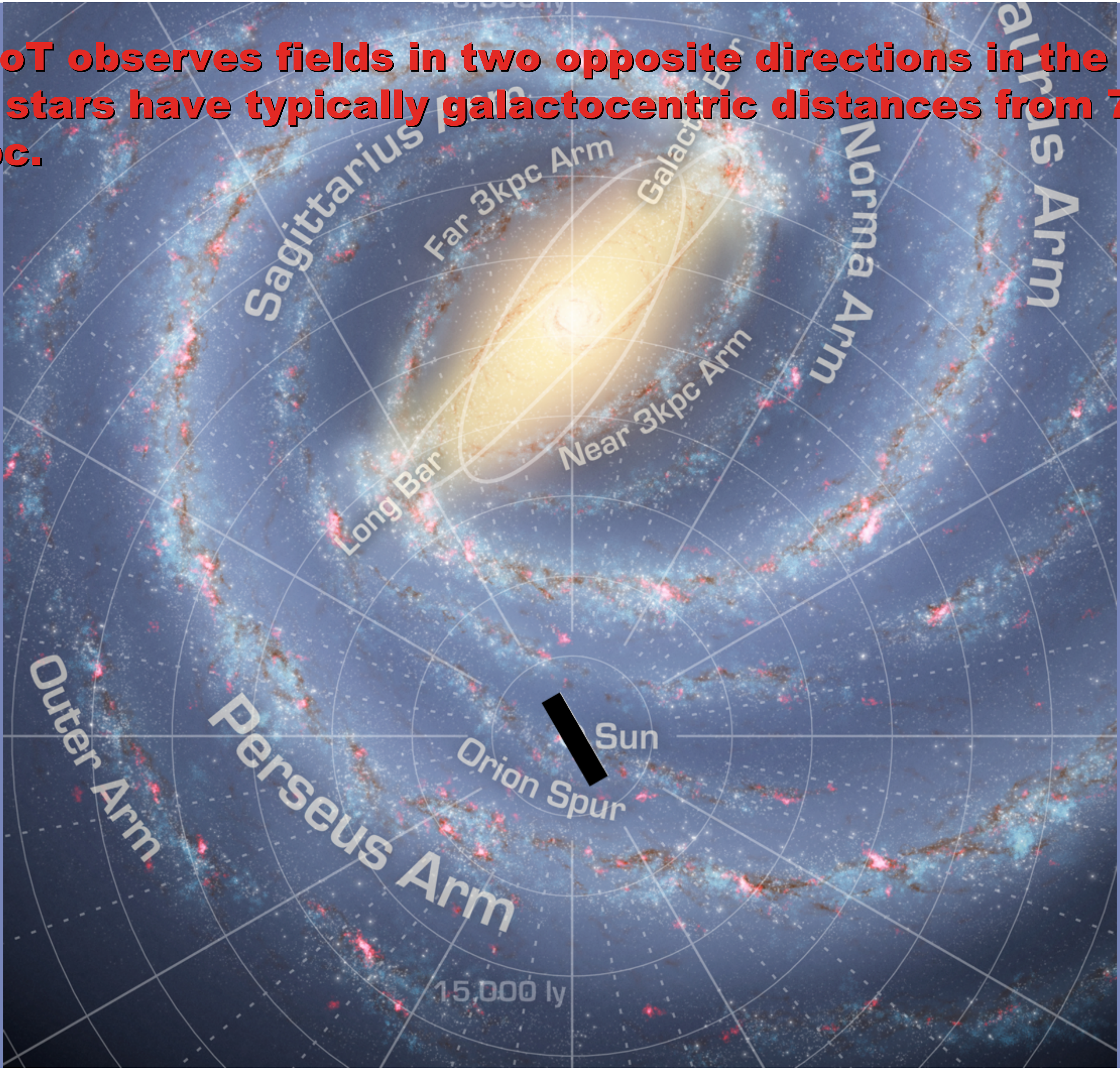
(Convection, Rotation et Transites planétaires)

Mass: 605 kg	Size: 4.2m wide by 9m high
Telescope aperture: 27cm	Focal length: 1.2 m
Scale: 2.3 arcsec per pixel	**Photometric mask: typically 25x35 arcsec**
FOV: 2.8x1.4 deg for planets	**Photometry simultaneously in the three colours**





CoRoT observes fields in two opposite directions in the sky. The stars have typically galactocentric distances from 7 to 9 kpc.

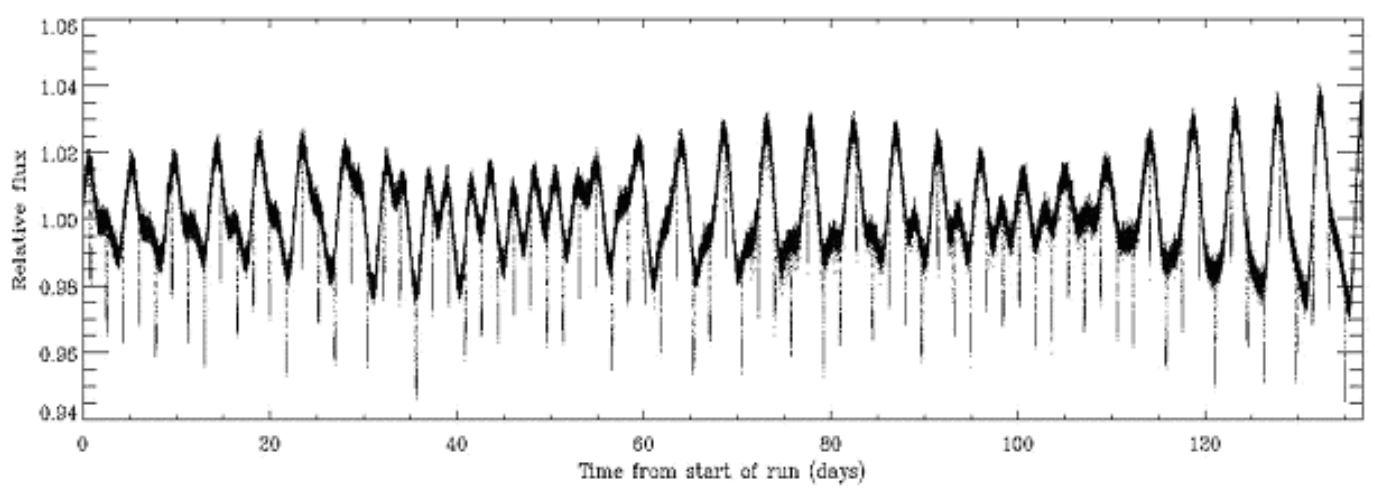


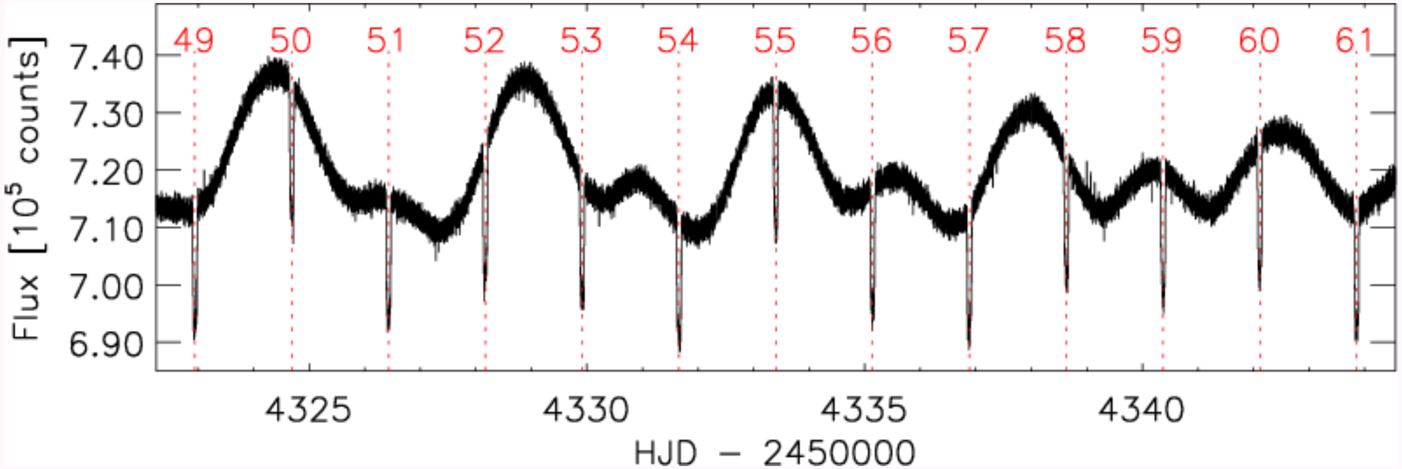
Discoveries made by CoRoT

- The first rocky planet outside the solar-system: CoRoT-7b.
- The first “temperate” (T_{eq}=250-430 K) transiting planet: CoRoT-9b
- The first transiting planet of a young, active star: CoRoT-2b
- The first transiting brown dwarfs orbiting stars: CoRoT-3b (22 M_{jup}) and CoRoT-15b (63 M_{jup}).
- The first detection of the reflected light of an extrasolar planet: CoToT-1b.

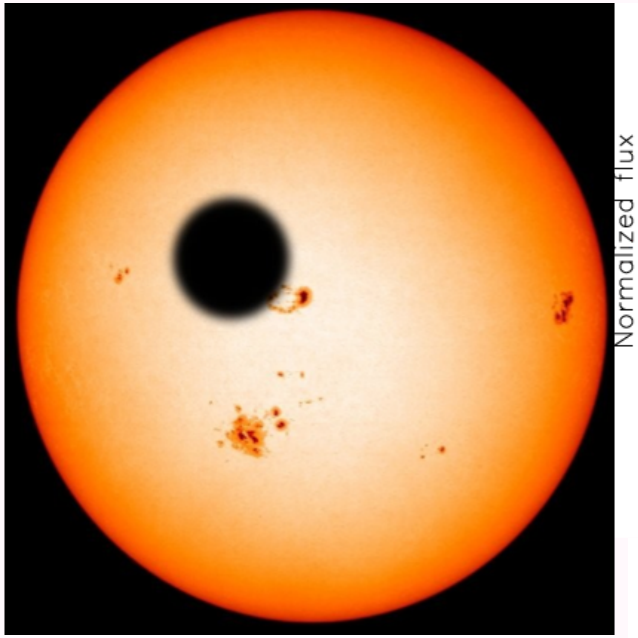
CoRoT-Exo-2b:

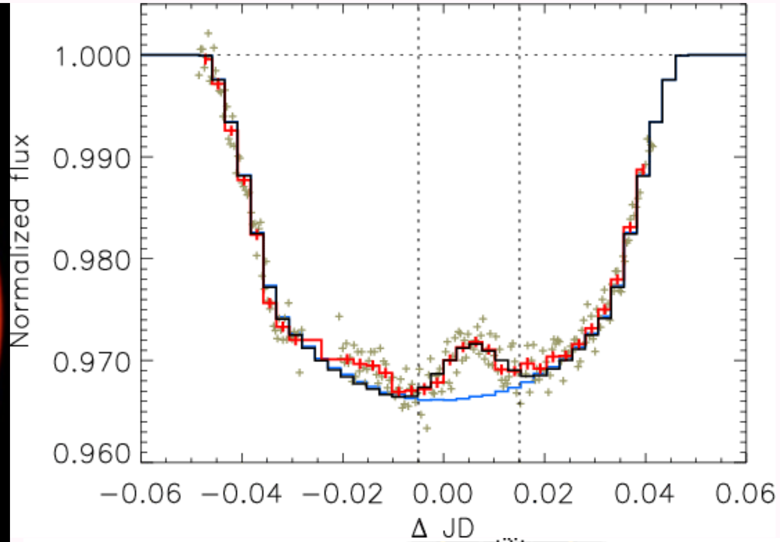
A star witha an age of 100 Myrs. It has large spots and a transiting planet



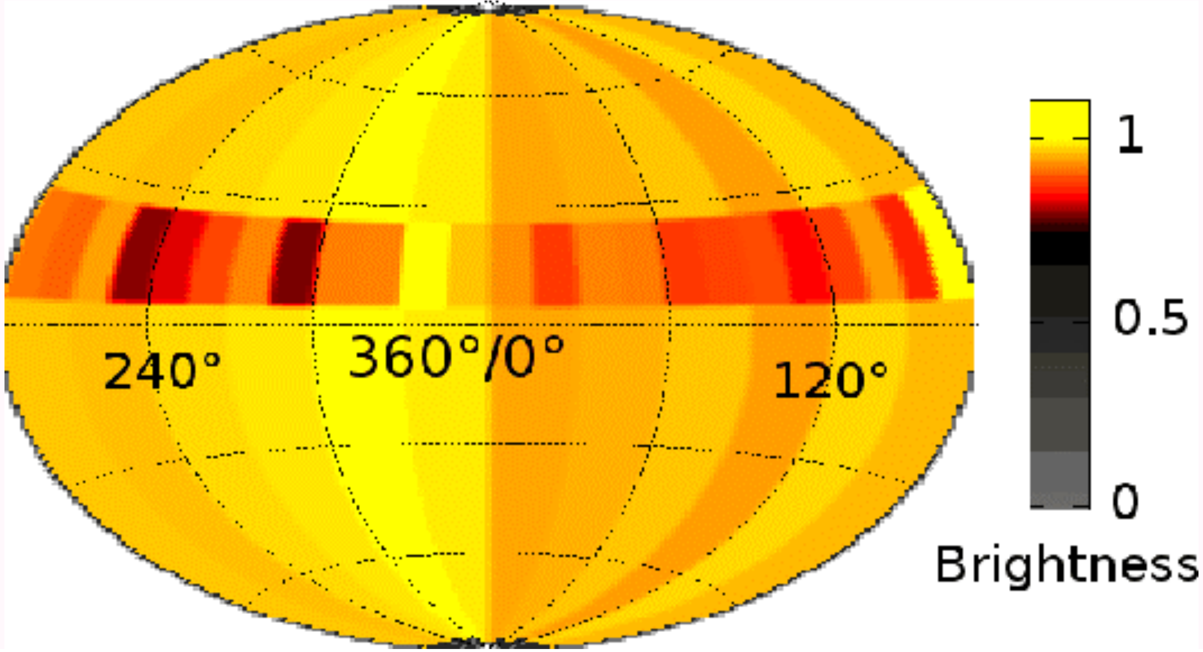


Transit mapping: the distribution of spots on the stellar surface

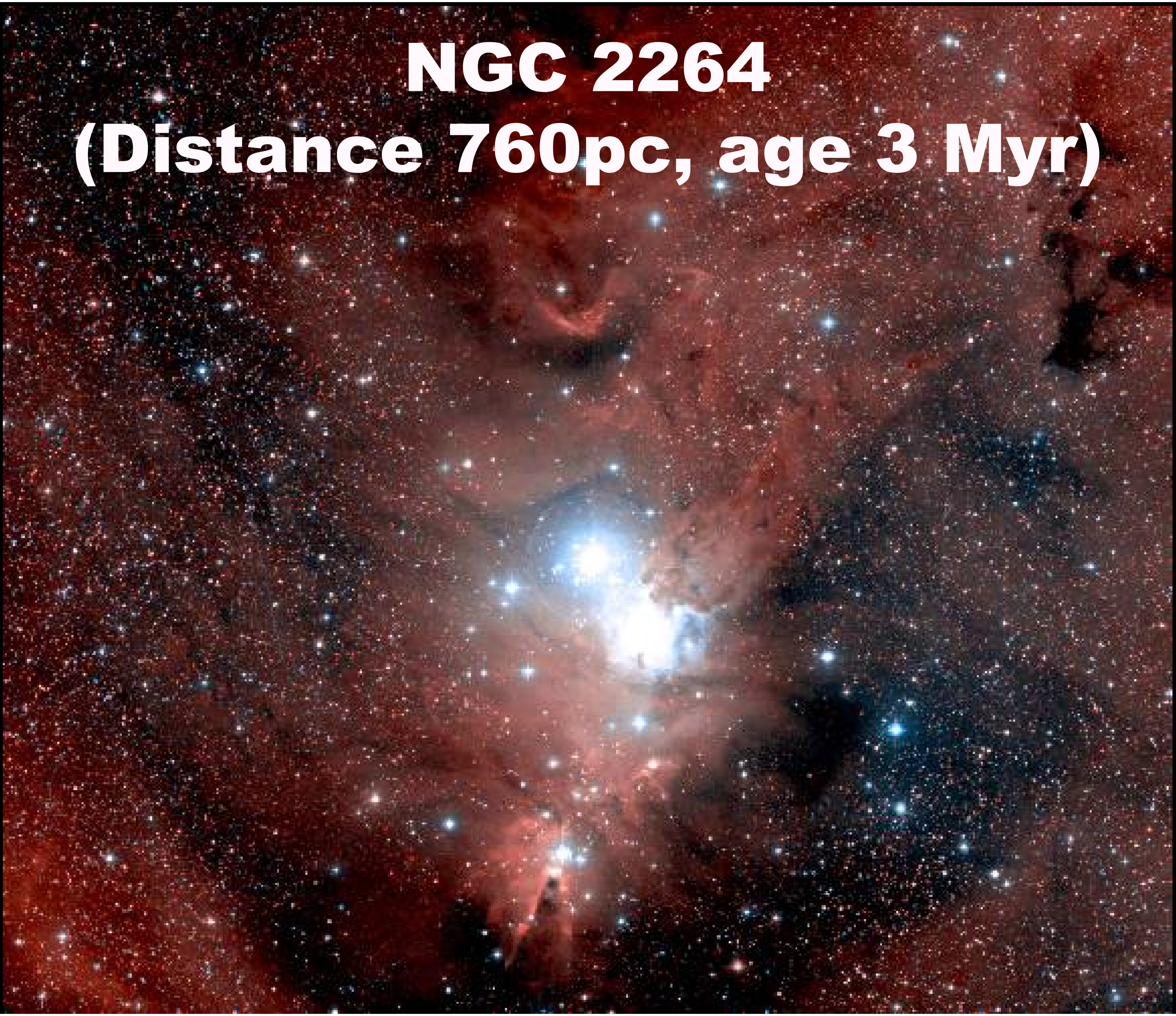




- Star: 0.97 +/-0.06 Msun
- Star: 0.90+/-0.02 Rsun
- Star: G7V (12.6 mag)
- Planet: 3.31+/-0.16 Mjup
- Planet: 1.47+/-0.03 Rjup
- Orbital period: 1.742 days



NGC 2264
(Distance 760pc, age 3 Myr)



CoRoT planets

name	M*[Msun]	period[d]	Rplanet[RJ]	Mplanet[MJ]	density[gcm^{-3}]	mv	spec	CoRoT_ID	
CoRoT1b	0.95±0.15	1.5089557	1.49±0.08	1.03±0.12	0.38±0.05	13.6	G0V	IRa01_E2_1126	COLOR
CoRoT2b	0.97±0.06	1.7429964	1.465±0.029	3.31±0.16	1.31±0.04	12.6	G7V	LRc01_E2_0192	COLOR
CoRoT3b	1.37±0.09	4.25680	1.01±0.07	21.7±1.0	26.4±5.6	13.3	F3V	LRc01_E1_0523	COLOR
CoRoT4b	1.16±0.02	9.20205	1.17±0.05	0.75±0.01	0.58±0.15	13.7	F8V	IRa01_E1_0330	COLOR
CoRoT5b	1.00±0.02	4.0378962	1.388±0.046	0.467±0.03	0.22±0.3	14.0	F9V	LRa01_E1_1031	COLOR
CoRoT6b	1.05±0.05	8.886593	1.166±0.035	2.96±0.34	2.32±0.31	13.9	F9V	LRc02_E1_0632	COLOR
CoRoT7b	0.93±0.03	0.853585	0.141±0.009	0.022±0.004	9.6±2.7	11.7	G9V	LRa01_E2_0165	COLOR
CoRoT8b	0.88±0.04	6.21229	0.57±0.02	0.22±0.03	1.6±0.1	14.3	K1V	LRc01_E2_1145	COLOR
CoRoT9b	0.99±0.04	95.2738	1.05±0.04	0.84±0.07	0.90±0.13	13.7	G3V	LRc02_E1_0651	COLOR
CoRoT10b	0.89±0.05	13.2406	0.97±0.07	2.75±0.16	3.70±0.83	15.2	K1V	LRc01_E2_1802	MONO
CoRoT11b	1.27±0.05	2.99433	1.43±0.03	2.33±0.34	0.99±0.15	12.9	F6V	LRc02_E1_0202	COLOR
CoRoT12b	1.078±0.08	2.828042	1.44±0.13	0.917±0.07	0.41±0.11	15.5	G4V	LRa01_E2_3459	MONO
CoRoT13b	1.09±0.02	4.03519	0.885+/-0.014	1.308±0.066	2.34±0.23	15.0	G0V	LRa02_E2_2165	MONO
CoRoT14b	1.13±0.09	1.51214	1.09±0.07	7.6±0.6	7.3±1.5	16.0	F9V	LRa02_E2_5503	MONO
CoRoT15b	1.32±0.12	3.06036	1.12±0.23	63.3±4.1	59±35	15.5	F7V	SRa02_E1_4106	MONO
CoRoT16b	1.098±0.08	5.3534208	1.17±0.15	0.54±0.08	0.44±0.17	15.6	G5V	LRc03_E2_2590	MONO
CoRoT17b	1.04±0.10	3.7681	1.02±0.07	2.43±0.30	2.82±0.38	15.5	G2V	LRc03_E2_2182	MONO
CoRoT18b	0.95±0.15	1.9000693	1.31±0.18	3.47±0.38	2.2±0.8	15.0	G9V	SRa03_E2_1347	COLOR
CoRoT19b	1.20±0.05	3.897159	1.29±0.03	1.142±0.051	0.51±0.05	14.0	G9V	SRa03_E2_0490	COLOR
CoRoT20b	1.14±0.08	9.24285	0.84±0.04	4.24±0.23	9.87±1.10	14.4	G2V	SRa03_E2_0999	COLOR
CoRoT21b	1.29±0.09	2.72474	1.30±0.14	2.53±0.37	1.53±0.53	16.1	F8IV	LRa01_E2_5277	MONO
CoRoT22b	1.15±0.08	9.7566	0.52±0.12	<0.15	<1.3	13.9	G0IV	LRc02_E1_0591	COLOR
CoRoT23b	1.14±0.08	3.6314	1.05±0.13	2.8±0.3	3.3±1.0	15.6	G0V	LRc05_E2_4607	MONO
CoRoT24b	0.91±0.09	5.1134	0.33±0.04	<0.112	<4.3	15.8	K1V	LRa02_E1_4601	MONO
CoRoT24c	0.86±0.09	11.759	0.44±0.04	0.127±0.047	2.0ア0.9	15.8	K1V	LRa02_E1_4601	MONO

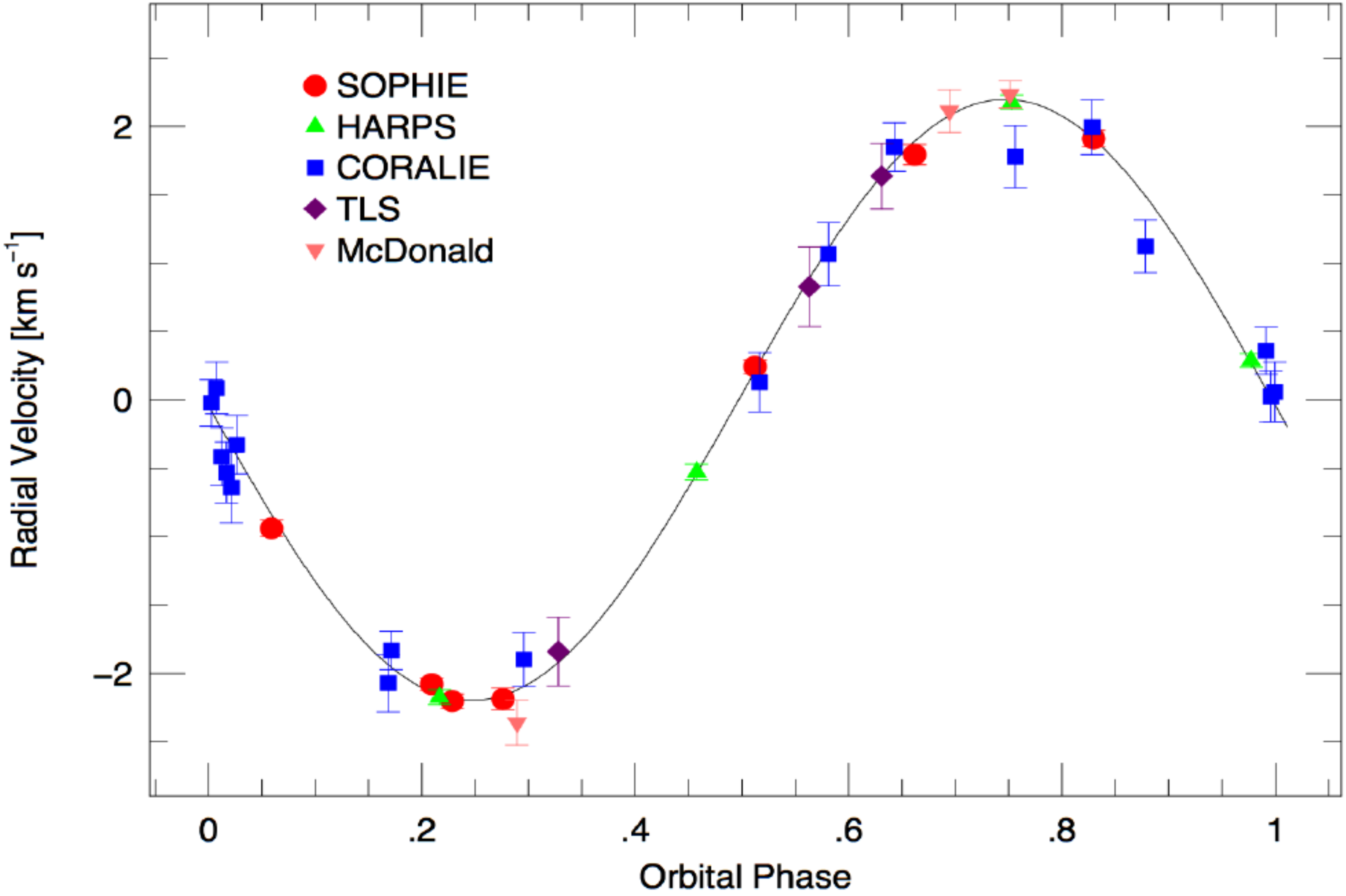
Ground based follow-up observations of CoRoT

Purpose of the ground based observations

- Excluding false-positives:

  e.g. eclipsing binaries in the photometric mask.
- Determining the stellar parameters: for example the mass and radius of the host star.
- Measuring the mass of the planet by means of radial-velocity measurements.
- Additional studies: atmosphere of the planet, spots on stellar surface, Rossiter-McLaughlin effect etc.

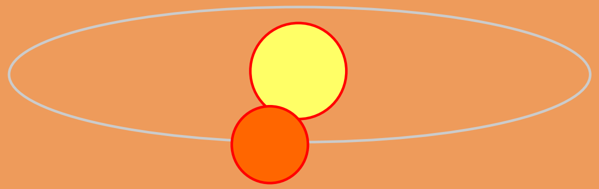
Radial-velocity measurements: mass of planet



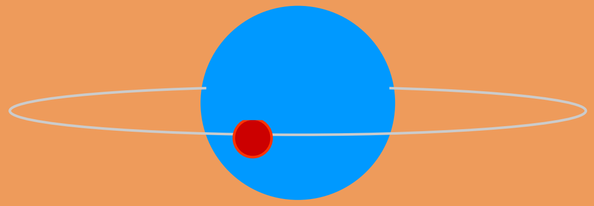
Excluding false positives

False positives produce signals that look like a transiting planet but are not

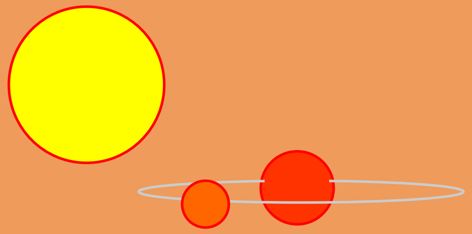
- **Eclipsing Grazing Binary:**
  Can be excluded by light-curve analysis or two RV-measurements.



- **Eclipsing Binary in a dwarf/giant system: Can be excluded by measuring stellar parameters.**



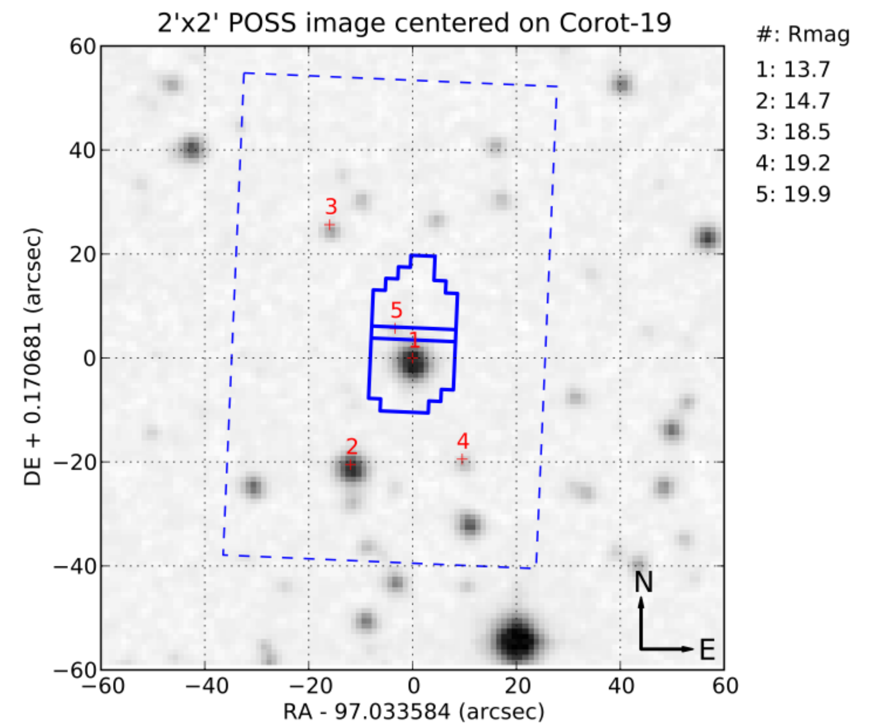
- **Eclipsing Binary in a triple system. Can largely be excluded by light-curve analysis.**

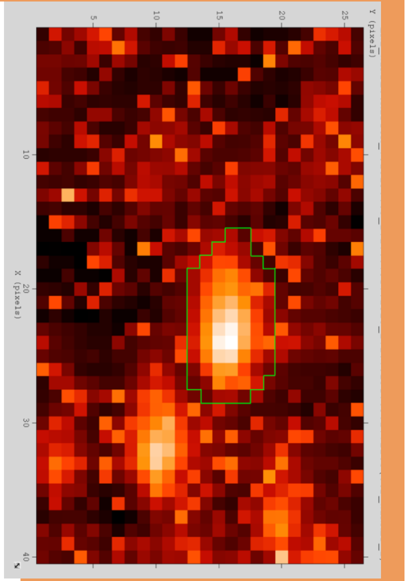


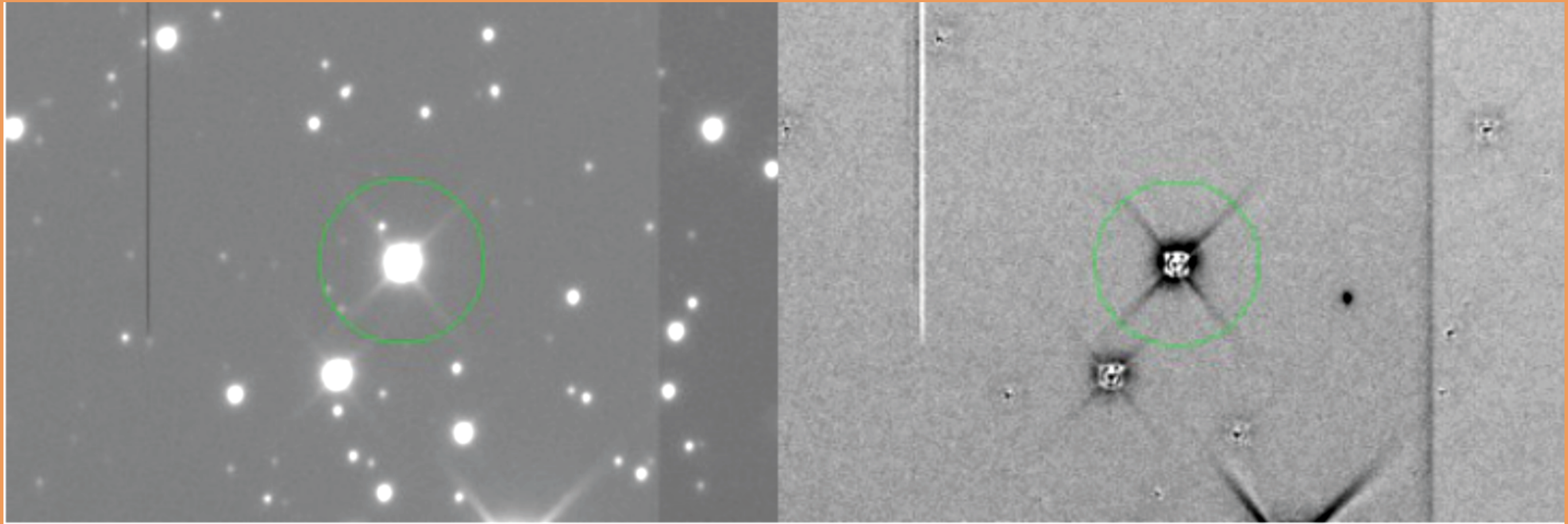
83% of the false-positives can be excluded by a detailed analysis of the light-curves!

I.) Excluding eclipsing binaries within the mask (size 25x35 arcsec):

Take one image during transit and out of transit with a seeing limited telescope.

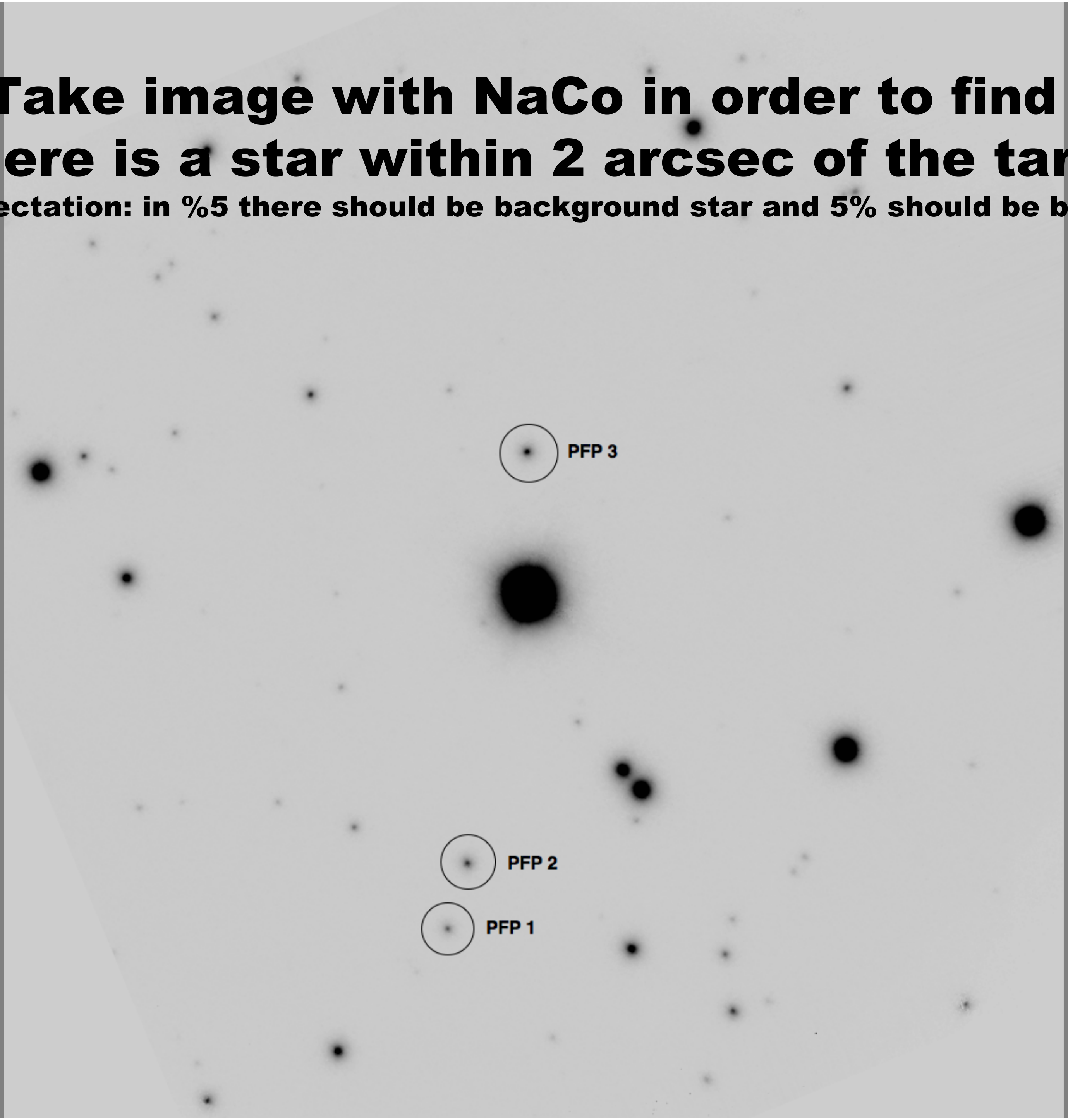




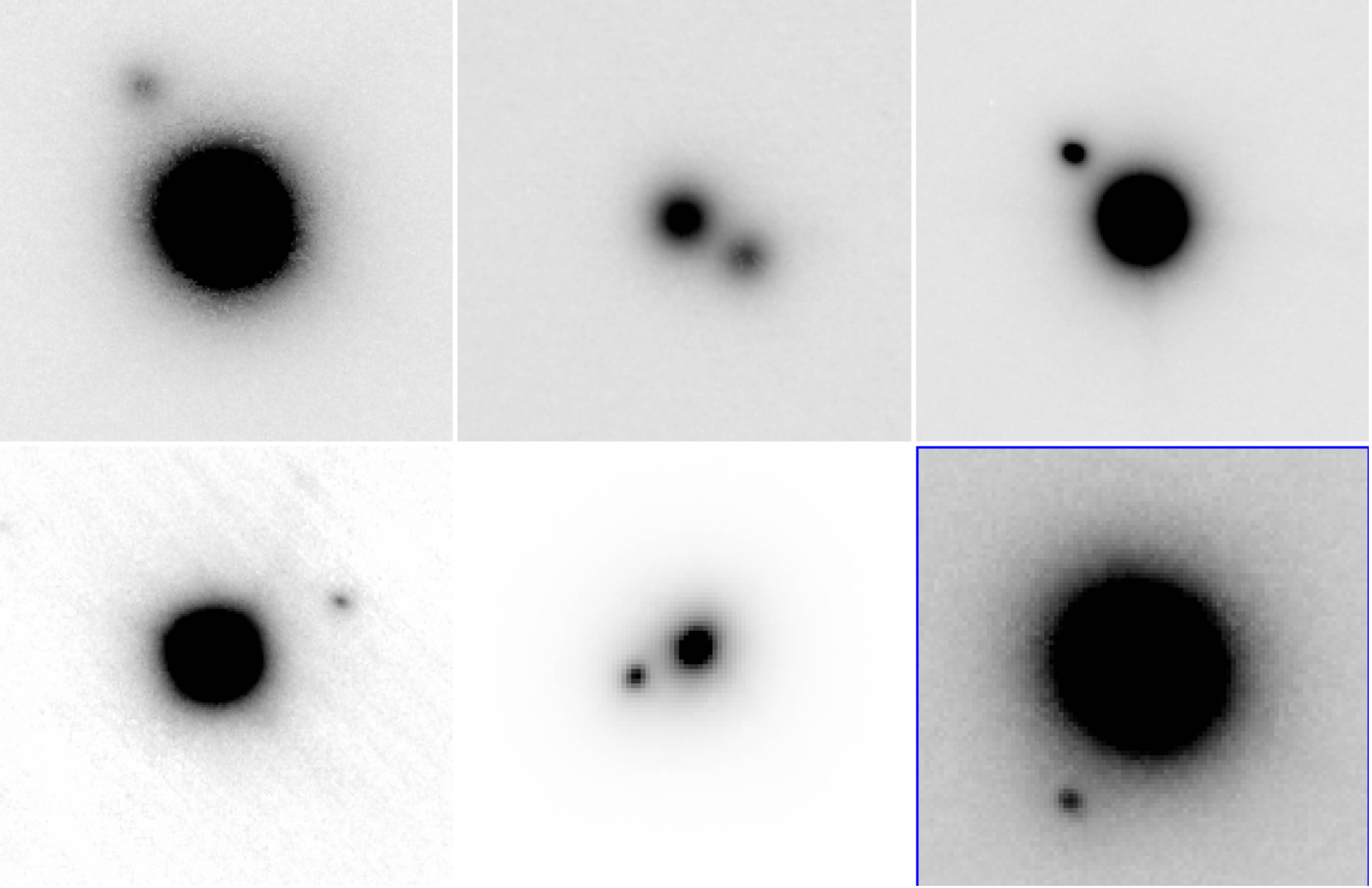


II.) Take image with NaCo in order to find out if there is a star within 2 arcsec of the target

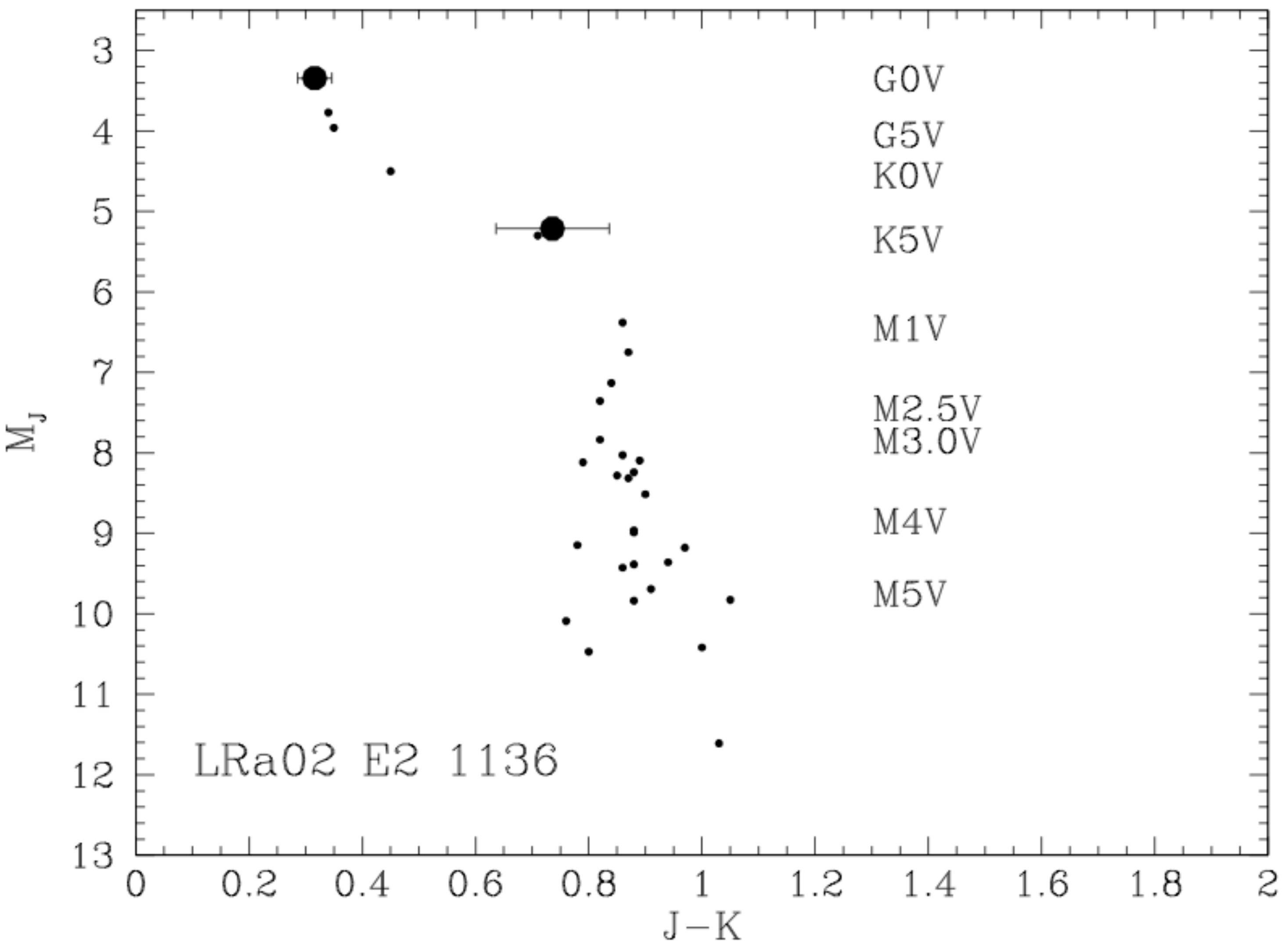
(expectation: in %5 there should be background star and 5% should be binaries)



Surprise: NaCo observations show that 30-40% of the CoRoT objects have a star within 2 arcsec.

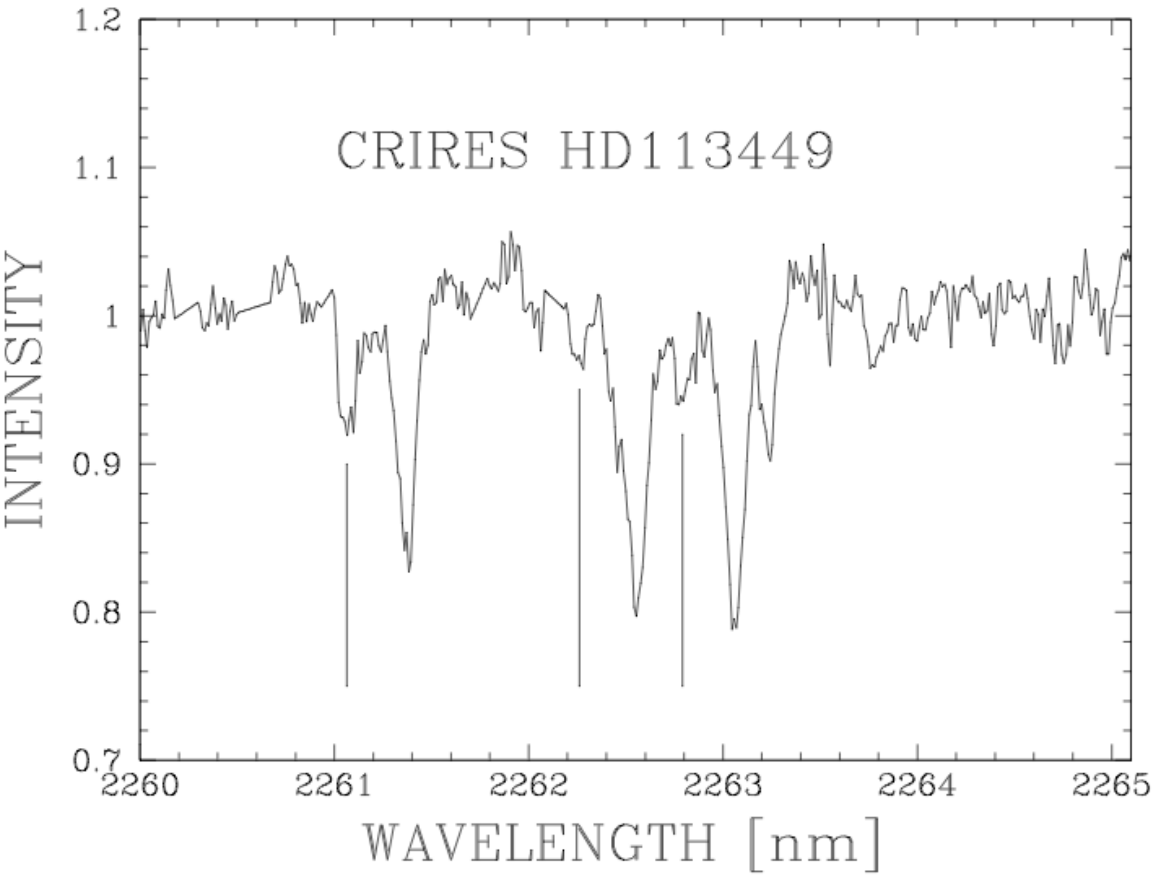


These stars are most likely true K and M-star companions.

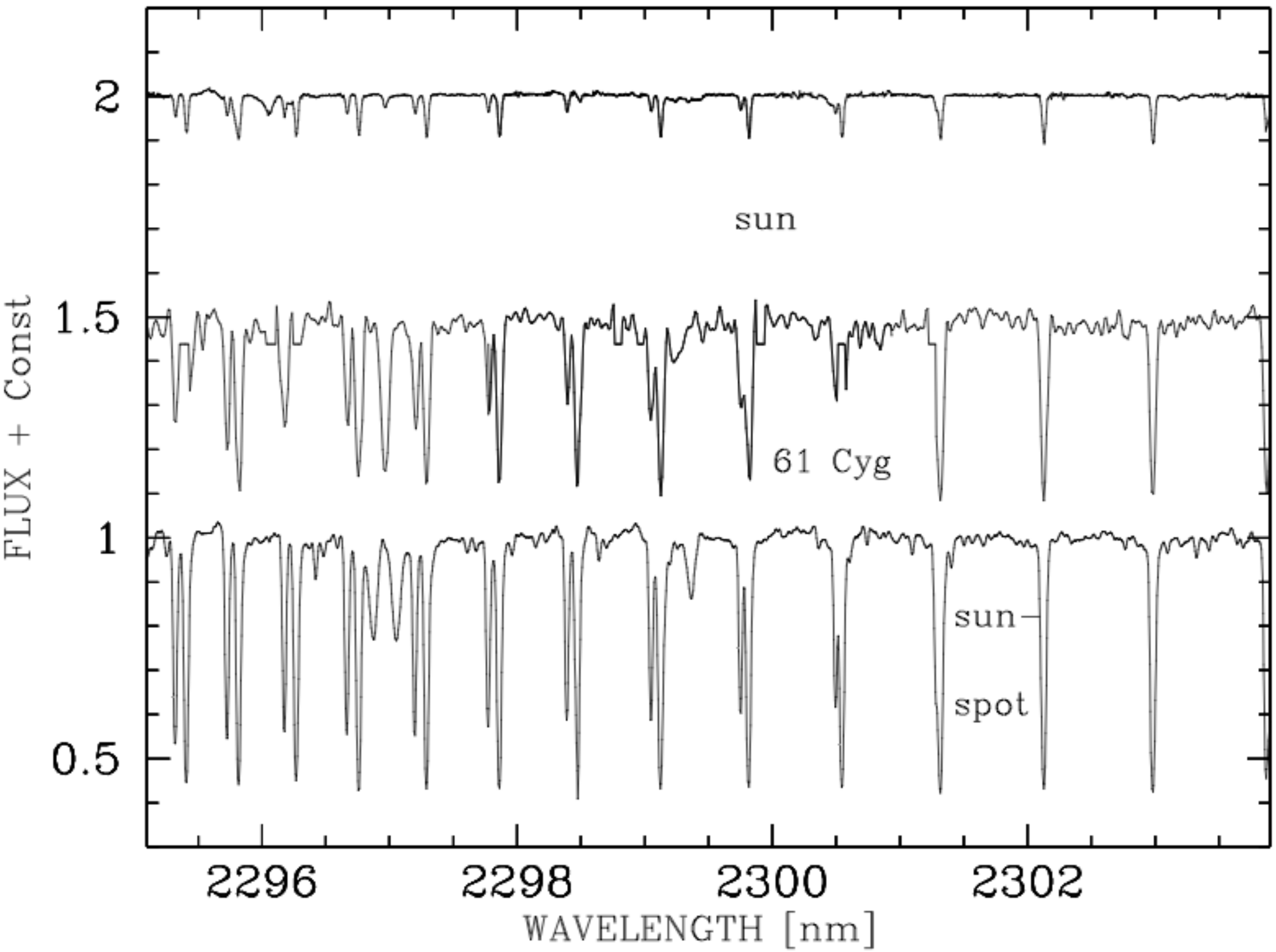


III.) Take CRIRES spectrum to exclude low-mass companions

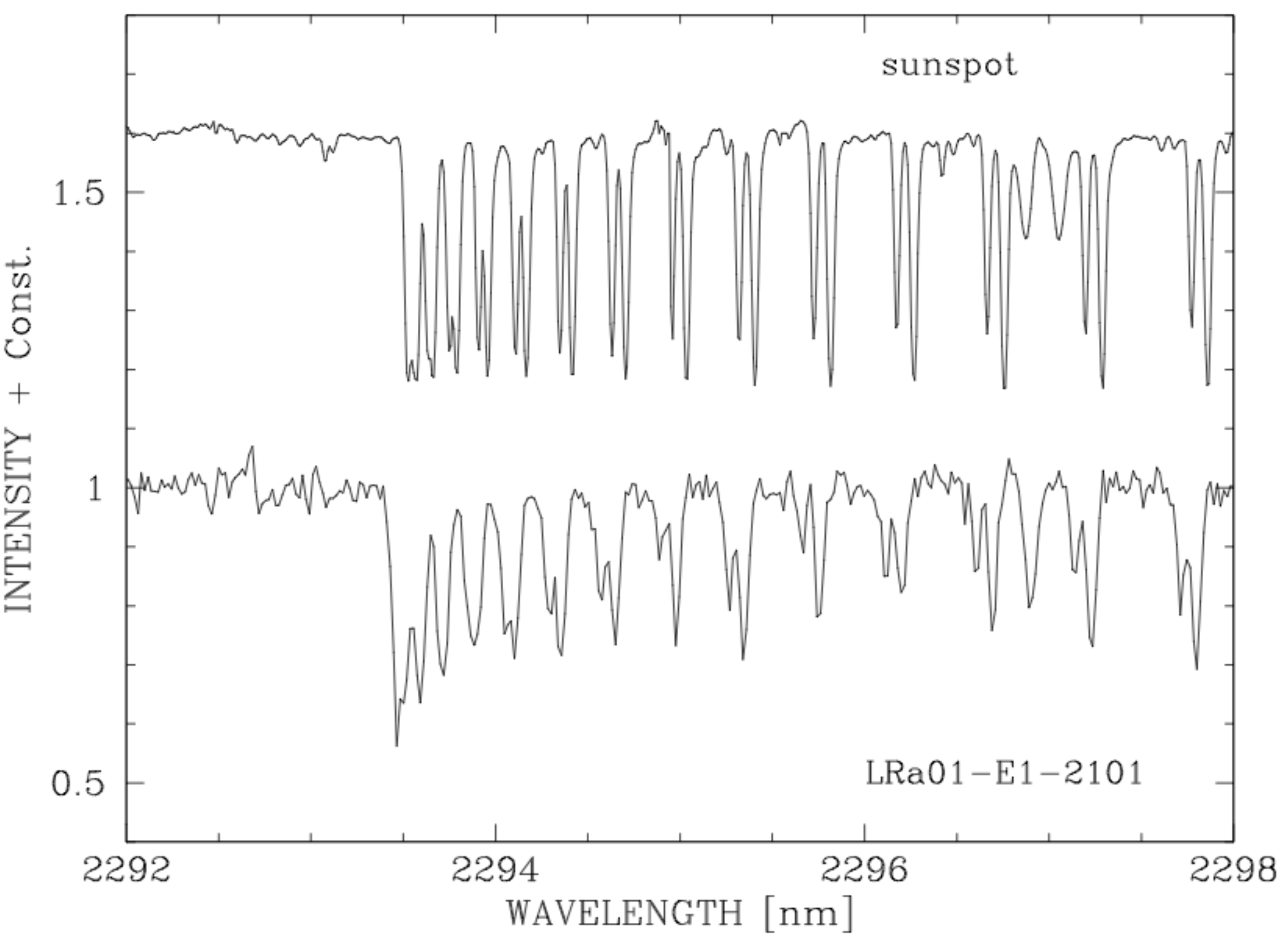
- Brightness-difference between M-star and G9V star much smaller in the IR than in the optical.
- Selected region were an M-star have strong lines, and G star on weak ones.



CO-lines are much stronger for K and M stars than for G-type stars.



CRIRES spectrum in K-band: K6V star



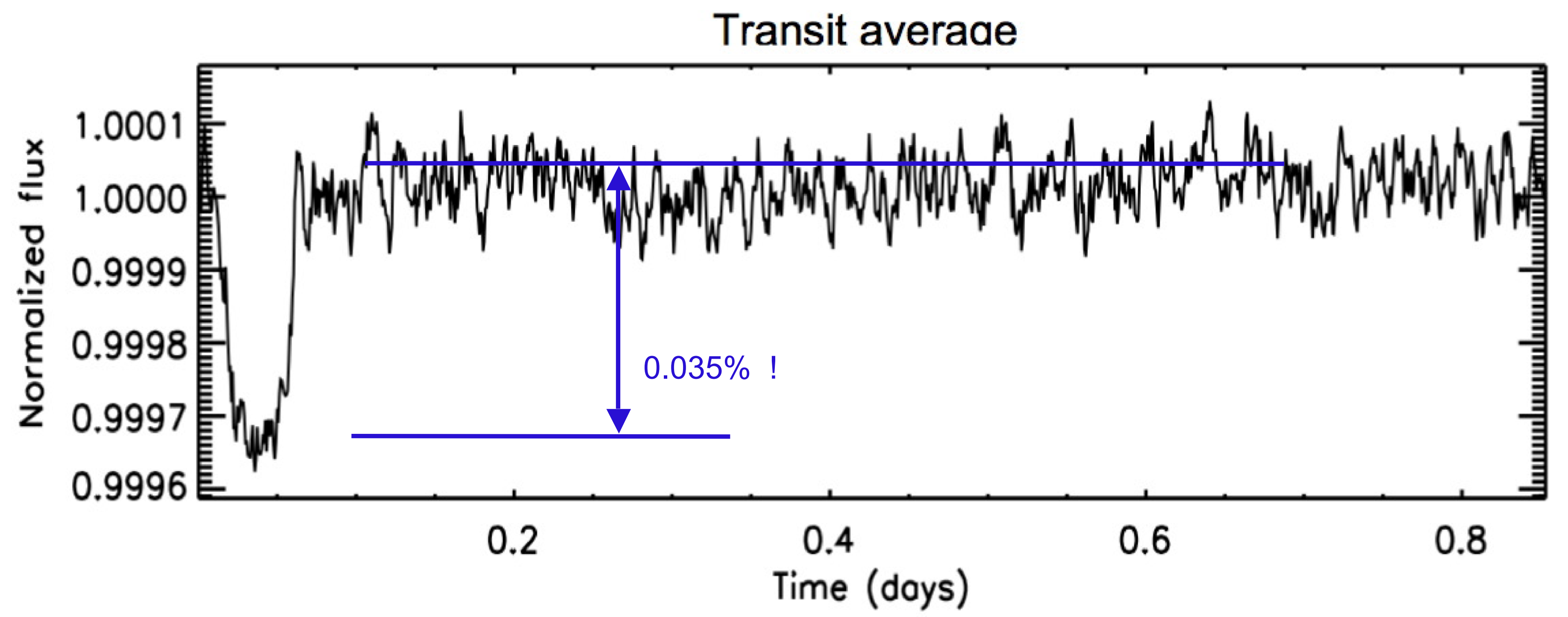
Reaching the realm of the rocky planets

The light-curve of CoRoT-7b

1.) 153 Transits observed

2.) Orbital period only 0.8536 days

3.) Transit very small ΔF/F = 0.035%



CoRoT-7b

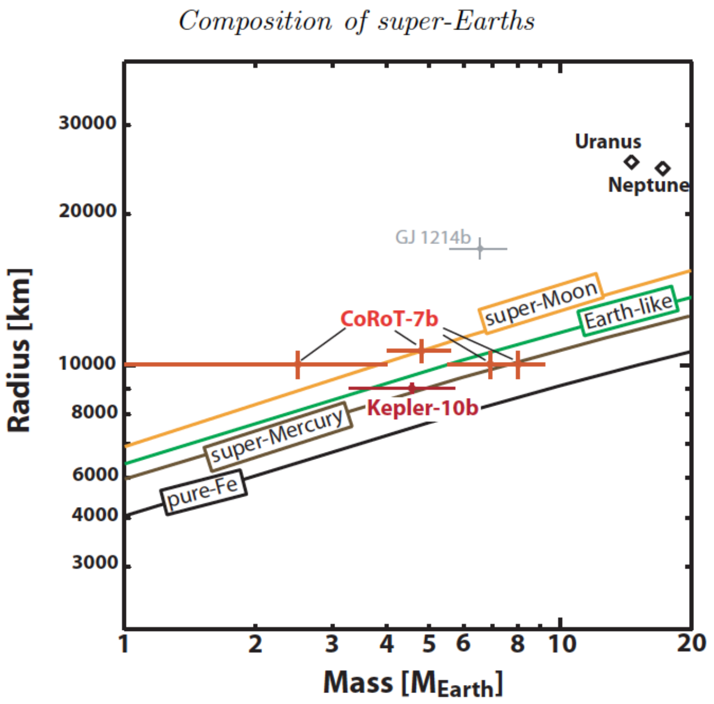
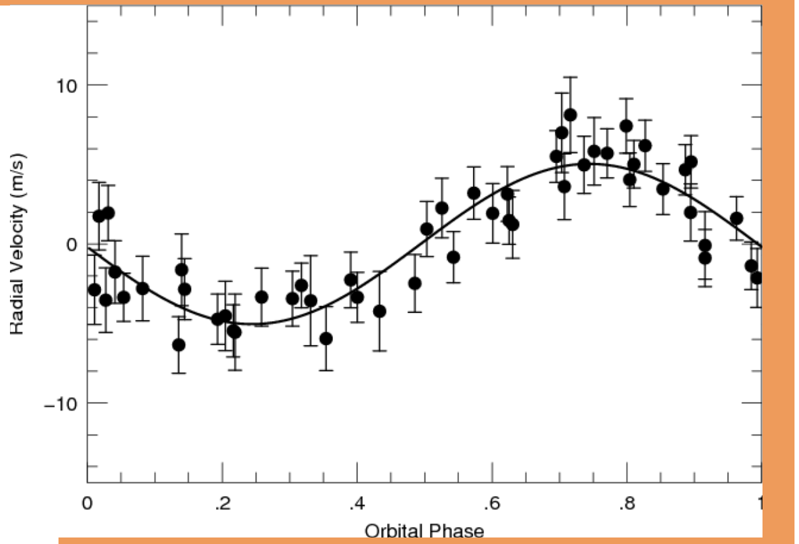


Figure 1. CoRot-7b and Kepler-10b's composition as rocky planets. The relationships for four rocky compositions: a super-moon (no iron), Earth-like (67% silicate mantle with 10% iron by mol + 33% iron core), super-Mercury (in this study as 37% silicate mantle with no iron by mol + 63% iron core), and pure iron are shown. Data for Kepler-10b, and CoRoT-7b (with its corresponding four mass estimates, and revised radius value – see text for references) are shown. Uranus, Neptune and GJ 1214b are shown for reference



Mass: 6.9 +/- 1.4 M_{Earth}

Radius: 1.58 +/- 0.10 R_{Earth}

Density: 9.6+/-2.7 g cm^{-3}

(Earth 5.515,

Venus 5.243,

Mercury 5.427 g cm^{-3})

(Valencia et al. 2011)

The densities of planets

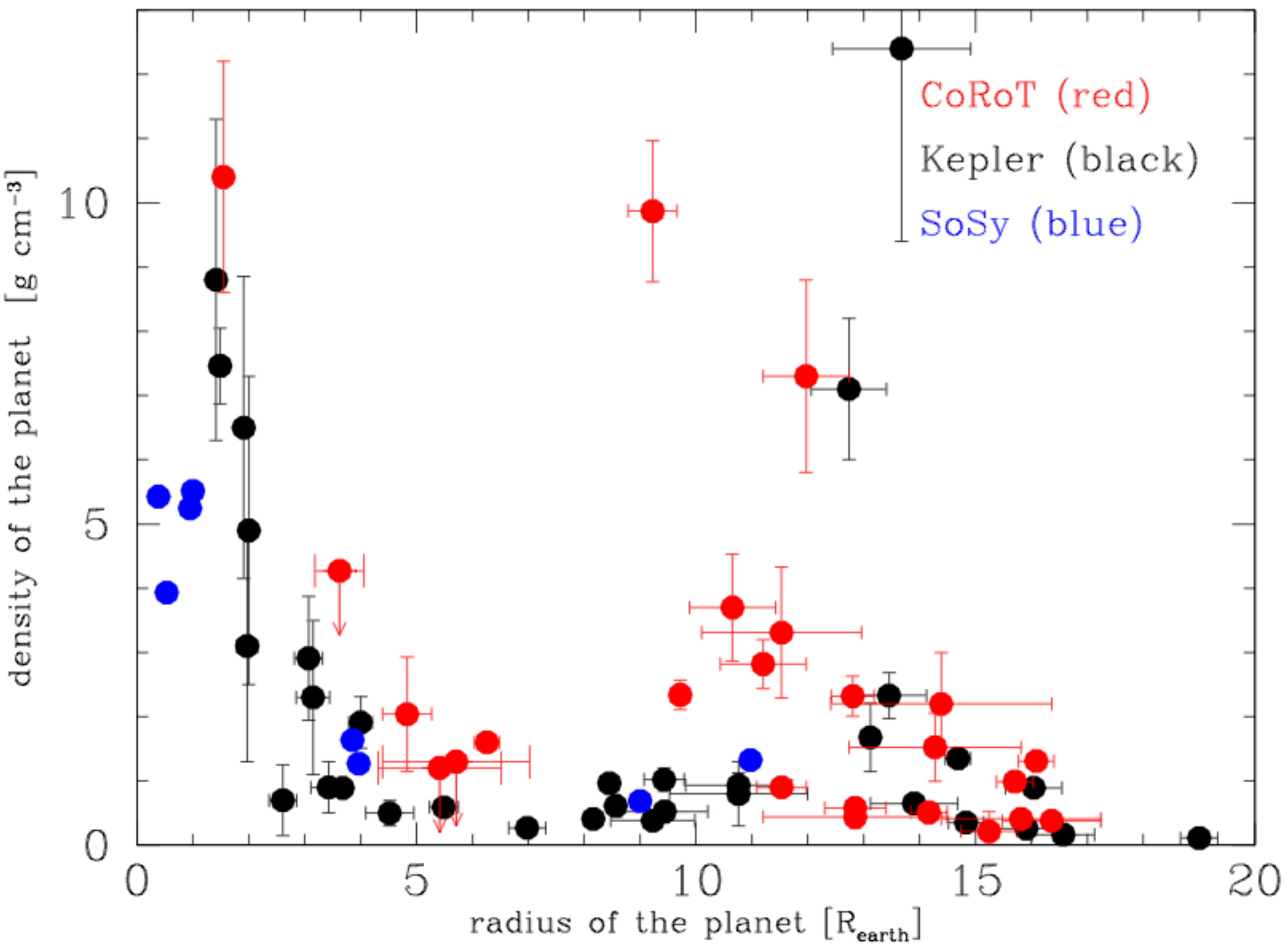
We have basically two species of planets in our solar-system :

- Gaseous (or icy) planets with masses larger than 15 M_{Earth} (radius larger than 4 R_{Earth}) and densities between 0.7 to 1.6 gcm^{-1}.
- Rocky planets with densities with between 3.7 to 5.5 gcm^{-1} that have masses of one M_{Earth} (or less)

----> Do we find the same for exoplanets?

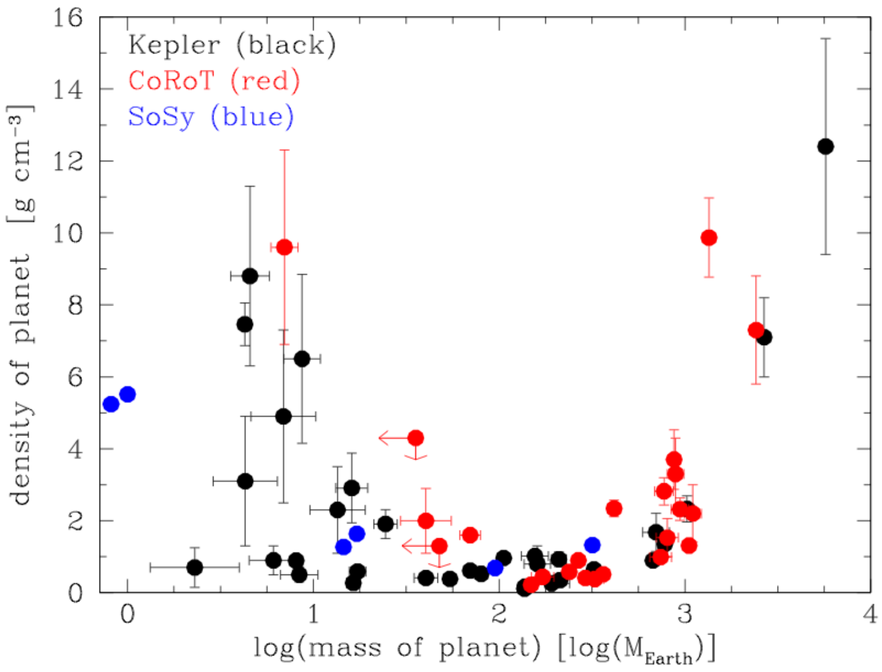
...surprise, surprise

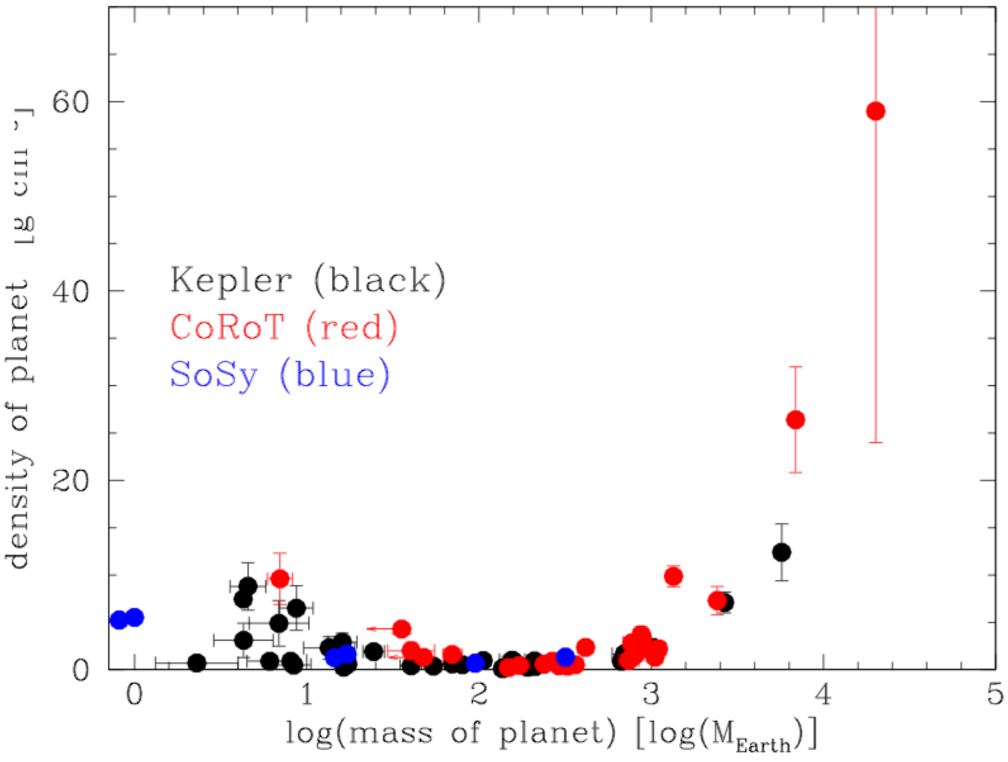
The radius-density diagram is more complicated than we have thought.



The density-mass relation for planets:

Planets of low as well as high masses can have large densities!





Statistics of exoplanets

So far CoRoT has measured the mass and radii of 25 planets:

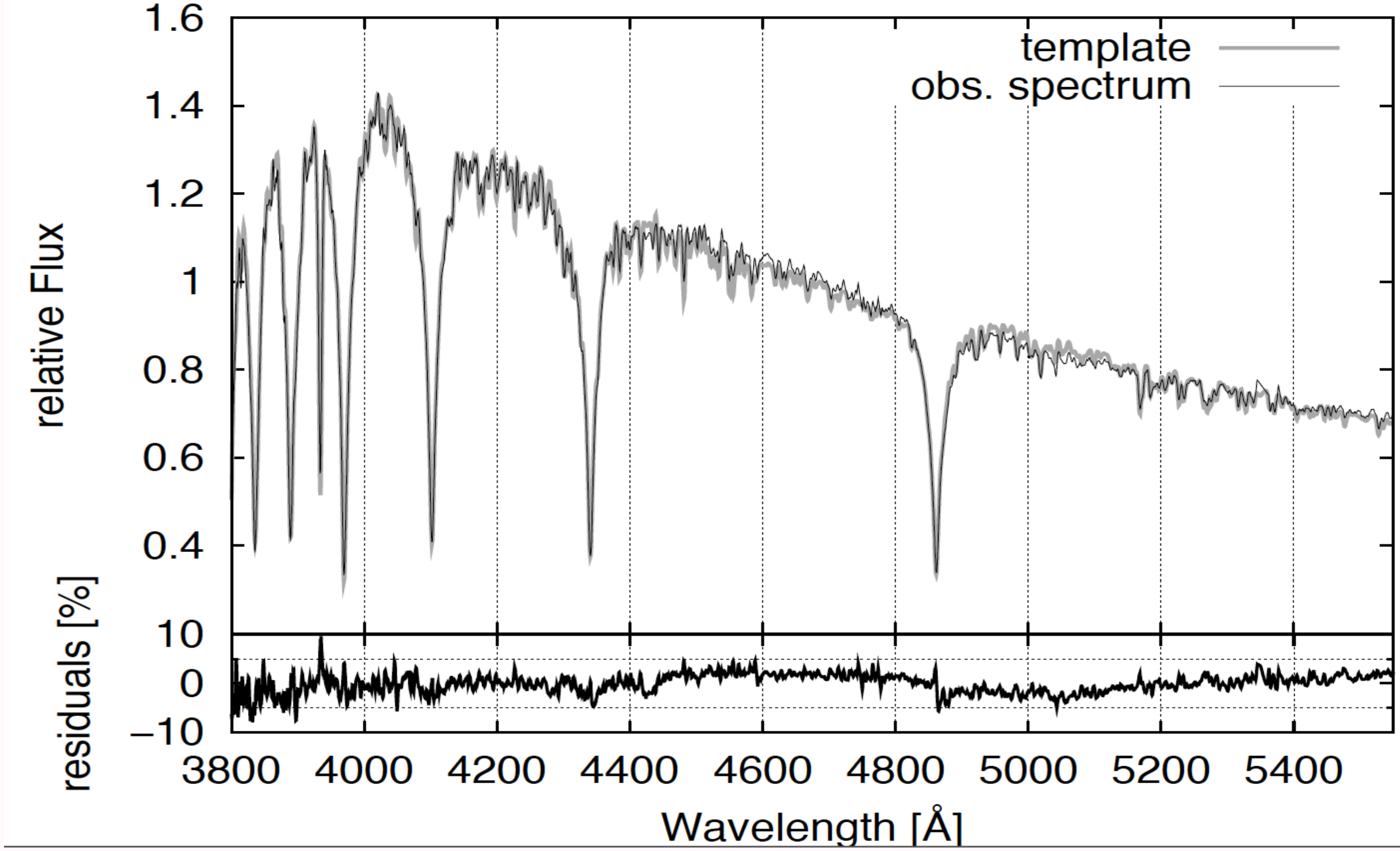
8 are orbiting F-stars
13 are orbiting G-stars
4 are orbiting K-stars

---> Does this indicate that planets are more common around G-type stars?

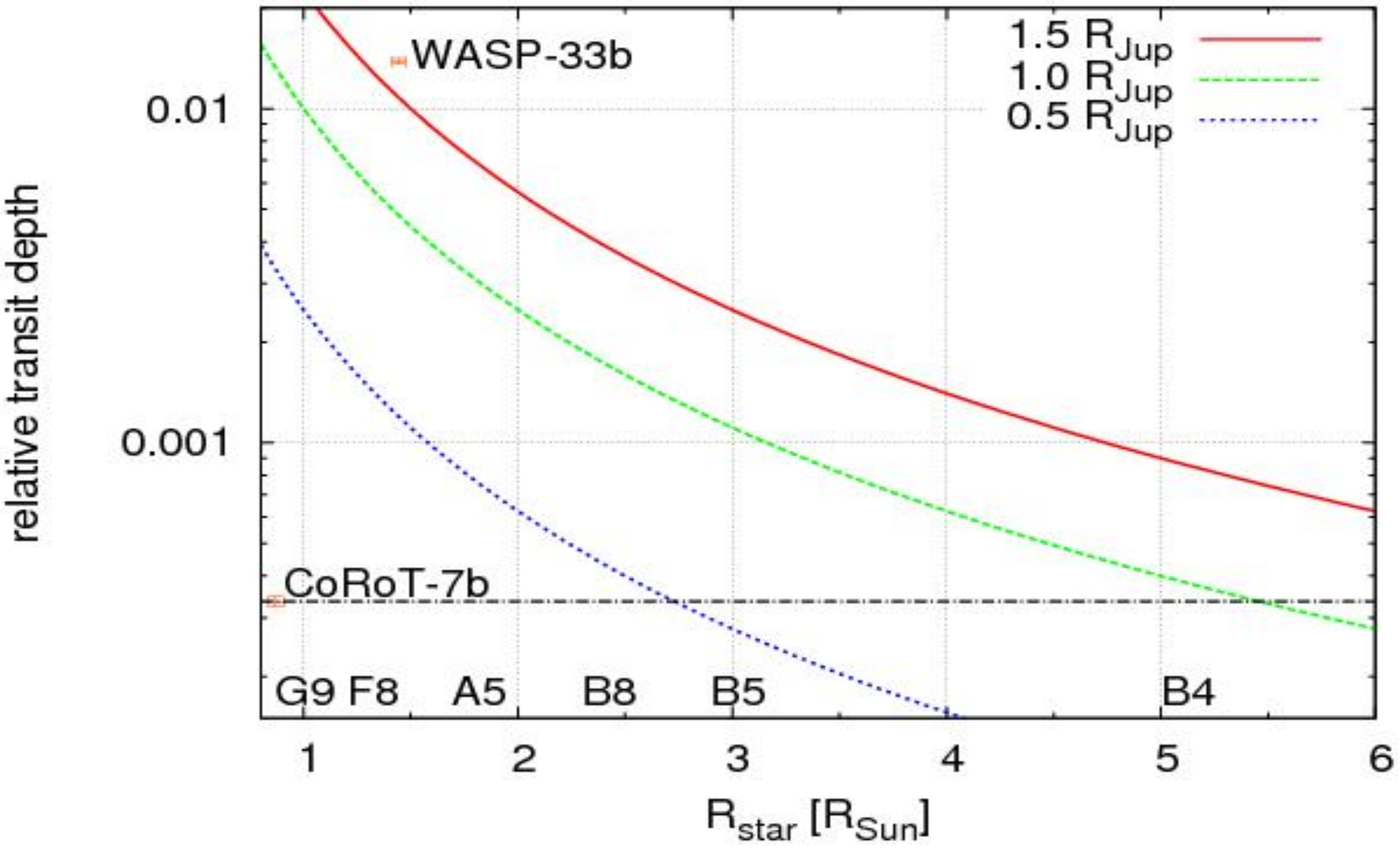
Certainly not, we have to know how many F, G, and K-stars the sample contains, and we have to take into account that the sensitivity for detecting planets is also different for different types of stars

AAOmega MOS spectrograph

In order to characterise the sample that CoRoT observes, we have obtained spectra of 11466 stars in 3 of the 24 CoRoT-fields



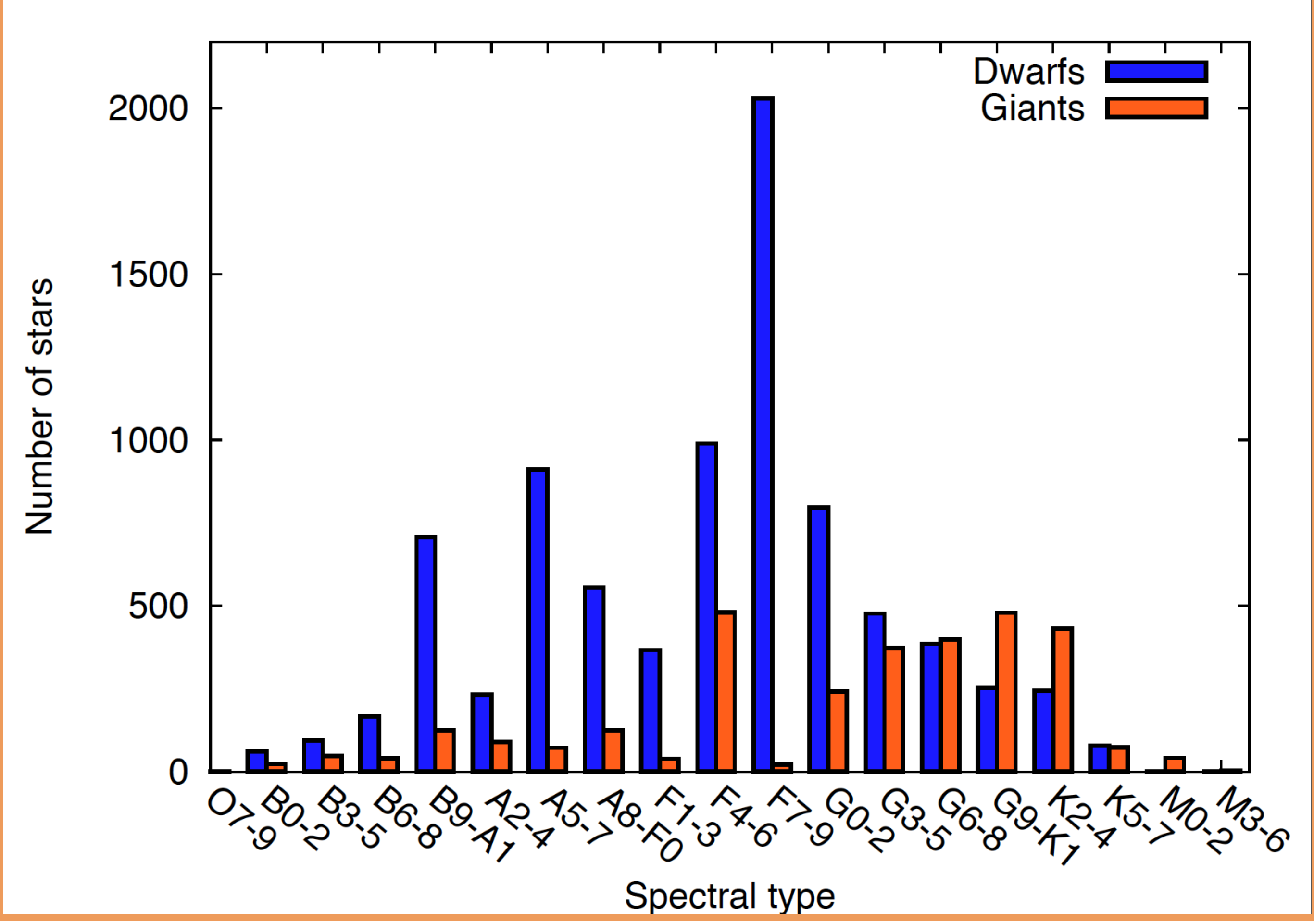
CoRoT has the capability to detect hot Jupiters of stars as early as B4V, and planets of 2 R_{Earth} around G-type stars



CoRoT finds one hot Jupiter amongst 2100+/-700 stars.

This corresponds to a frequency of 0.4+/-0.2% hot Jupiters
(RV-surveys: Cumming et al. 2008: 0.4+/-0.3% Naef et al. 2005 0.7+/-0.5%)

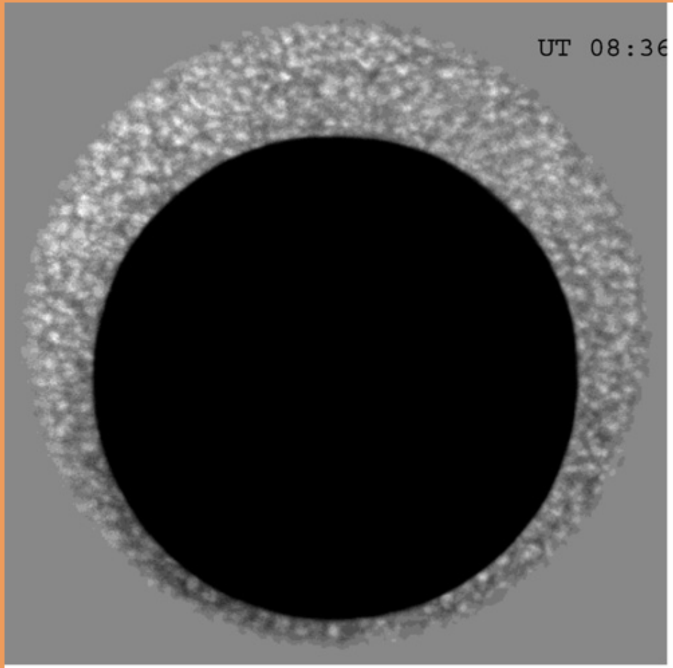
The frequency of hot Jupiters around F-stars is less, or equal to that of G-stars.

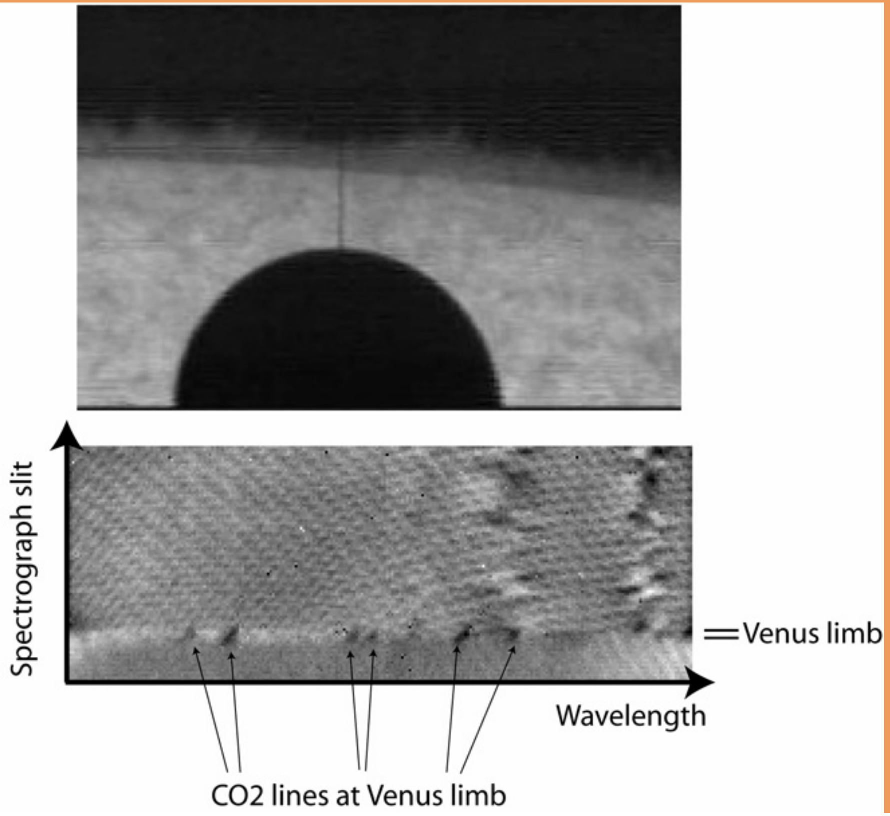


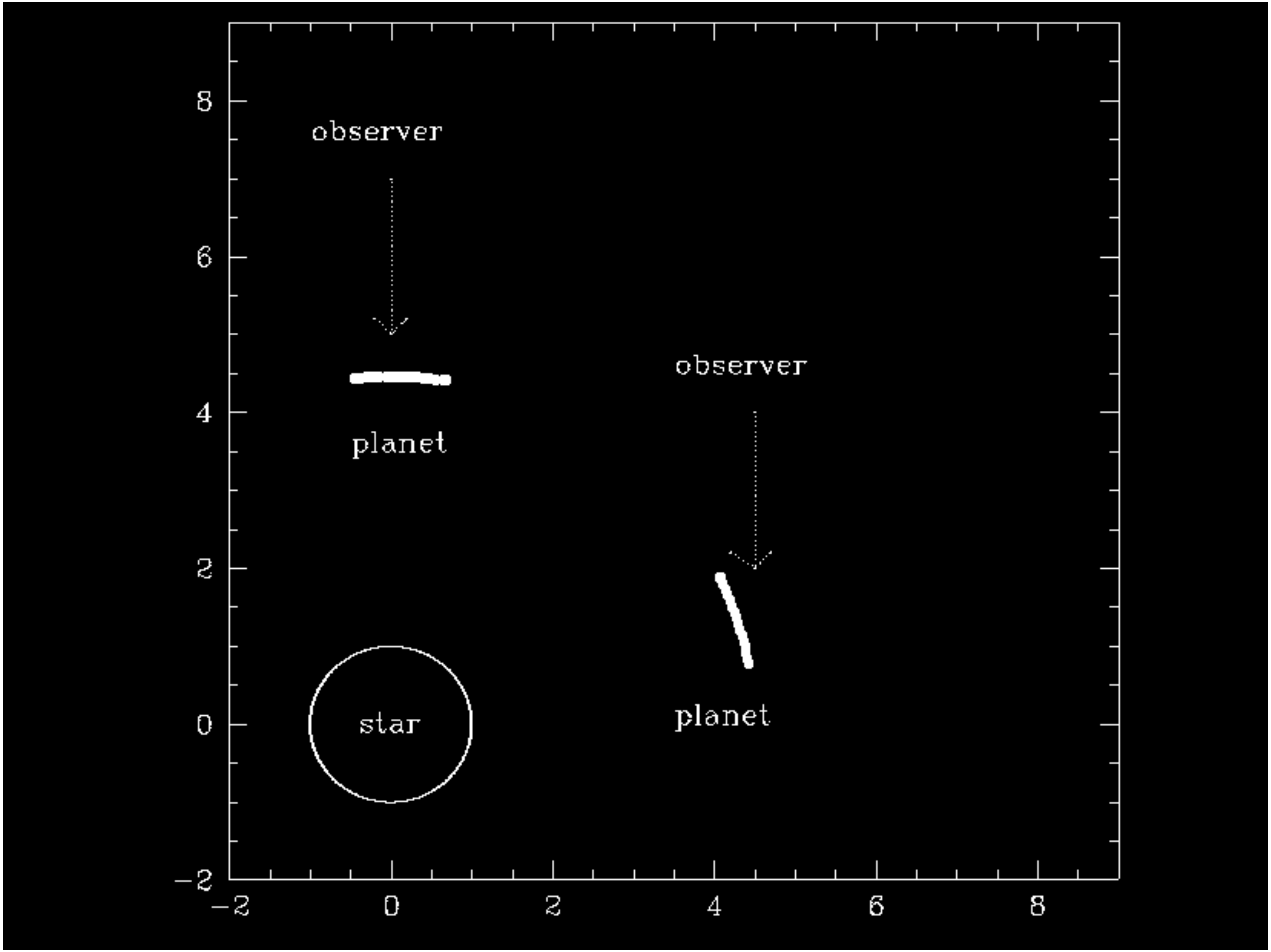
The atmosphere of the CoRoT-7b

The exosphere of CoRoT 7b: UVES observations

Spectroscopic observation during the transit allow to study the atmosphere in the same way as it was done for Venus (Rauer et al. 2004) or Mercury (2006).






observer
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observer
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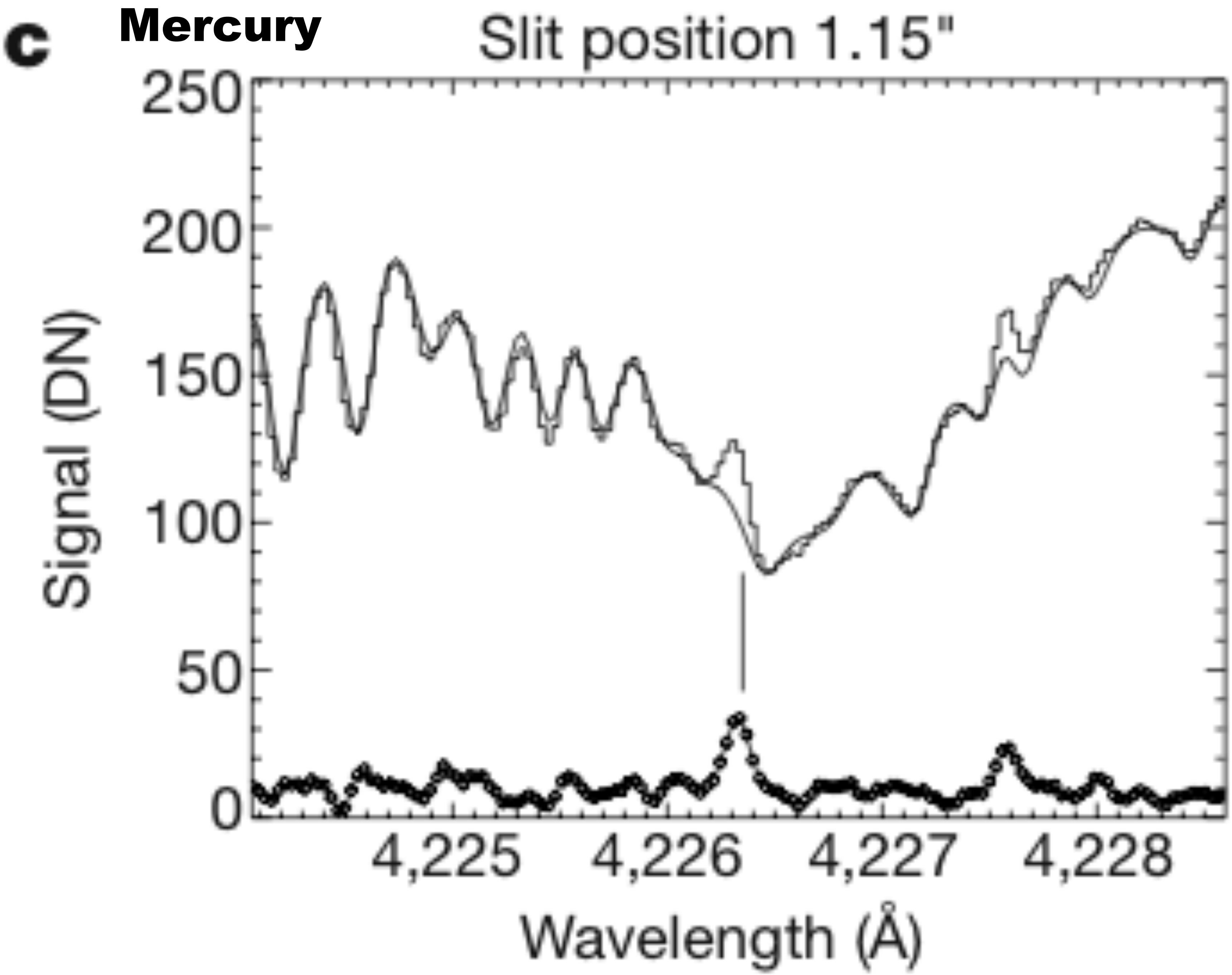
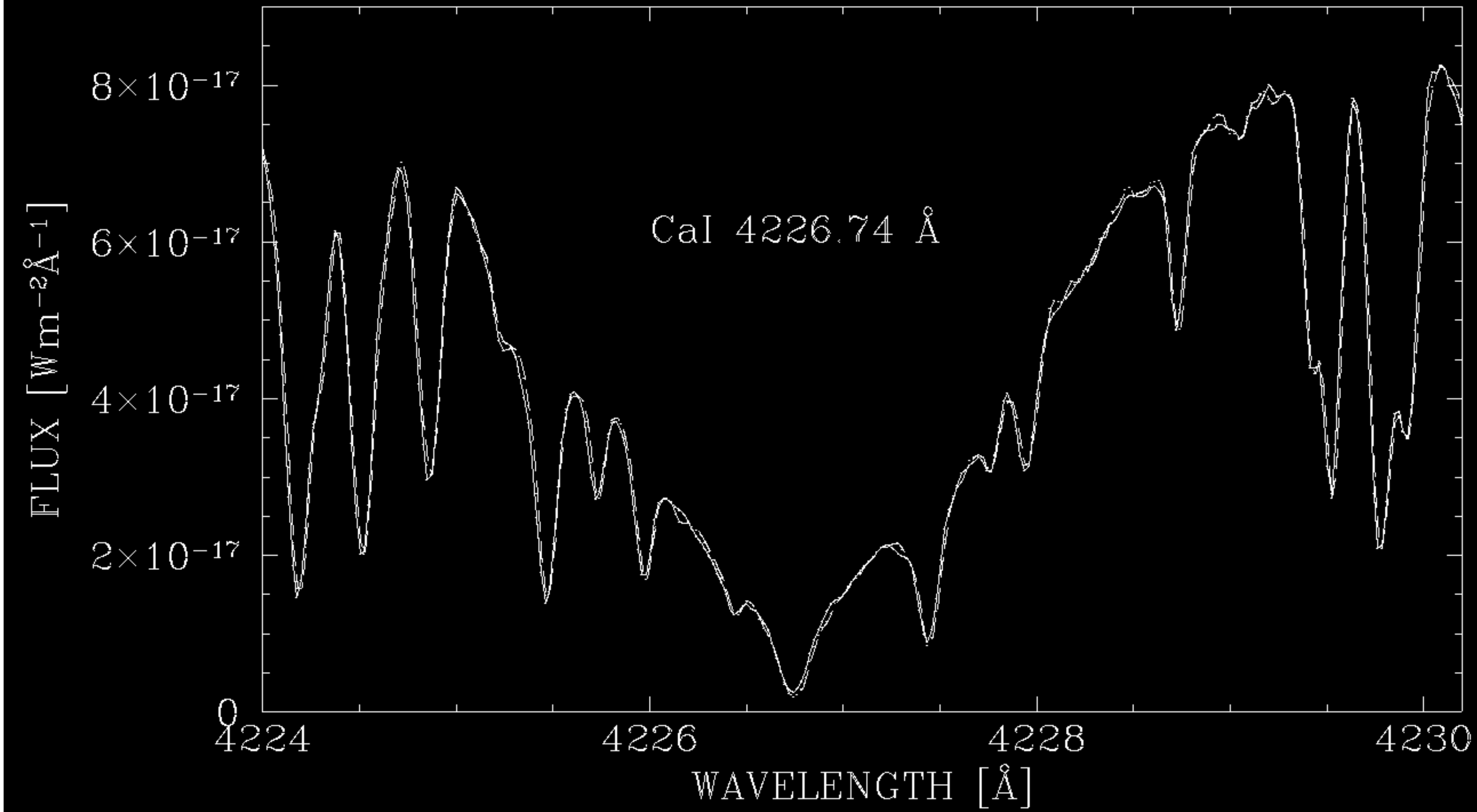
2
4
6
8


c
Mercury
Slit position 1.15"
Signal (DN)
250
200
150
100
50
0
4,225
4,226
4,227
4,228
Wavelength (Å)


CaI 4226.74 Å
FLUX [Wm⁻²Å⁻¹]
8×10⁻¹⁷
6×10⁻¹⁷
4×10⁻¹⁷
2×10⁻¹⁷
0
4224
4226
4228
4230
WAVELENGTH [Å]

Upper limits

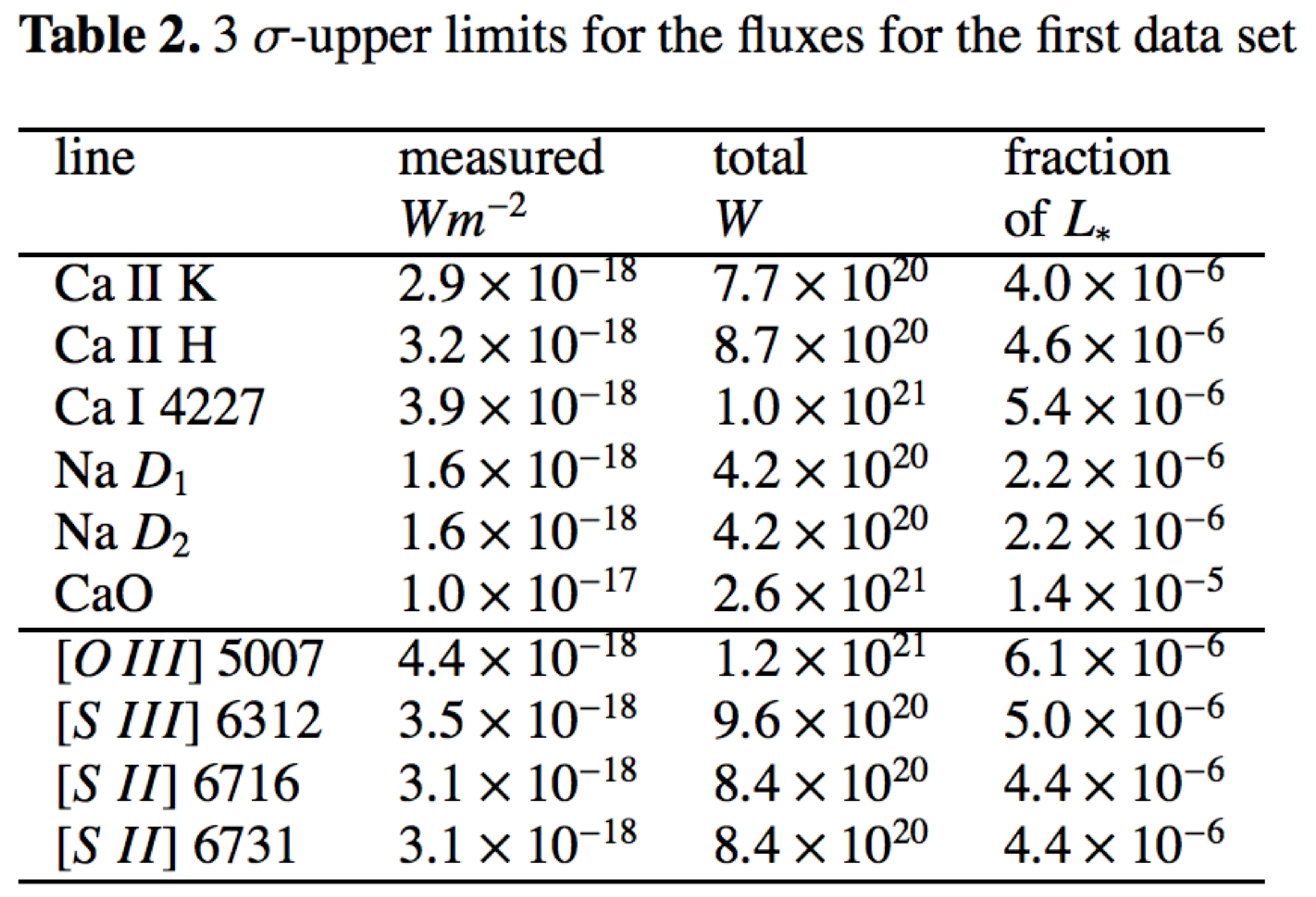


Table 2. 3 σ-upper limits for the fluxes for the first data set

line	measured Wm^{-2}	total W	fraction of L_*
Ca II K	2.9×10^{-18}	7.7×10^{20}	4.0×10^{-6}
Ca II H	3.2×10^{-18}	8.7×10^{20}	4.6×10^{-6}
Ca I 4227	3.9×10^{-18}	1.0×10^{21}	5.4×10^{-6}
Na D_1	1.6×10^{-18}	4.2×10^{20}	2.2×10^{-6}
Na D_2	1.6×10^{-18}	4.2×10^{20}	2.2×10^{-6}
CaO	1.0×10^{-17}	2.6×10^{21}	1.4×10^{-5}
[*O III*] 5007	4.4×10^{-18}	1.2×10^{21}	6.1×10^{-6}
[*S III*] 6312	3.5×10^{-18}	9.6×10^{20}	5.0×10^{-6}
[*S II*] 6716	3.1×10^{-18}	8.4×10^{20}	4.4×10^{-6}
[*S II*] 6731	3.1×10^{-18}	8.4×10^{20}	4.4×10^{-6}

CARMENES

Two stabilised échelle spectrographs (R=82,000):

NIR
($\Delta\lambda \approx 0.9$-$1.7\mu$m)

VIS
($\Delta\lambda \approx 0.5$-$1.0\mu$m)

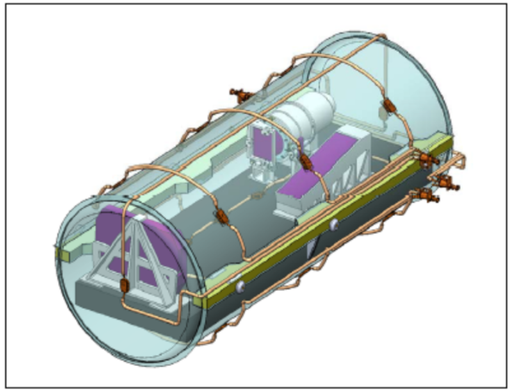


Figure 2. General view of the CARMENES NIR Optical Bench fully assembled.


Thank you