# Transiting extrasolar planets with CoRoT


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University of Exeter

and the CoRoT Exoplanet Science Team

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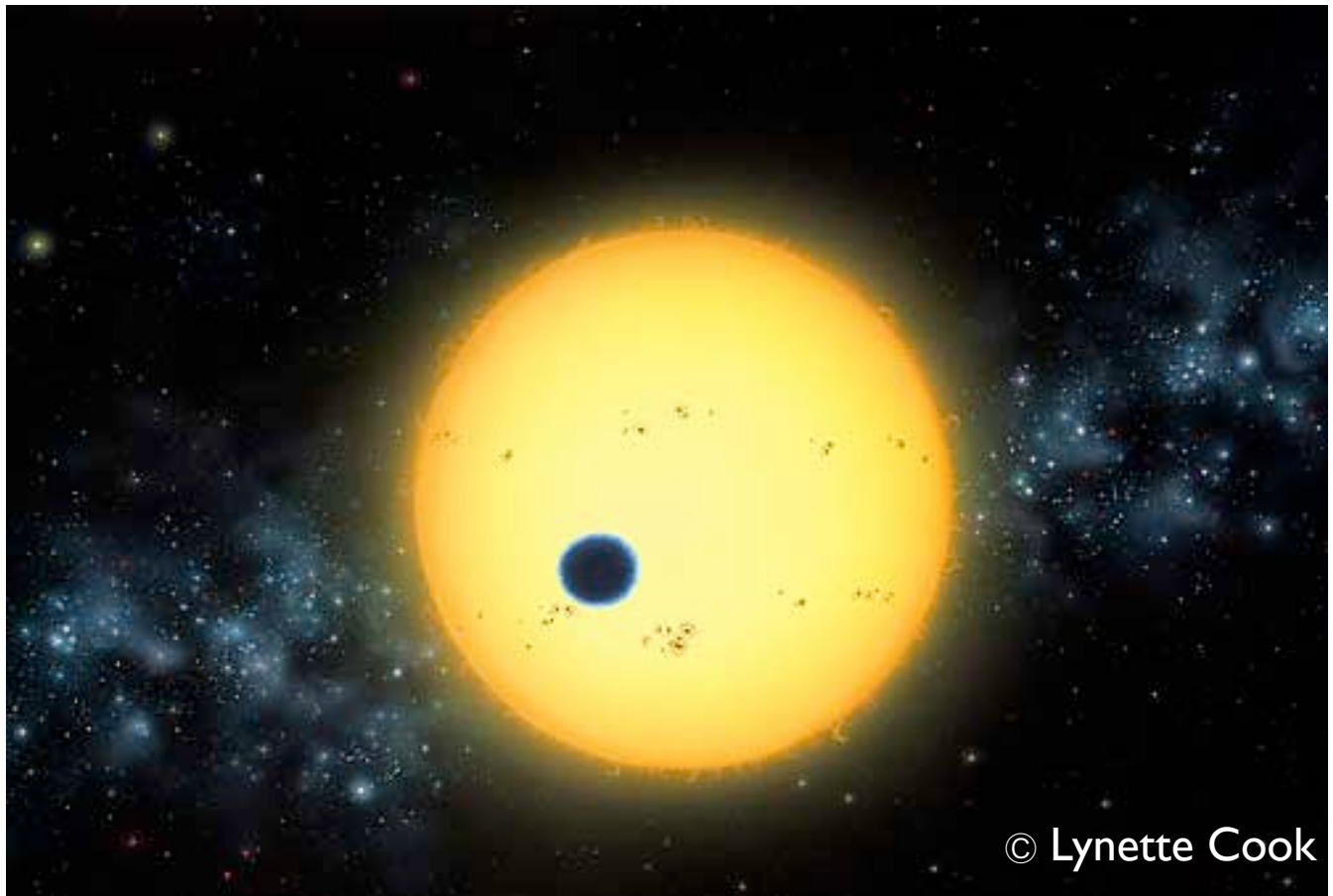
DAMTP 18.02.2008

# Outline

- Why build a space mission to search for transits?
- Brief introduction to the CoRoT mission
- Early results - CoRoT-exo-1b and CoRoT-exo-2b
- A few speculative teasers



# Modelling transits

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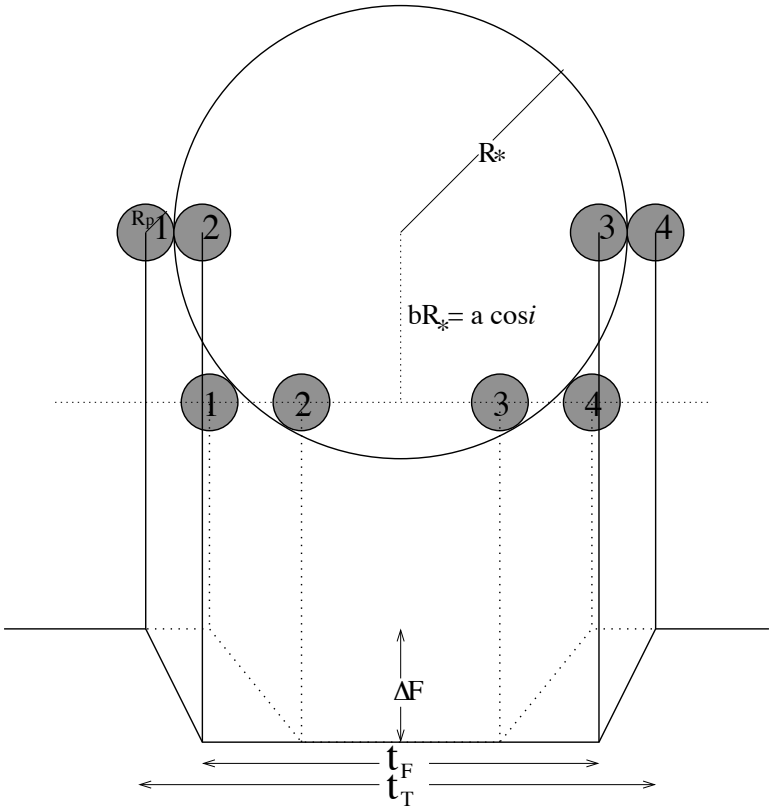

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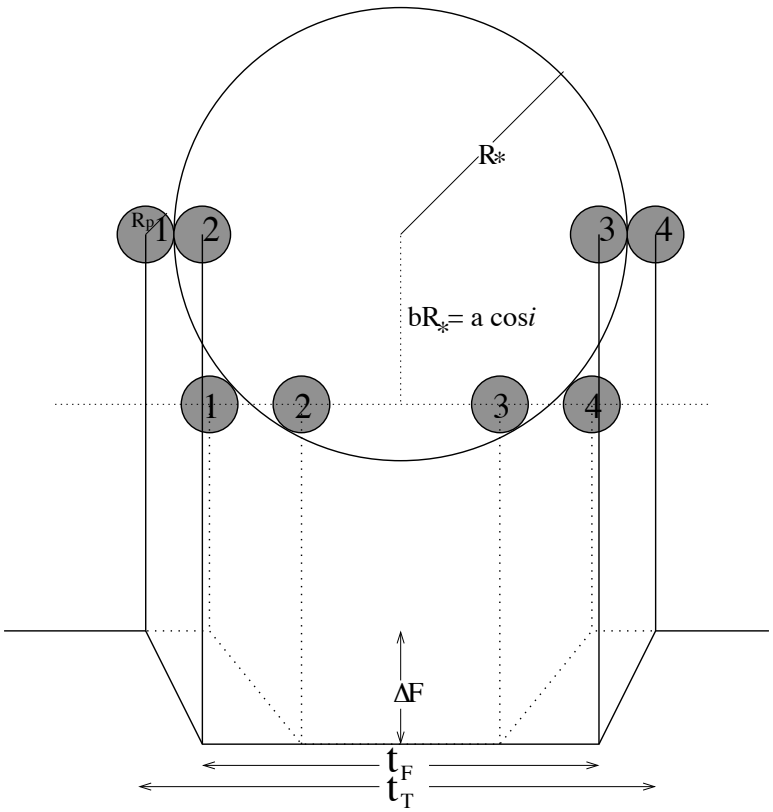


Ignoring limb-darkening and third light,

$$R_{\rm p} = R_\star \sqrt{\frac{\Delta F}{F}}$$

$$b \equiv \frac{a}{R_*}\cos i = \left[\frac{(1-\sqrt{\Delta F})^2 - \frac{\sin^2\frac{t_F\pi}{P}}{\sin^2\frac{t_T\pi}{P}}(1+\sqrt{\Delta F})^2}{1-\frac{\sin^2\frac{t_F\pi}{P}}{\sin^2\frac{t_T\pi}{P}}}\right]^{1/2}$$

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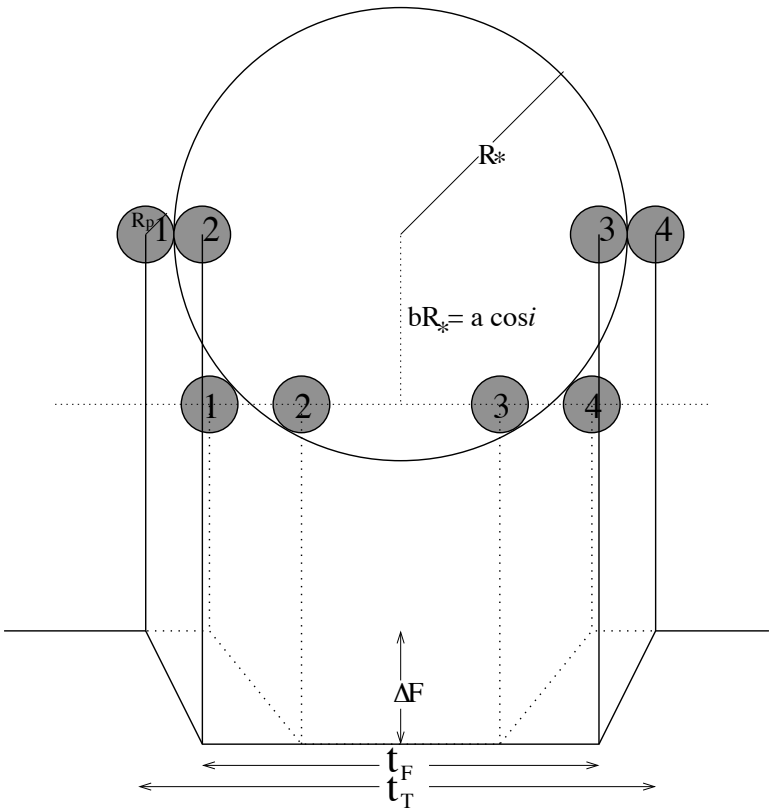


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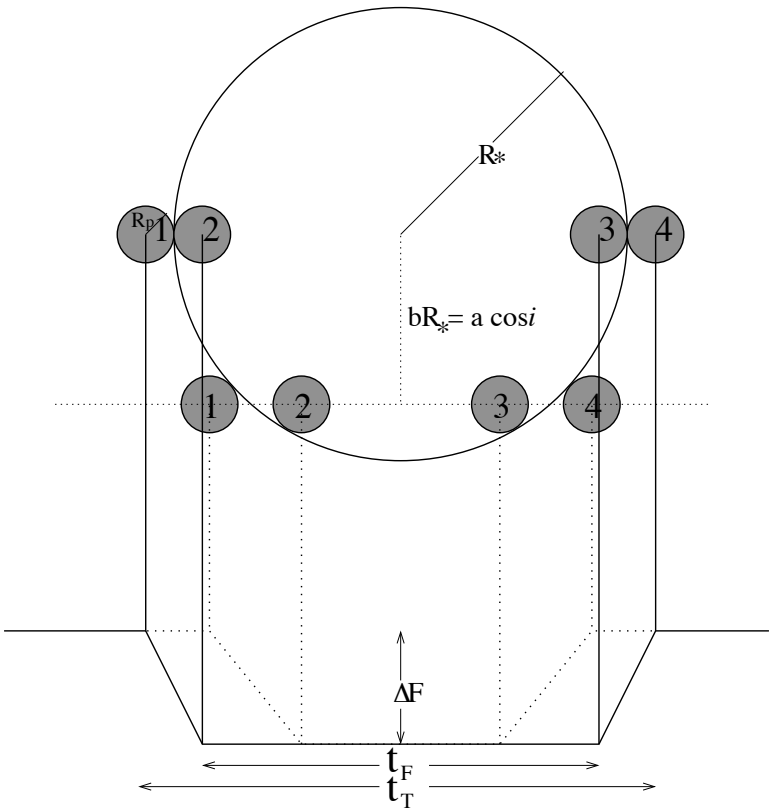


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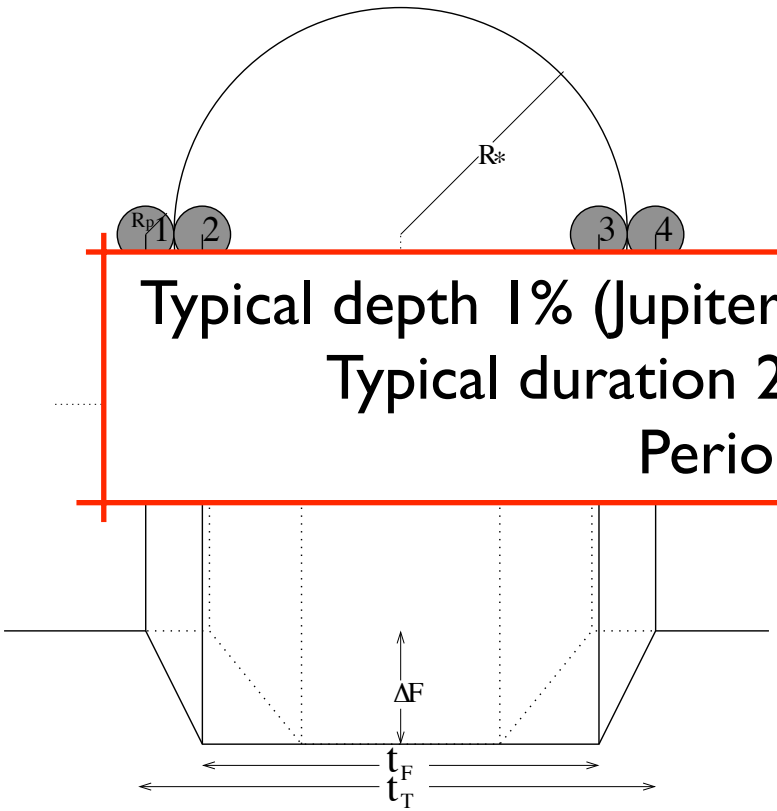


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Typical depth 1% (Jupiter on Sun) to 0.01% (Earth on Sun)
Typical duration 2h (0.03 AU) to 13h (1AU)
Periods 1d to years

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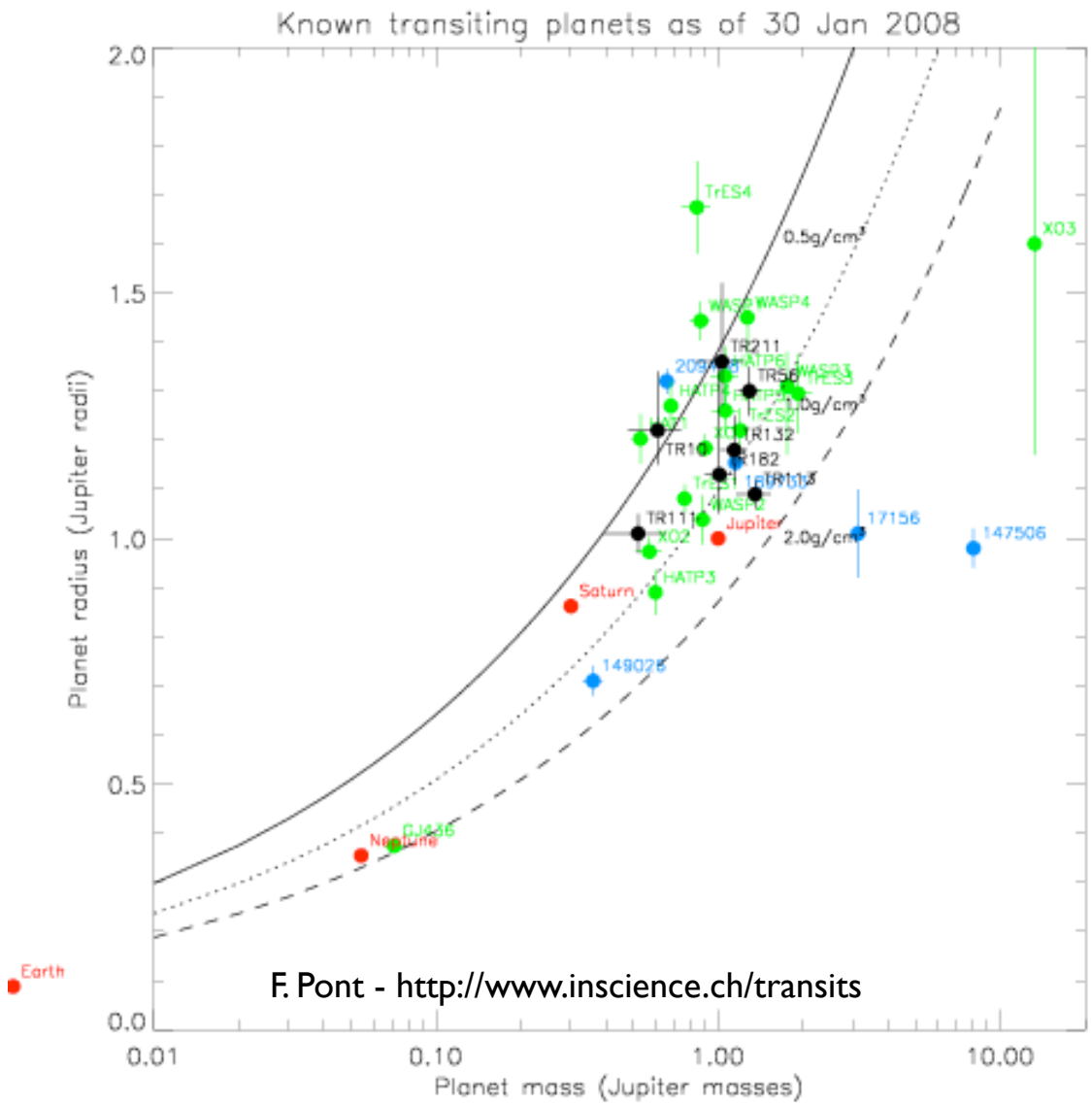
# Why build CoRoT?

## 1. transits = physics

# Structure and composition




F. Pont - http://www.inscience.ch/transits

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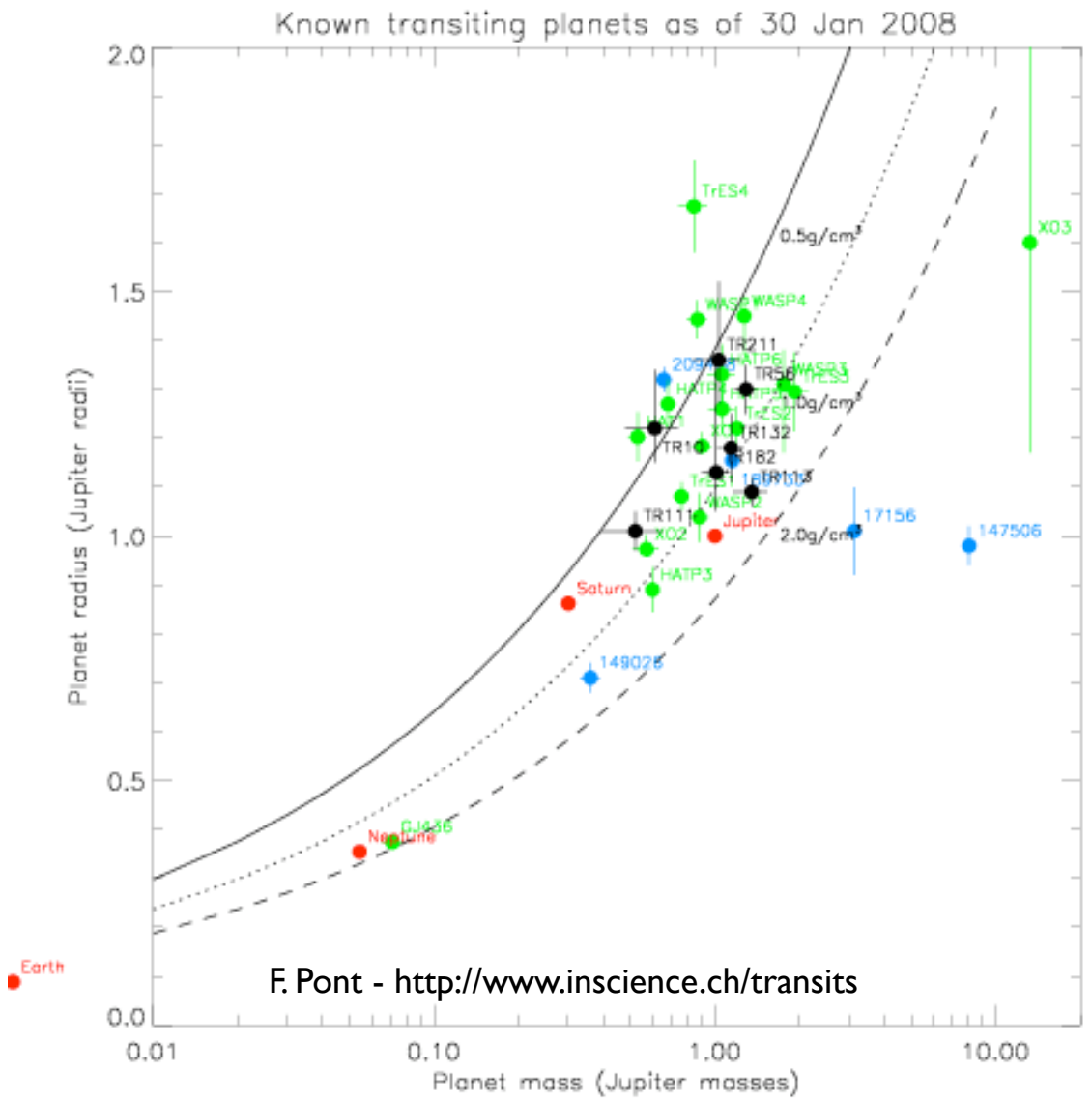
Of the known planets, several are (very) **inflated** - additional ***heat source***?

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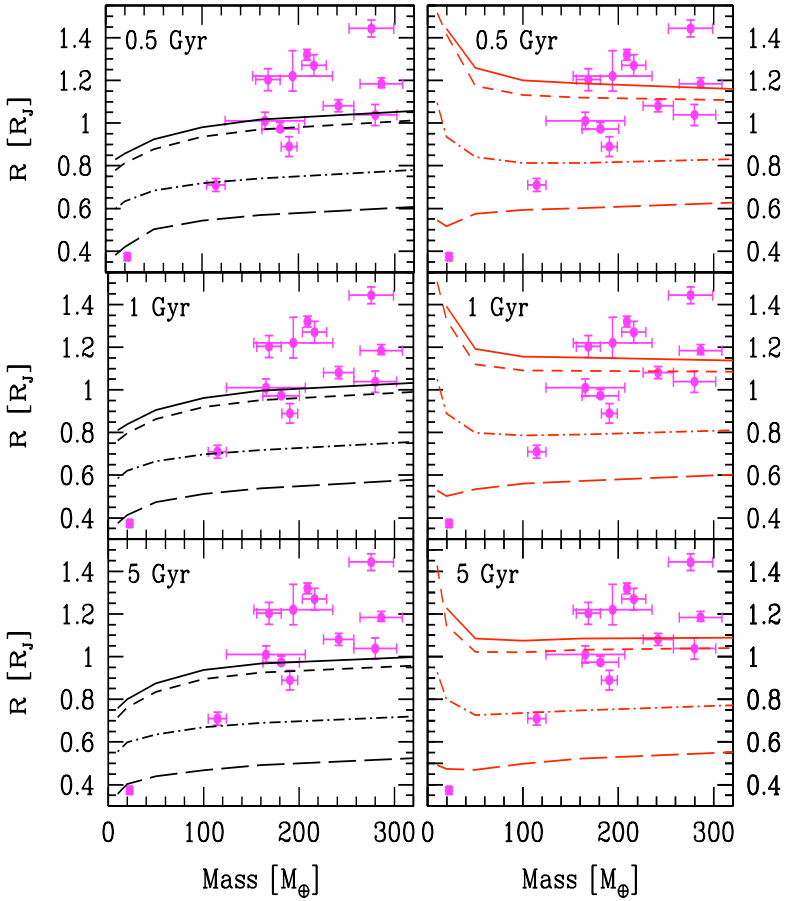


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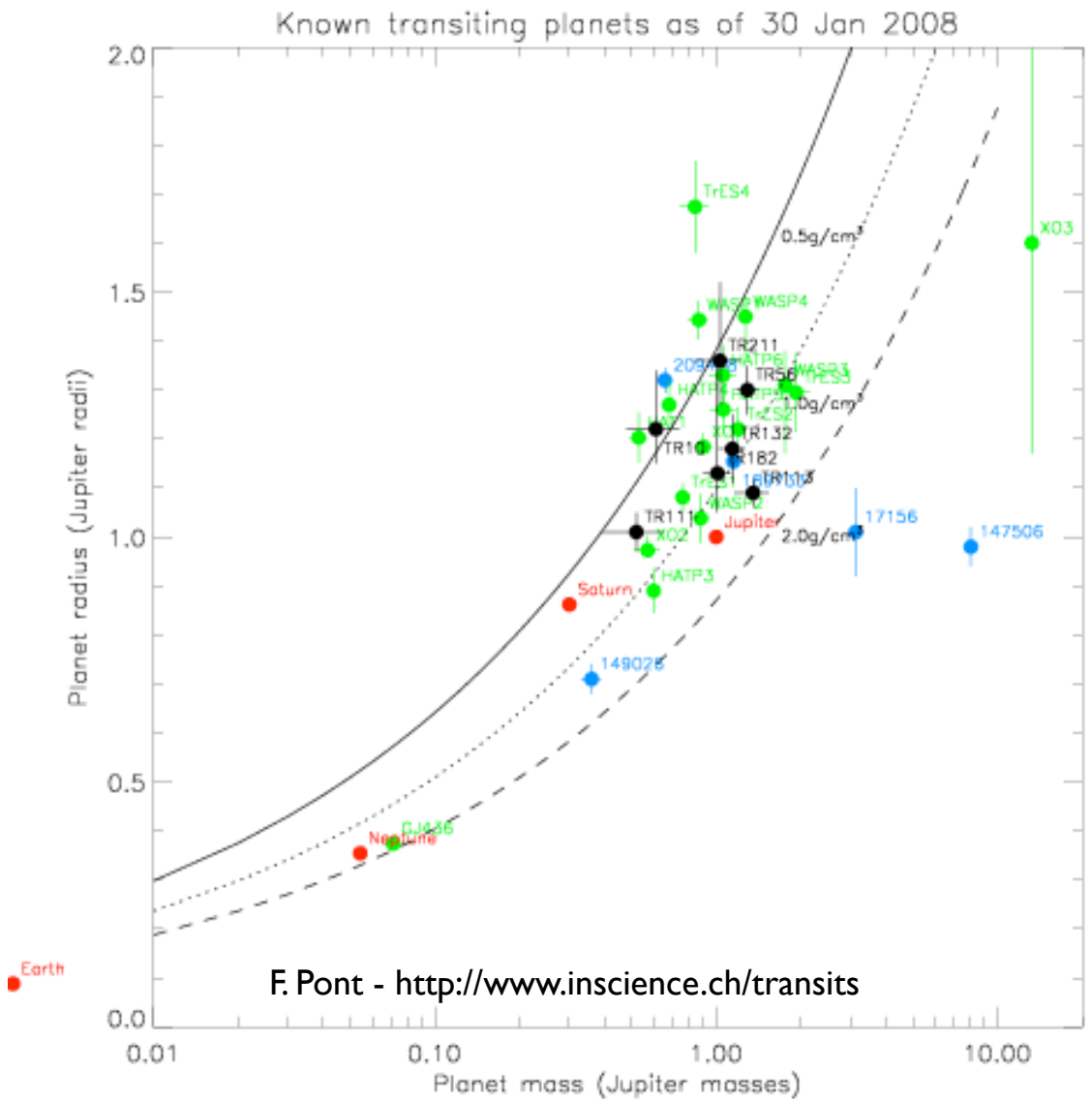


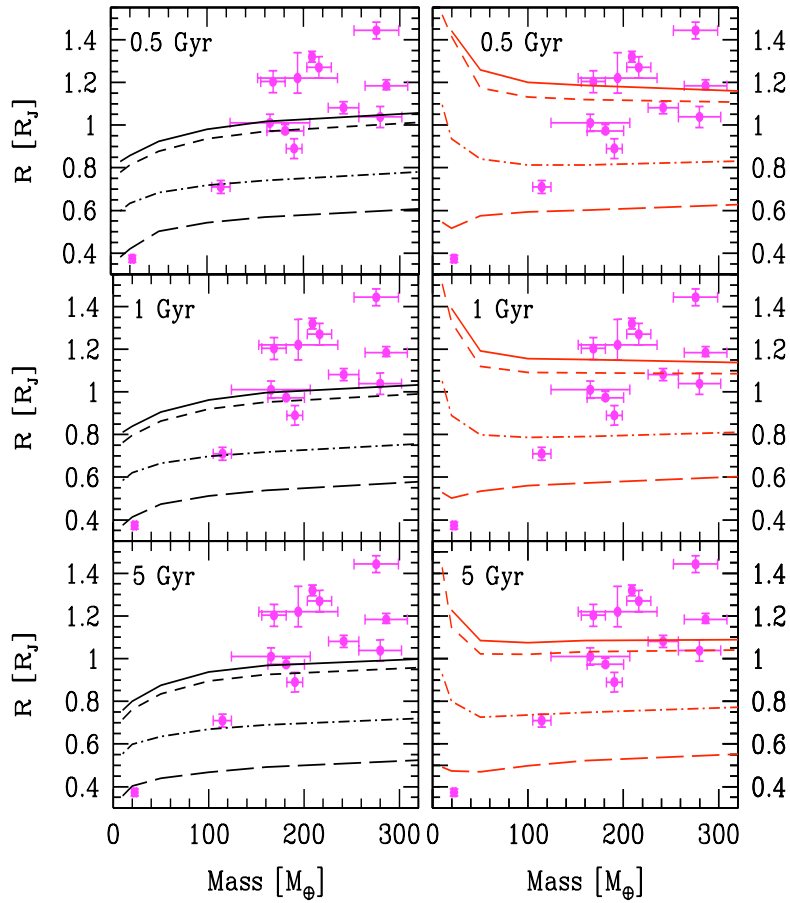


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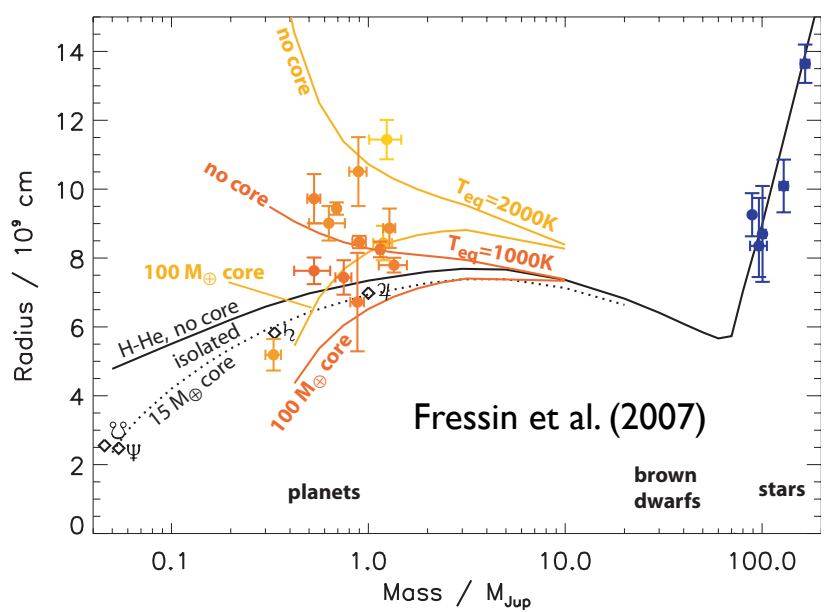


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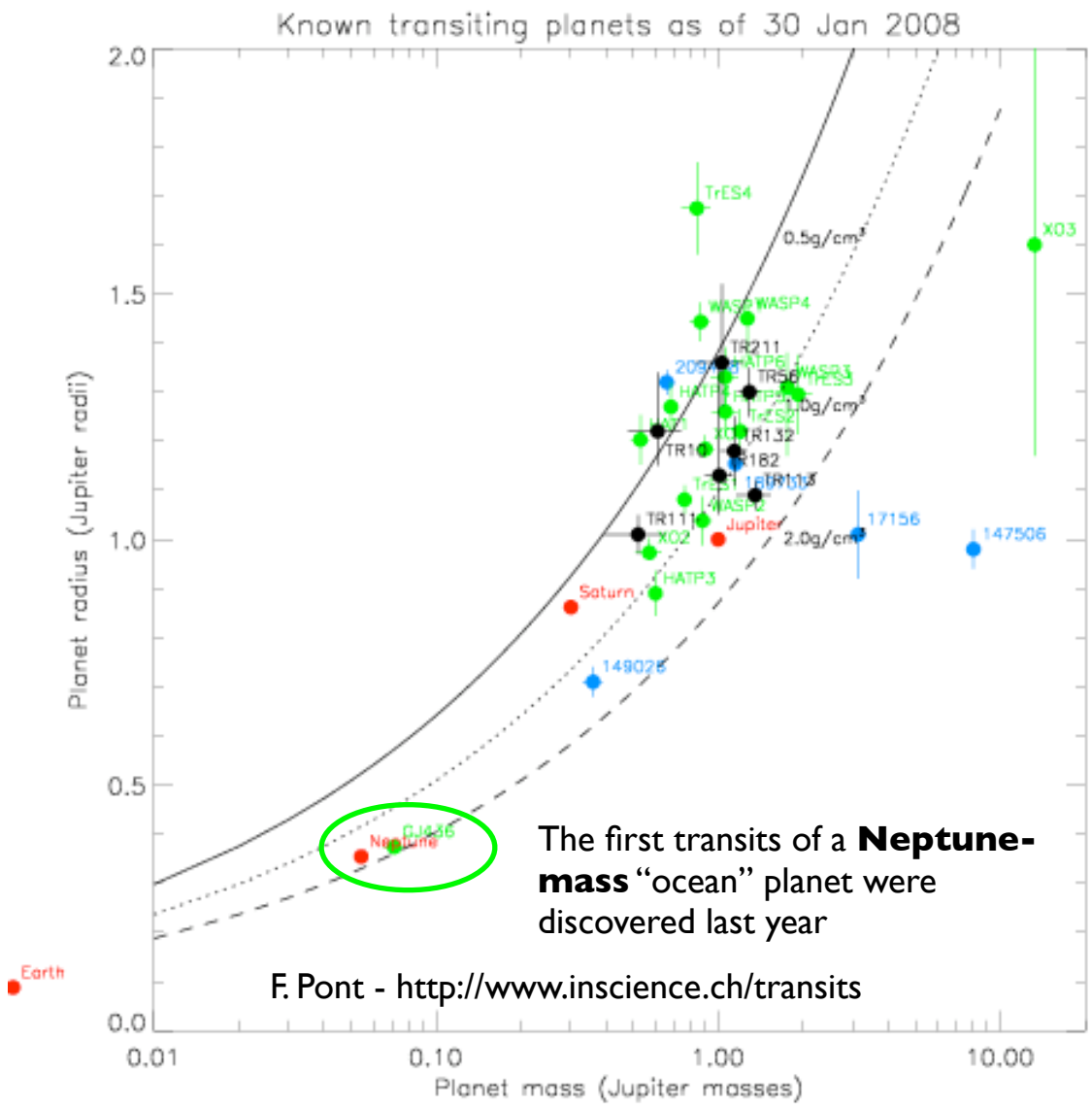
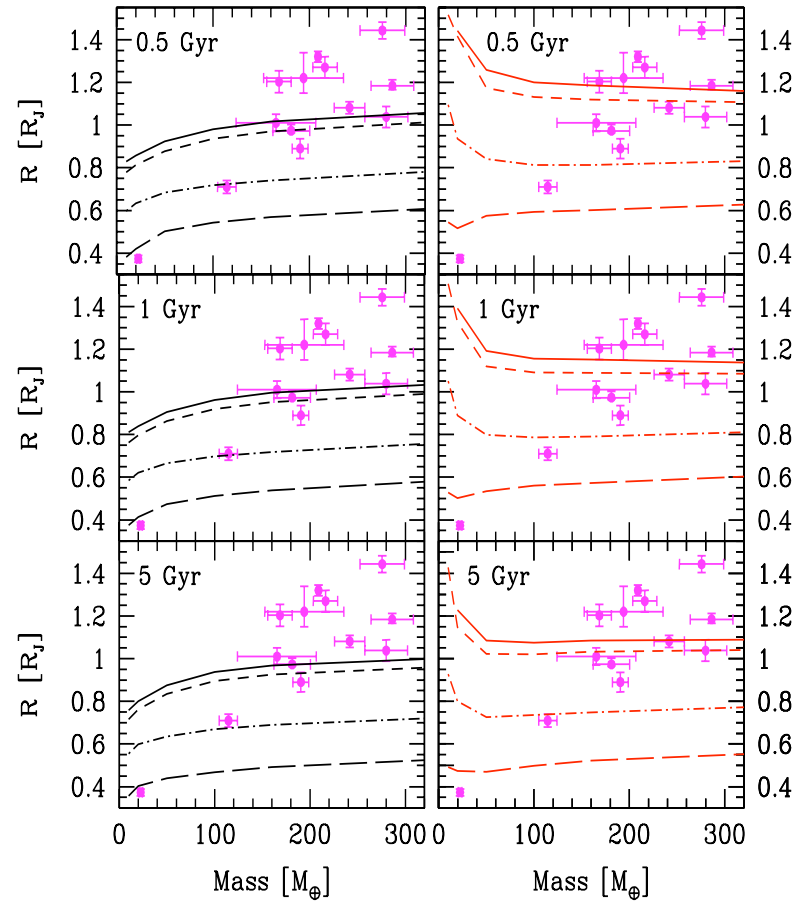



The first transits of a **Neptune-mass** "ocean" planet were discovered last year

F. Pont - http://www.inscience.ch/transits

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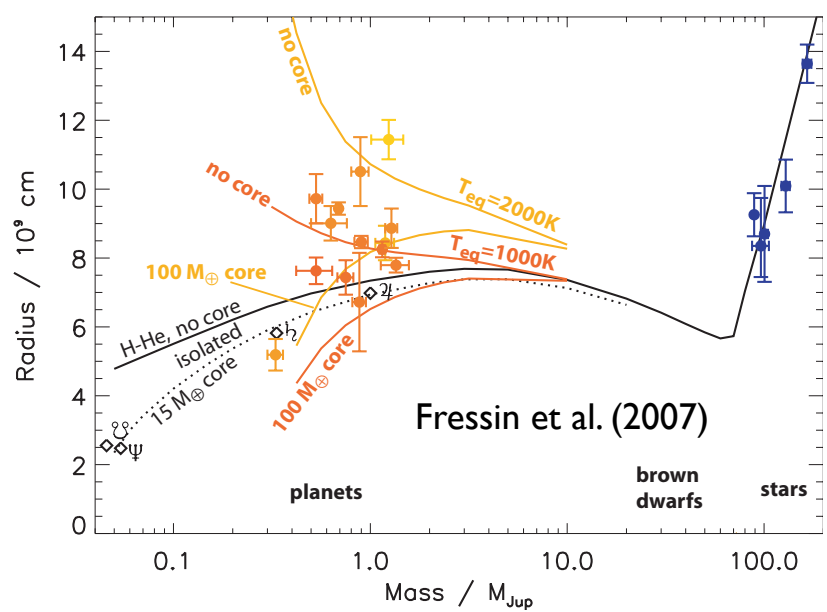


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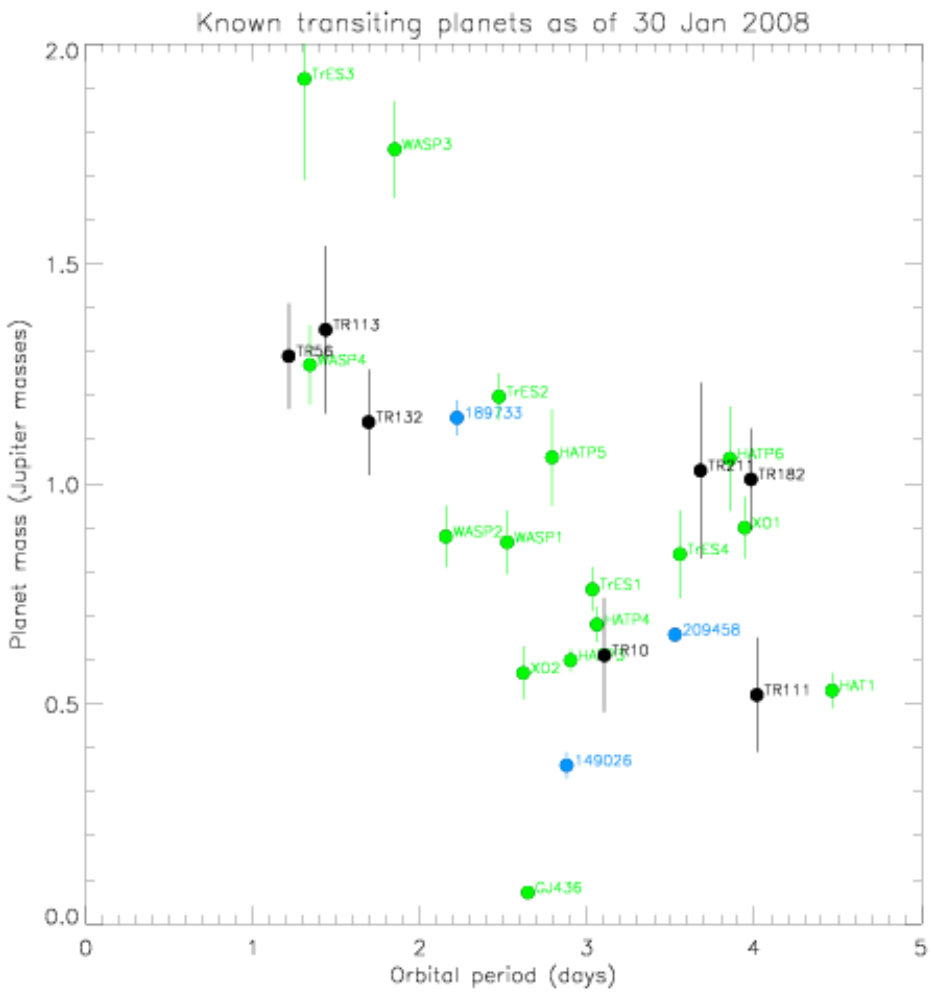
Mazeh & Zucker (2005) first pointed out a correlation between the true mass and period of transiting planets. Today, for giant planets it remains suggestive of a **minimum mass at a given period** - signature of evolutionary processes such as ***tidal evolution*** or ***evaporation***?



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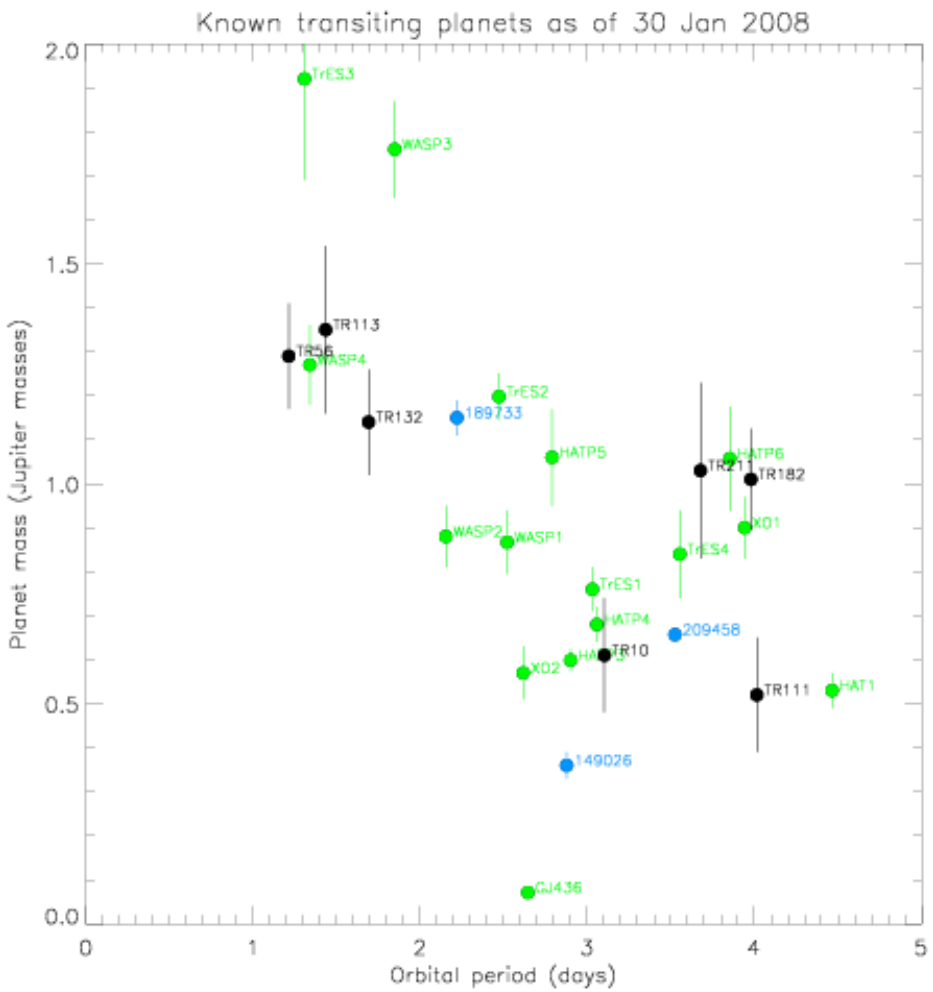
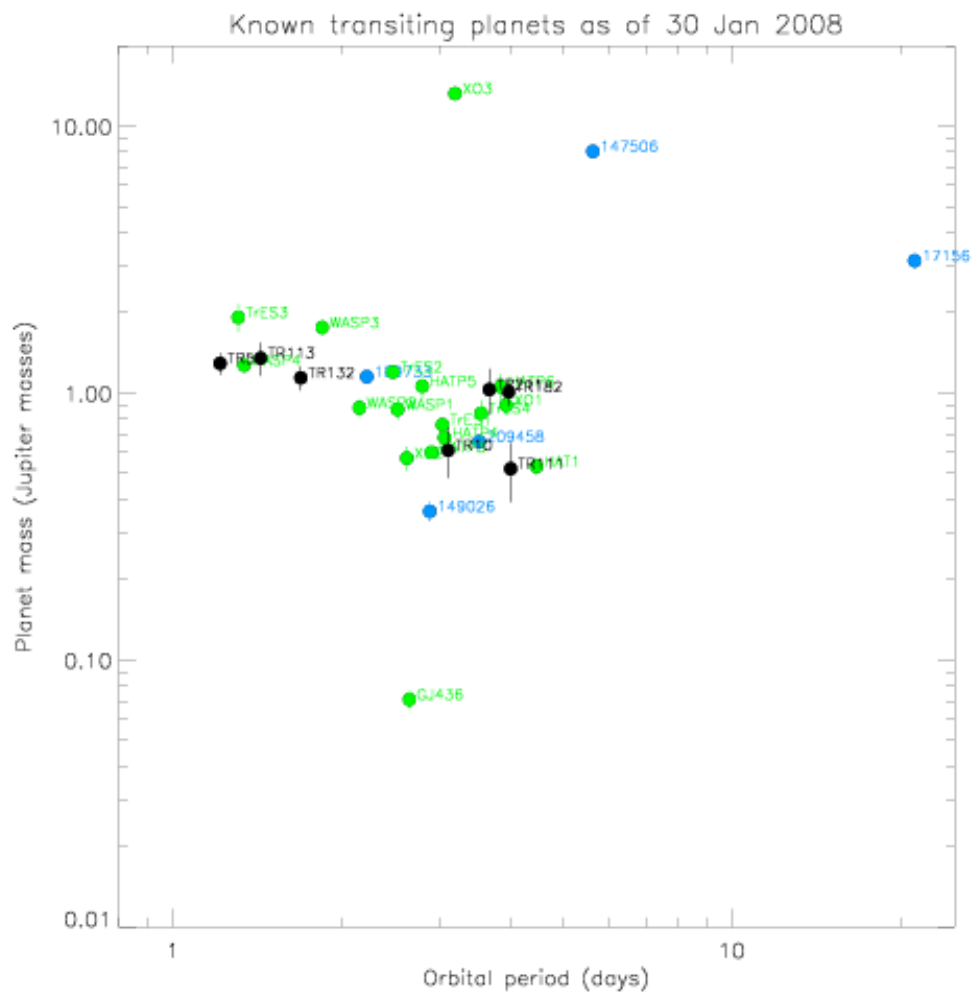
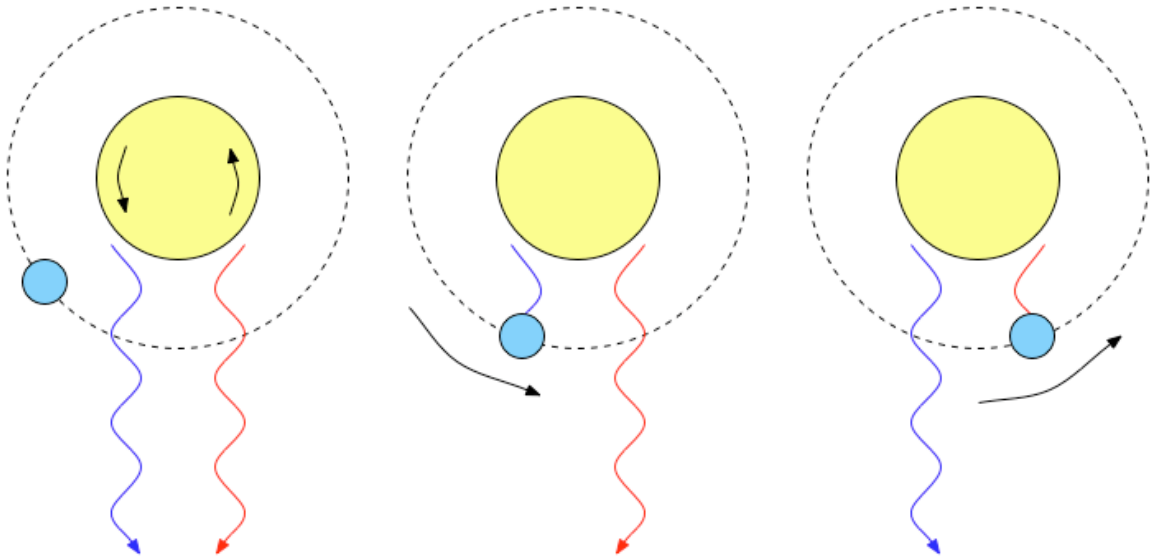
With recent discoveries of low and high mass transiting planets, we are starting to see **3 very distinct classes of planets** in this diagram: normal (very) hot Jupiters, supermassive hot Jupiters, and hot Neptunes. Could this indicate ***distinct formation and/or evolution mechanisms***?



# Formation and star-planet interaction



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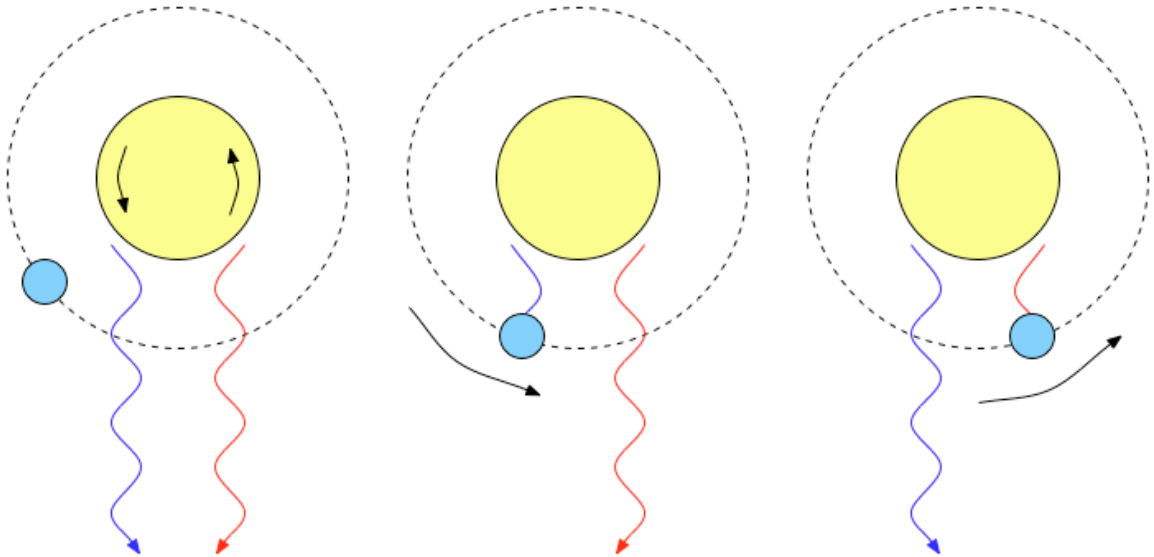
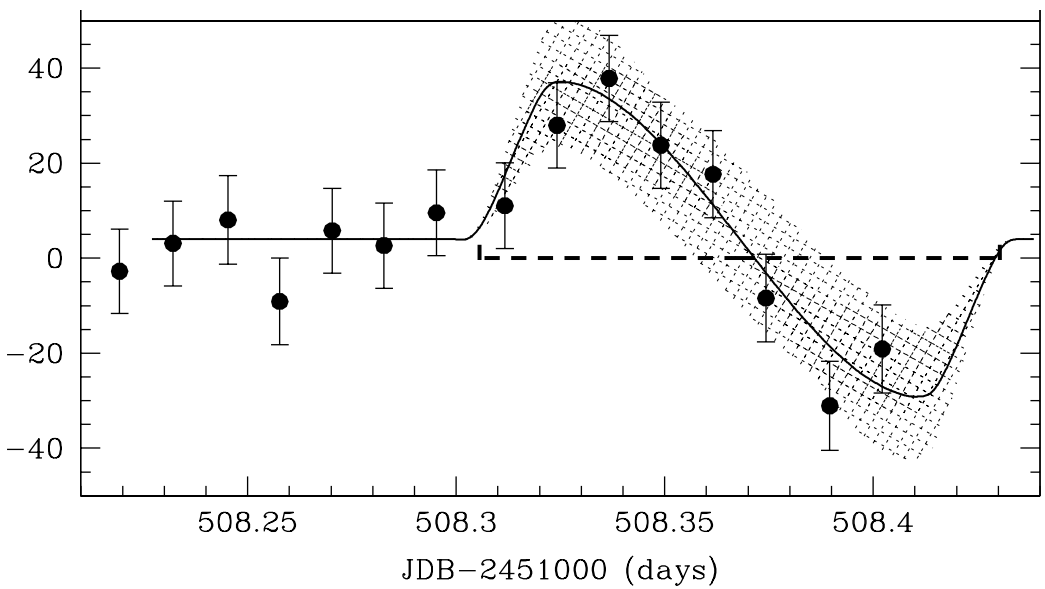


Queloz et al. (2000) - HD 209458b



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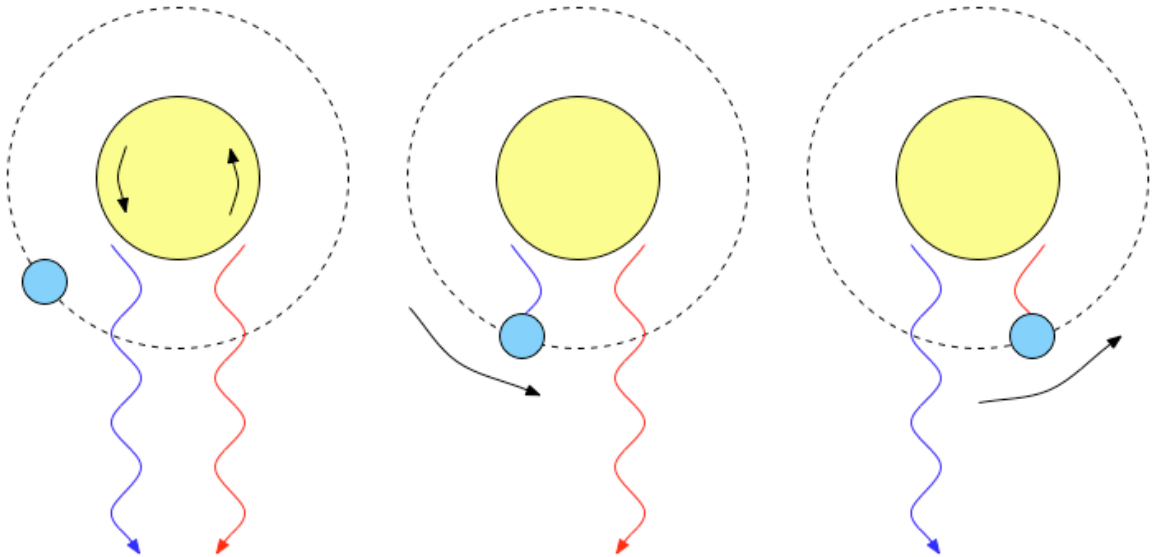

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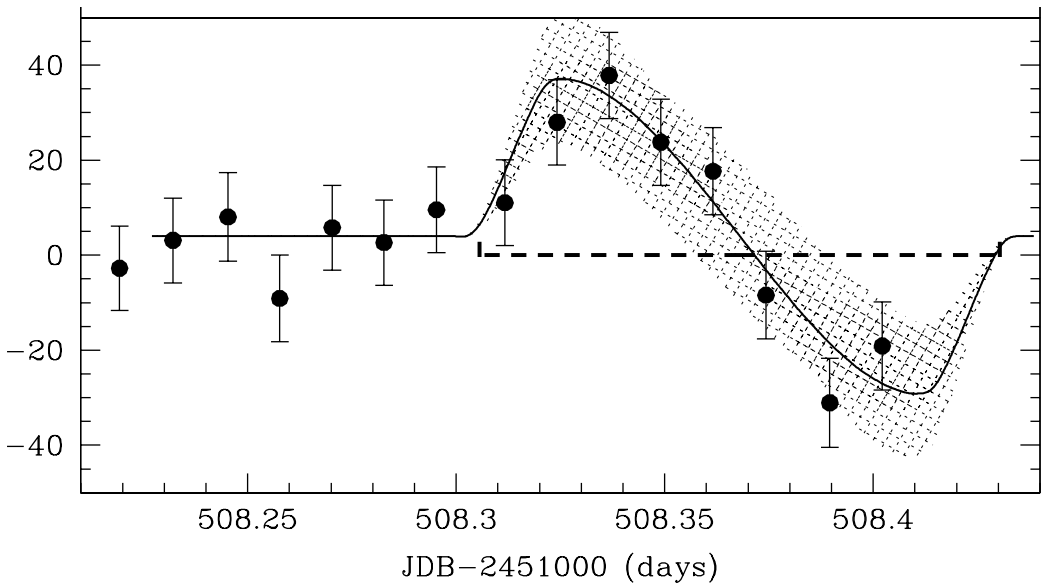
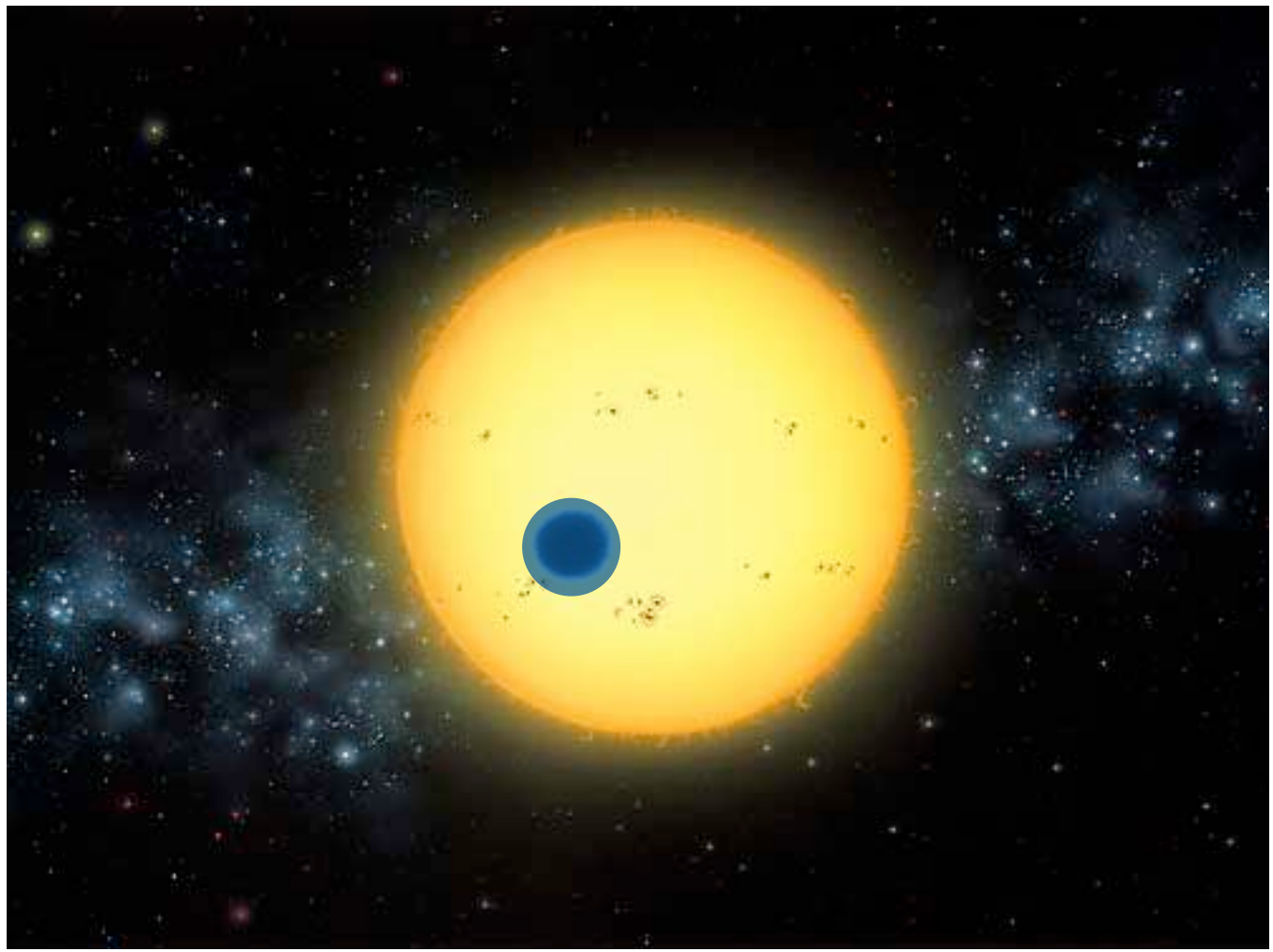



The ***Rossiter-McLaughlin effect***, or spectroscopic transit, is primarily sensitive to **relative inclination** of the planet's orbit and the star rotational equator.

All measurements to date (a handful of planets) are consistent with **coplanarity** or very small relative inclination. A significant deviation from co-planarity would be challenging to formation models.

# Atmospheric composition and dynamics

***Transmission spectroscopy*** probes the **atmospheric transparency gradient** near the limb (i.e. at the day-night terminator).



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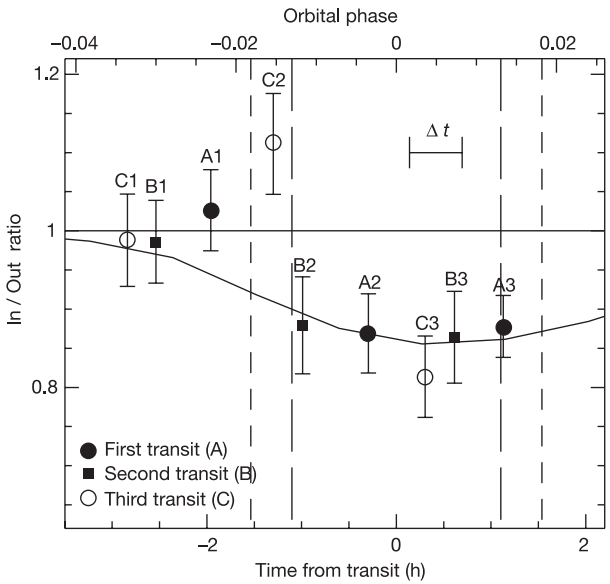


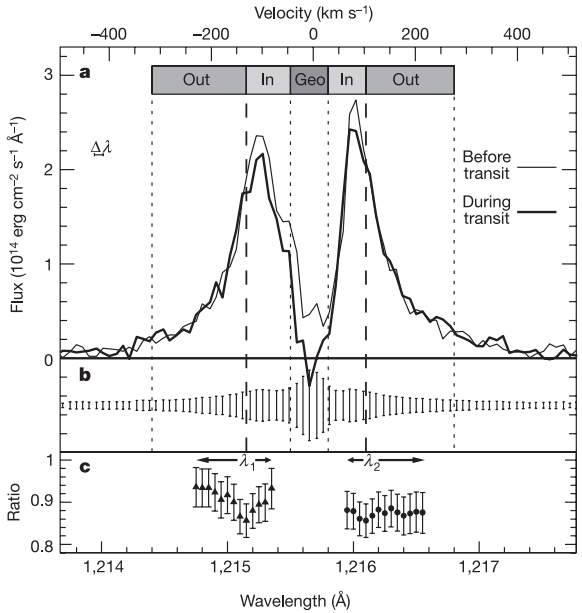


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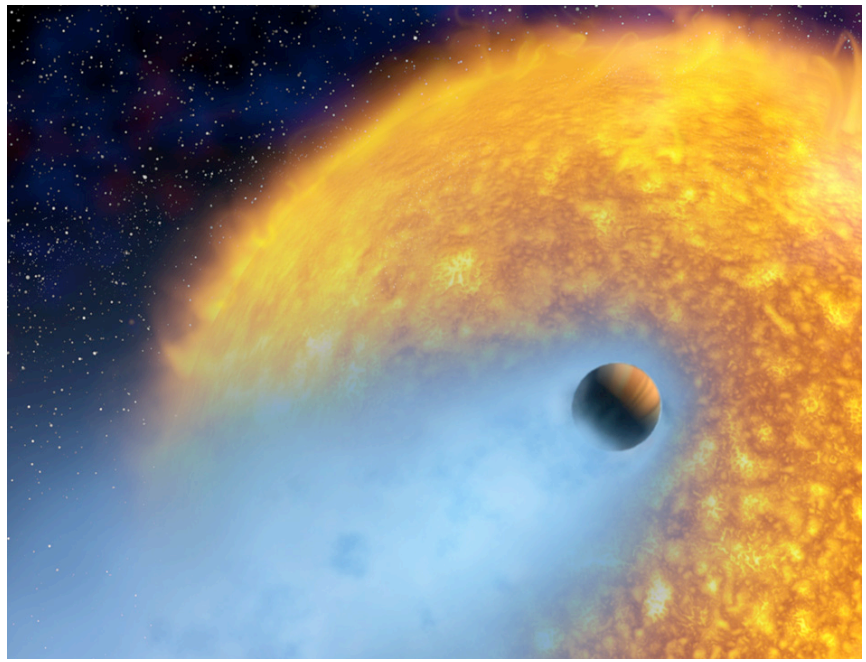
Vidal-Madjar et al. (2003, 2004) - evaporating exosphere



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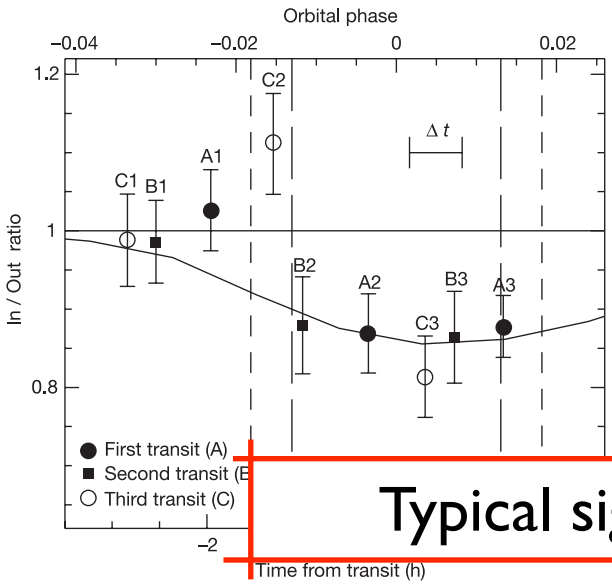


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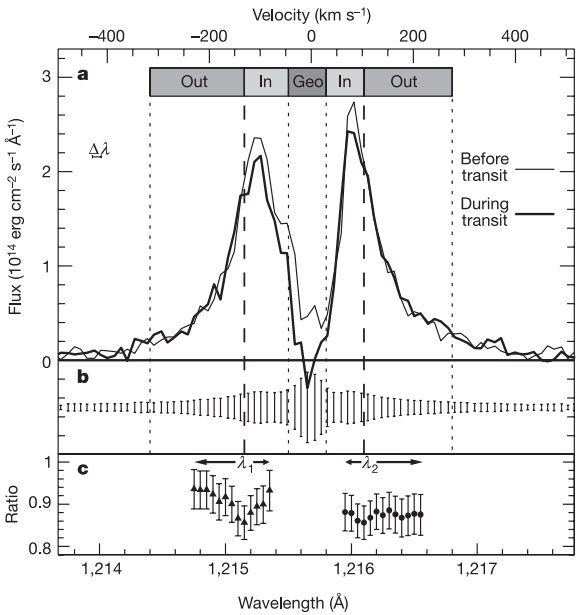
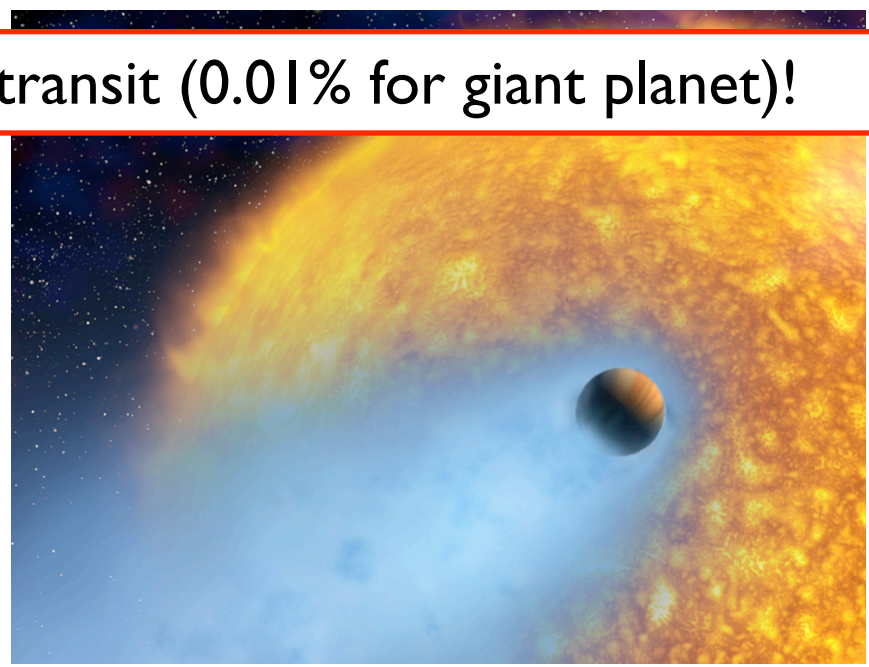
Typical signal 1% of transit (0.01% for giant planet)!



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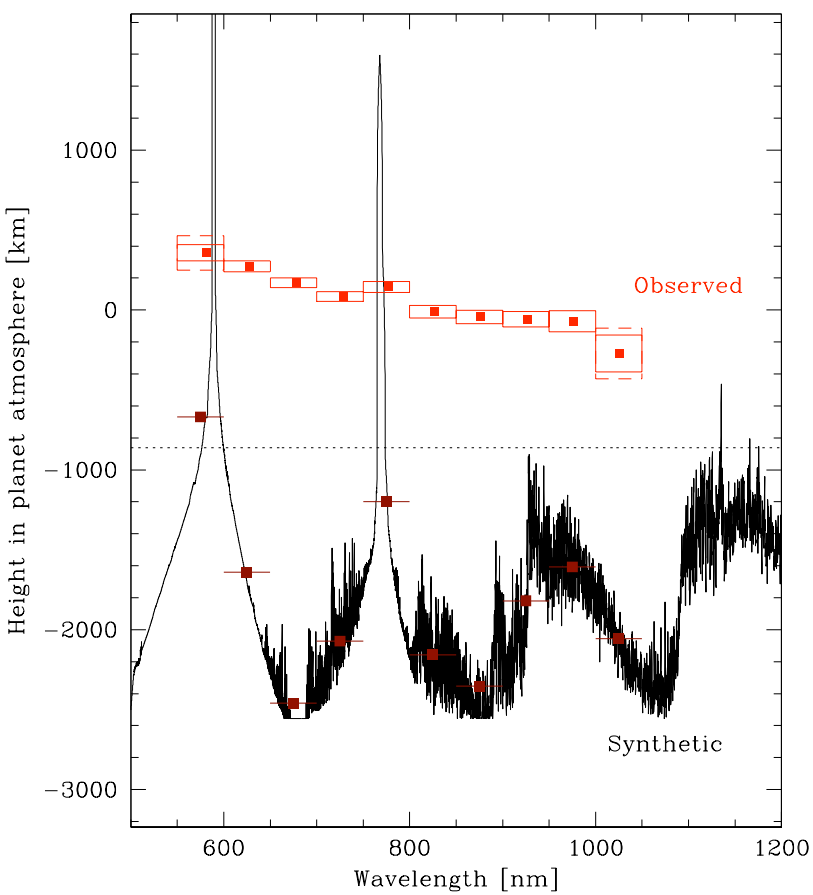
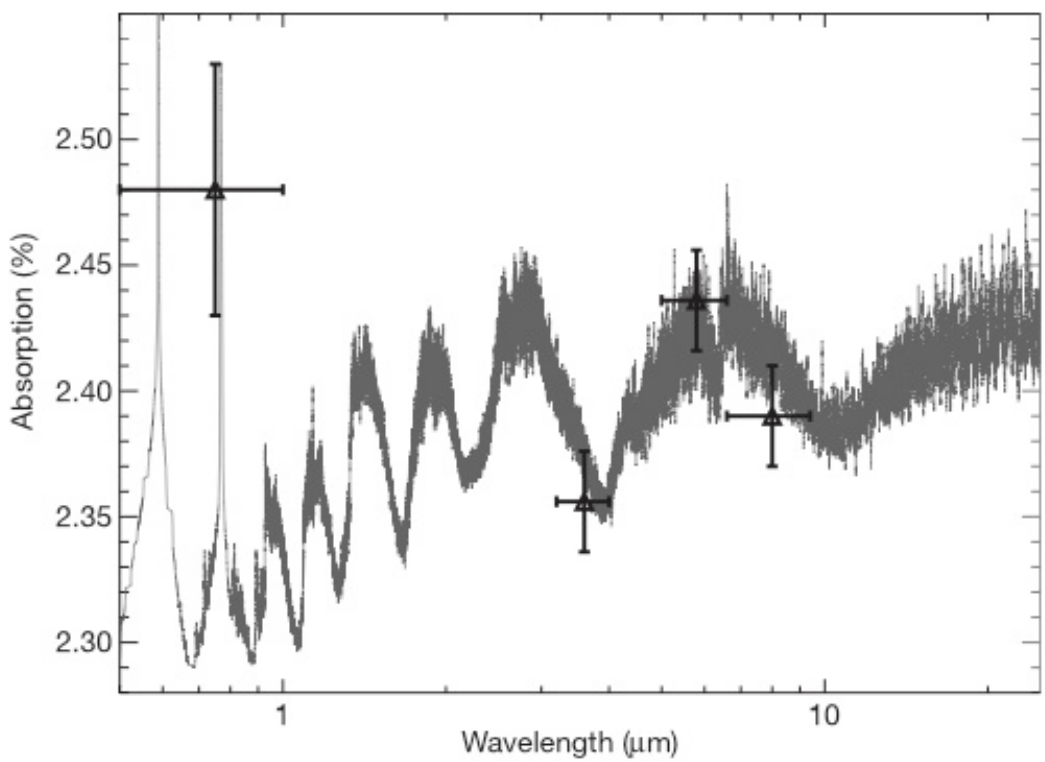
Pont et al. (2007) - visible - ~ micron size haze




Tinetti et al. (2007) - IR - $H_2O$ (?)



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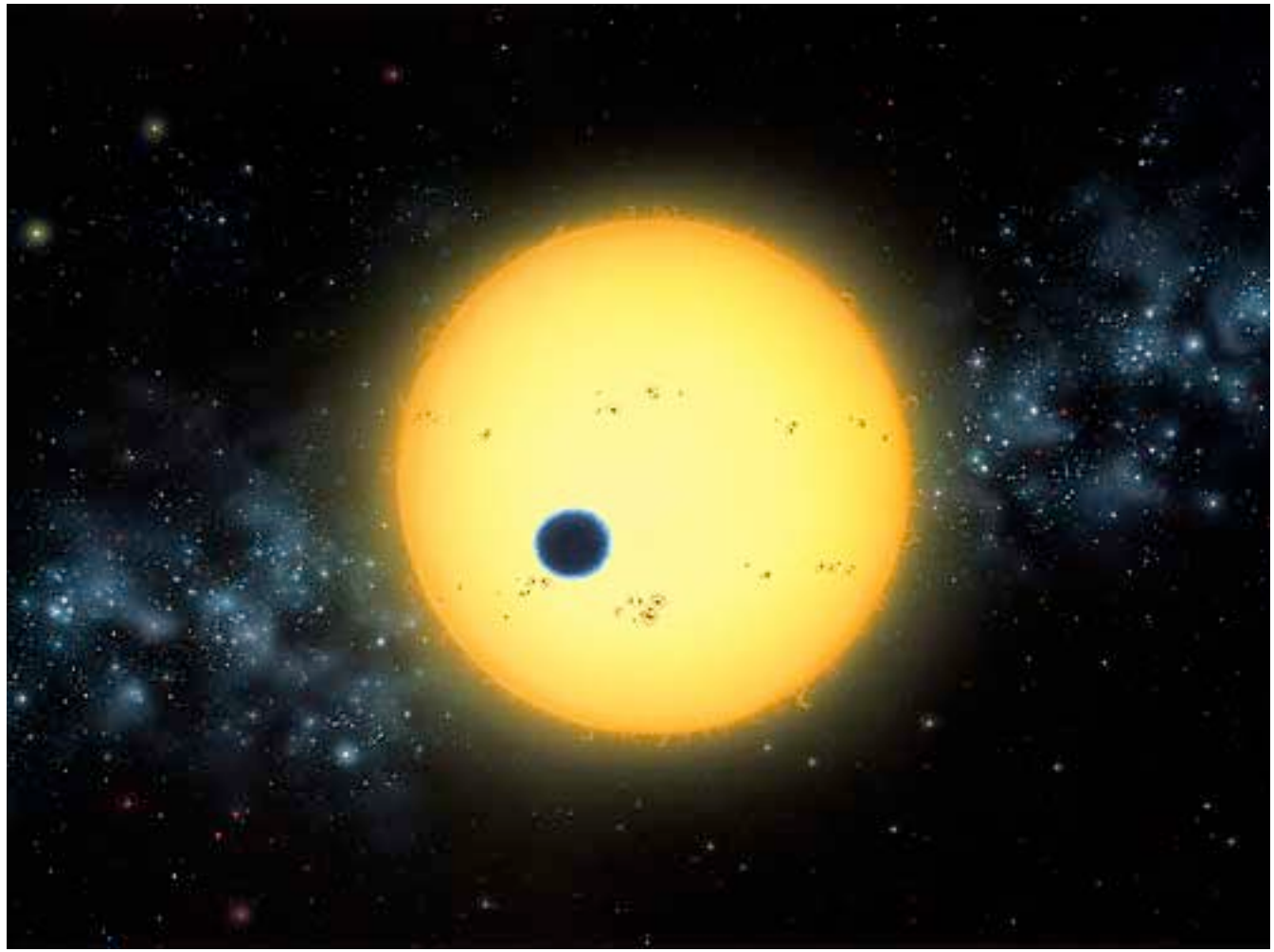

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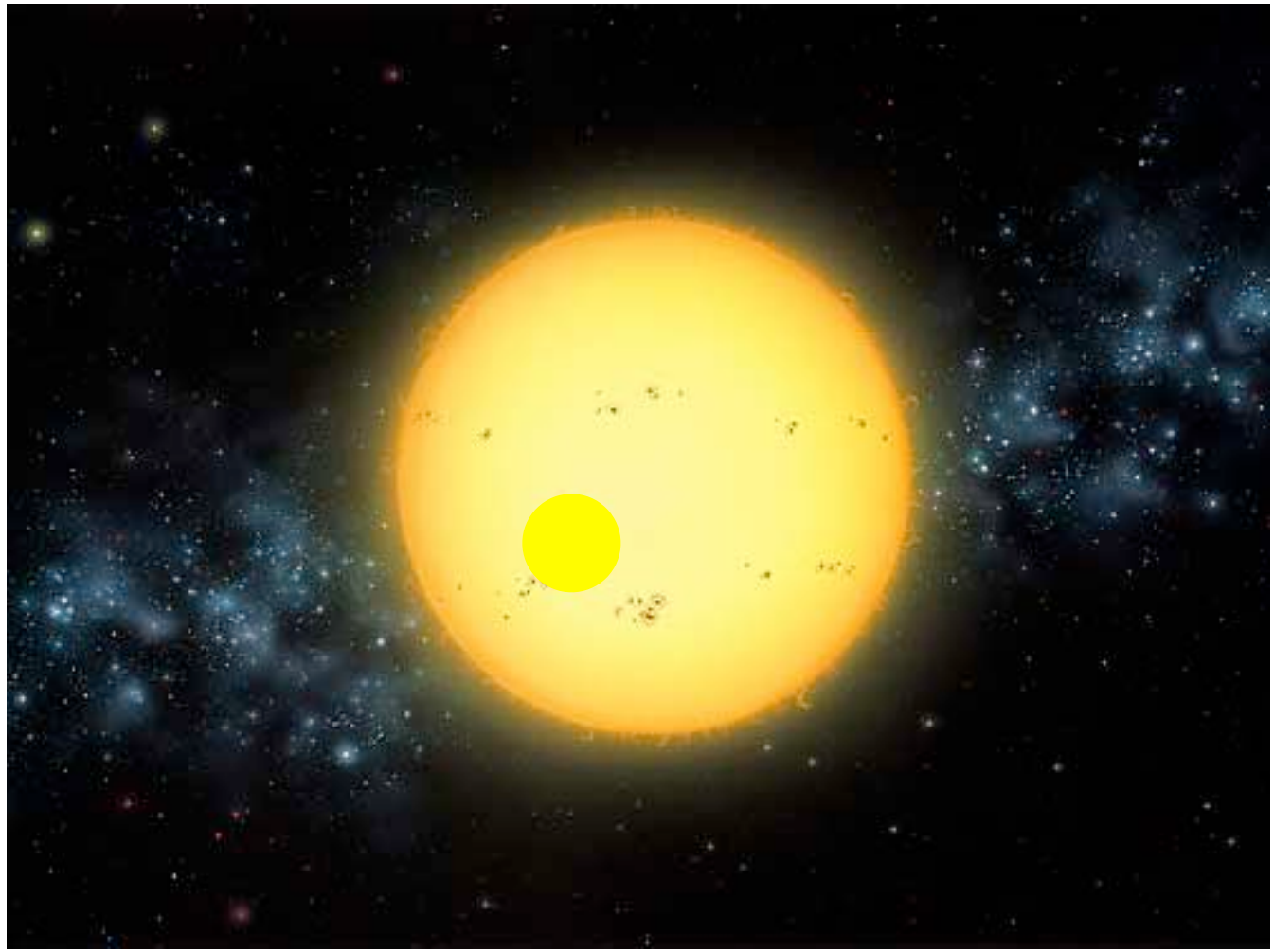

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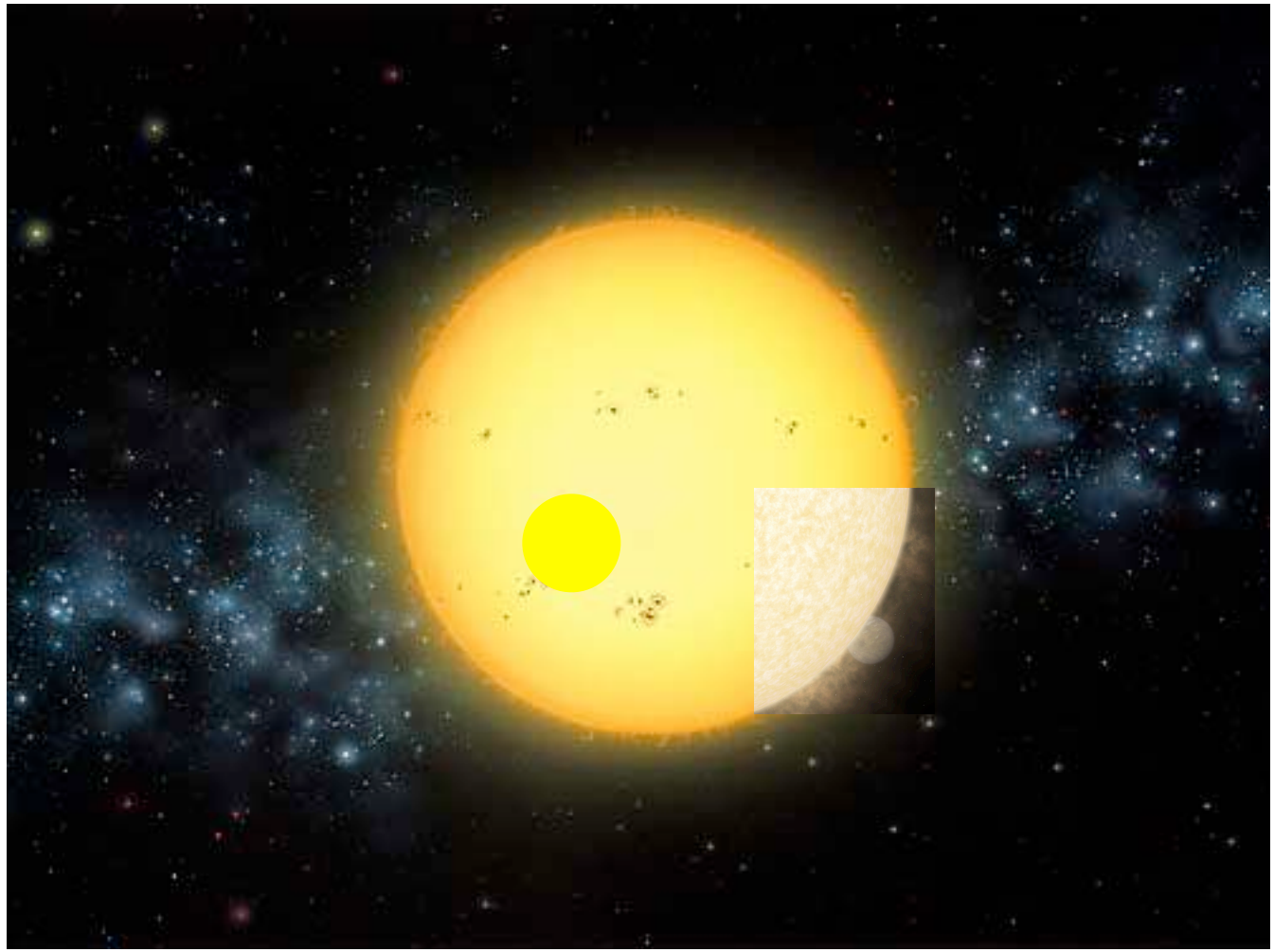

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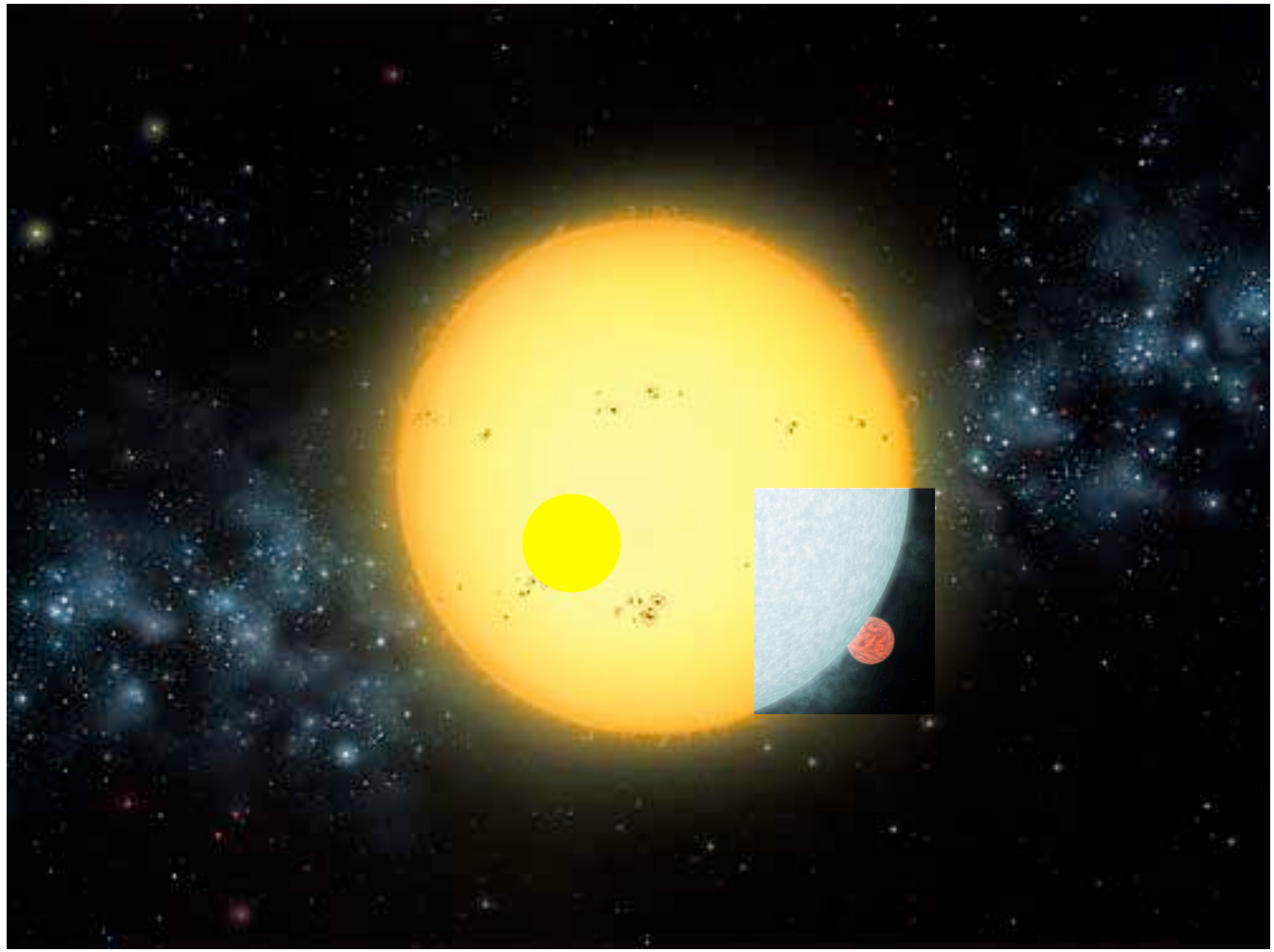

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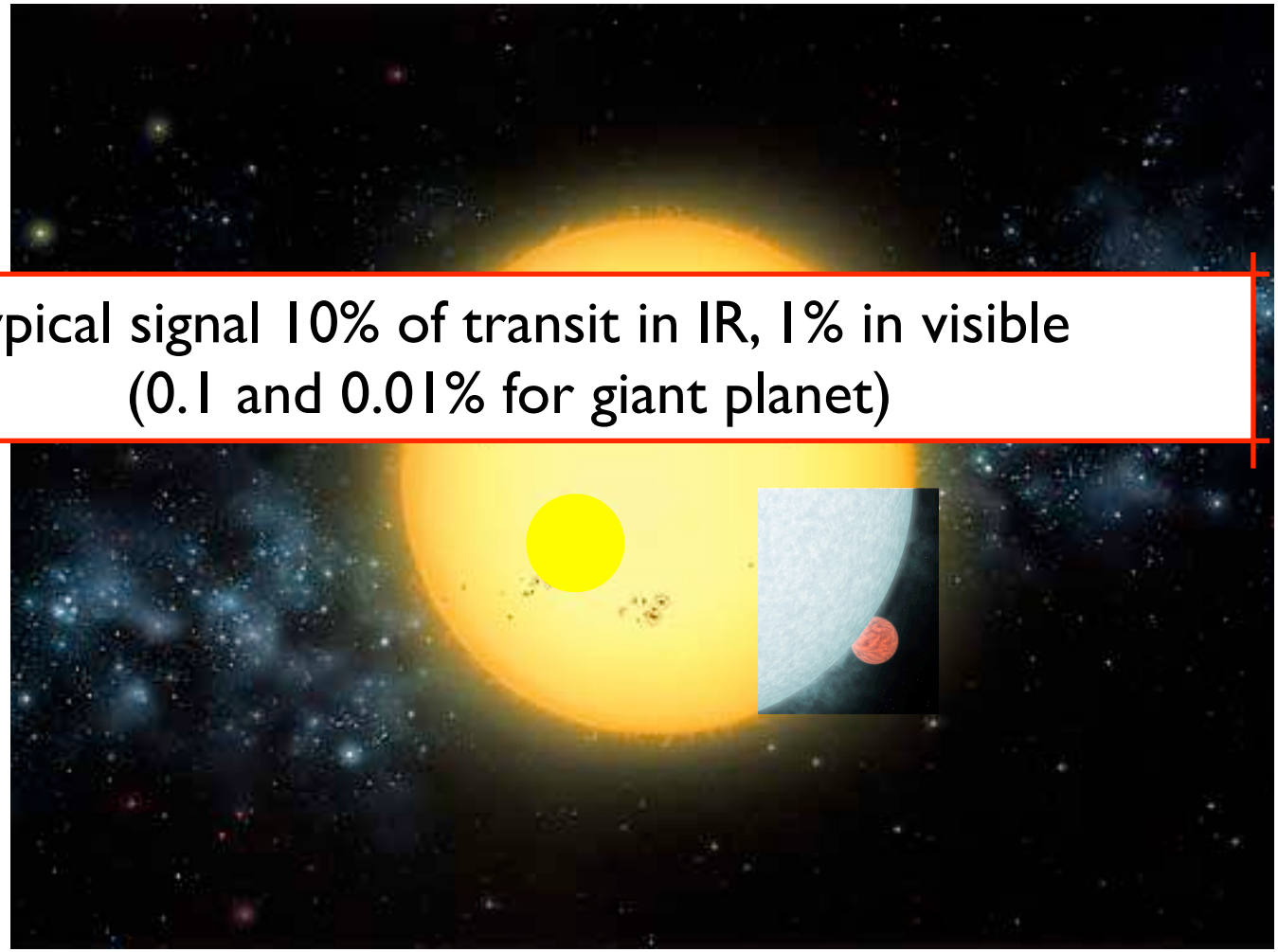

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(0.1 and 0.01% for giant planet)

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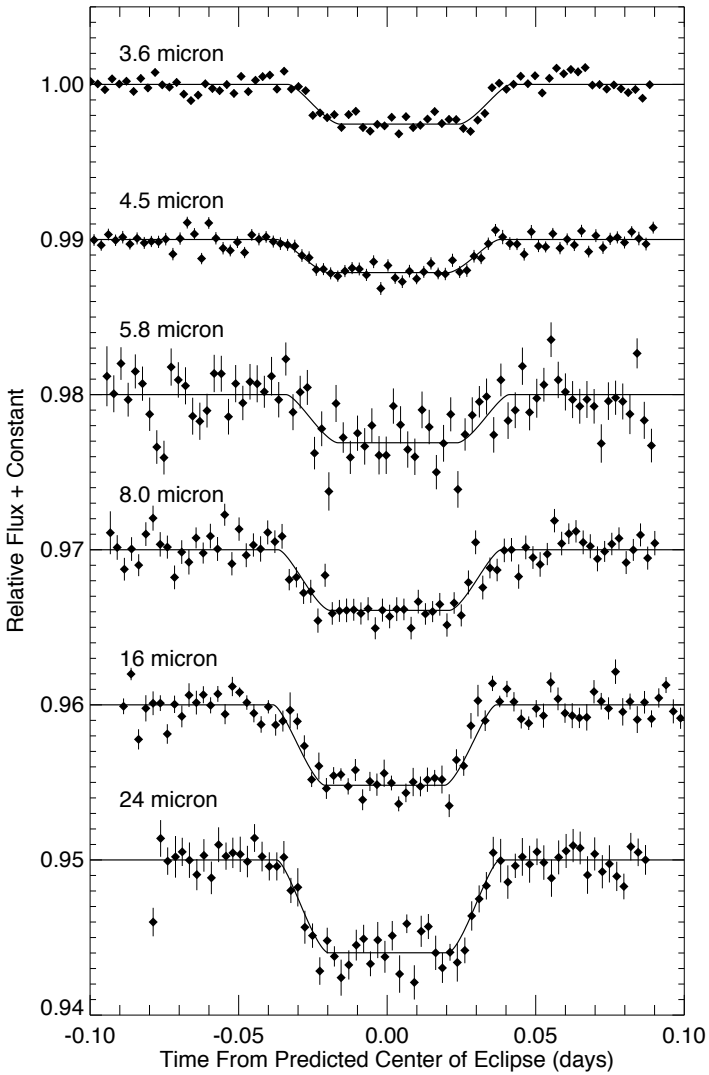
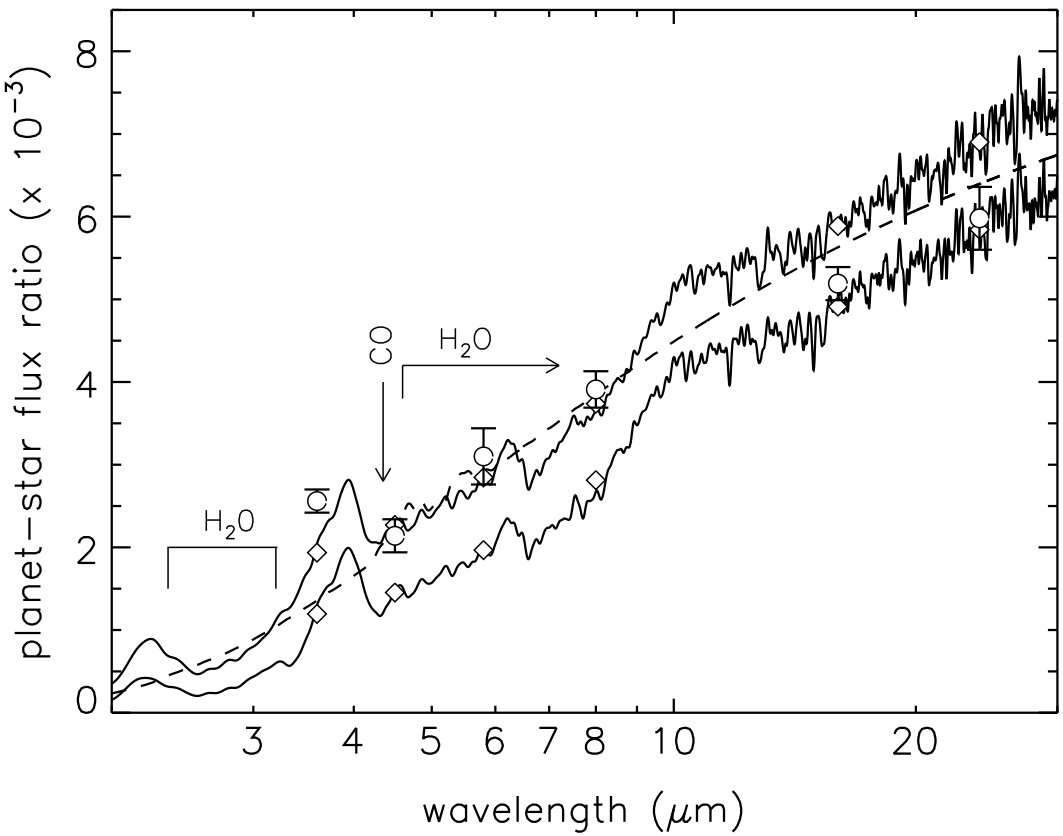
**IR detections** (e.g. Charbonneau et al. 2008 below): hot Jupiters are really ***hot (1000-2000K)***



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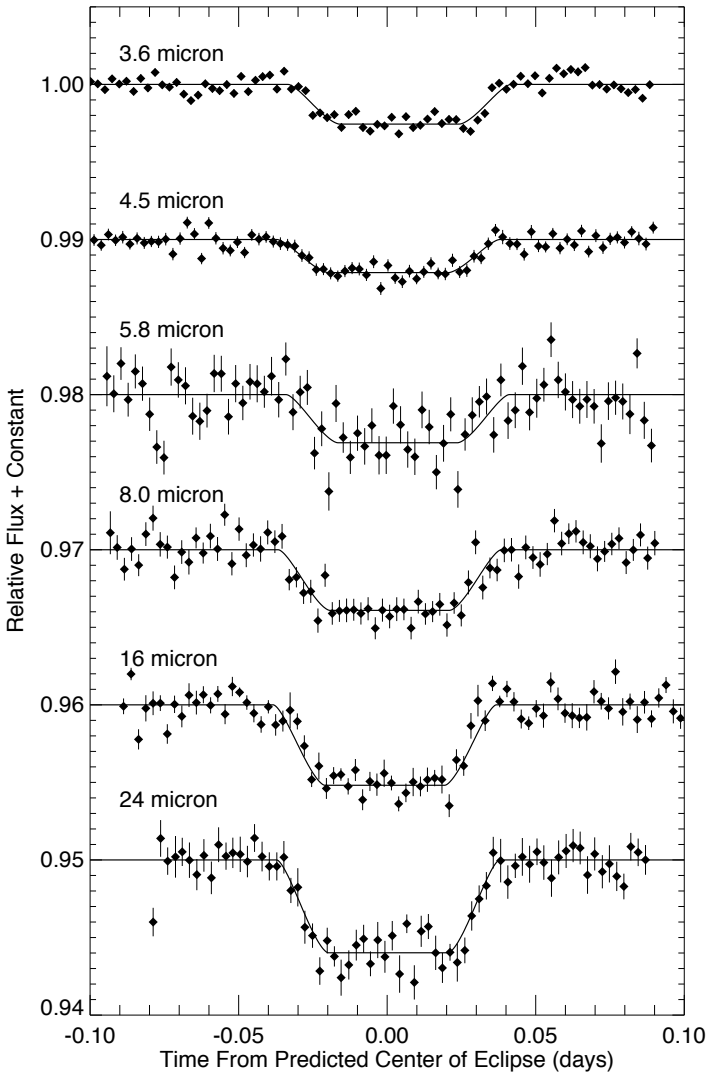
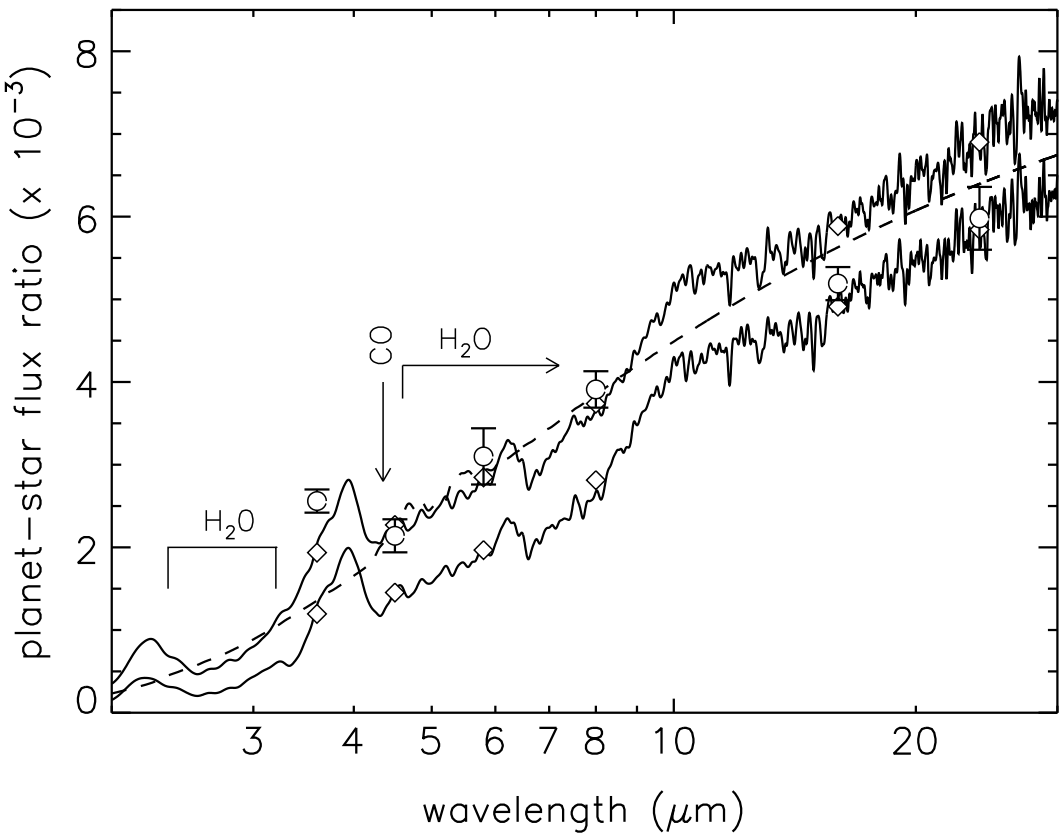
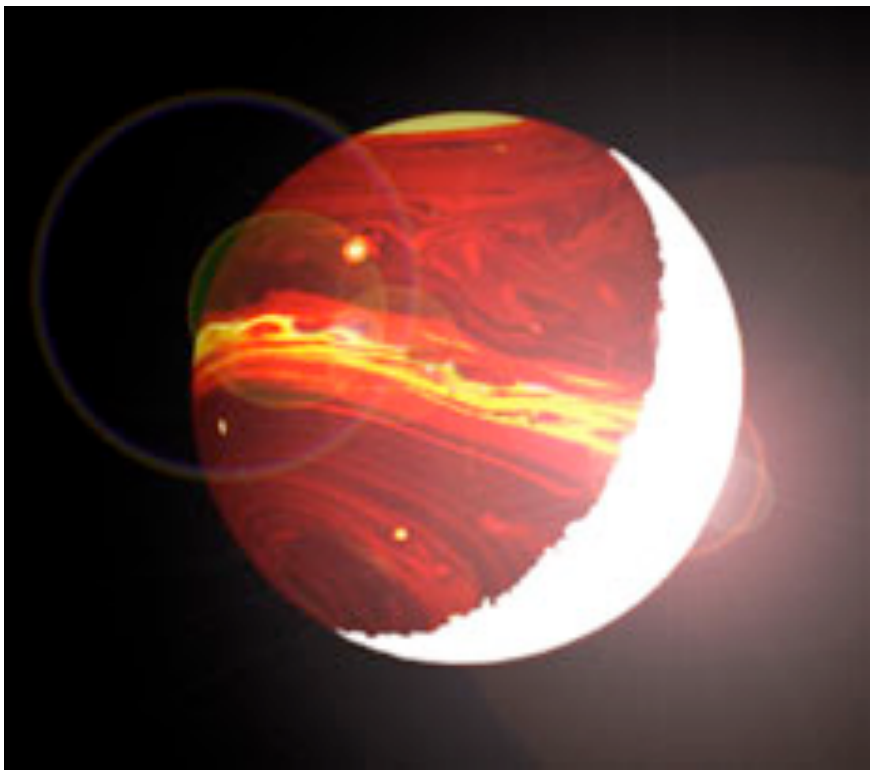



**Visible non-detections** (MOST satellite - Rowe et al. 2006): Hot Jupiters are really ***dark***.

# Atmospheric composition and dynamics

**Phase curves**, which can be measured for transiting and non-transiting planets, probe ***thermal emission (IR)*** or ***reflected and scattered light (visible)***.



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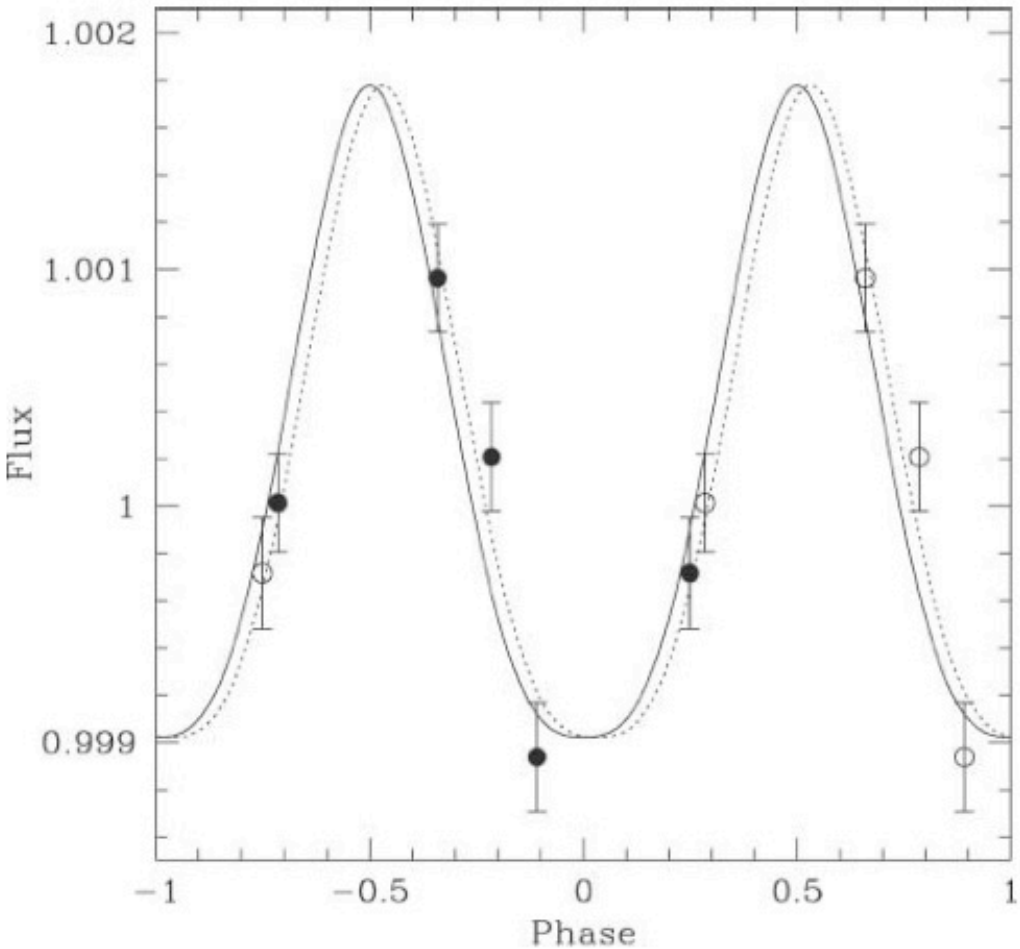

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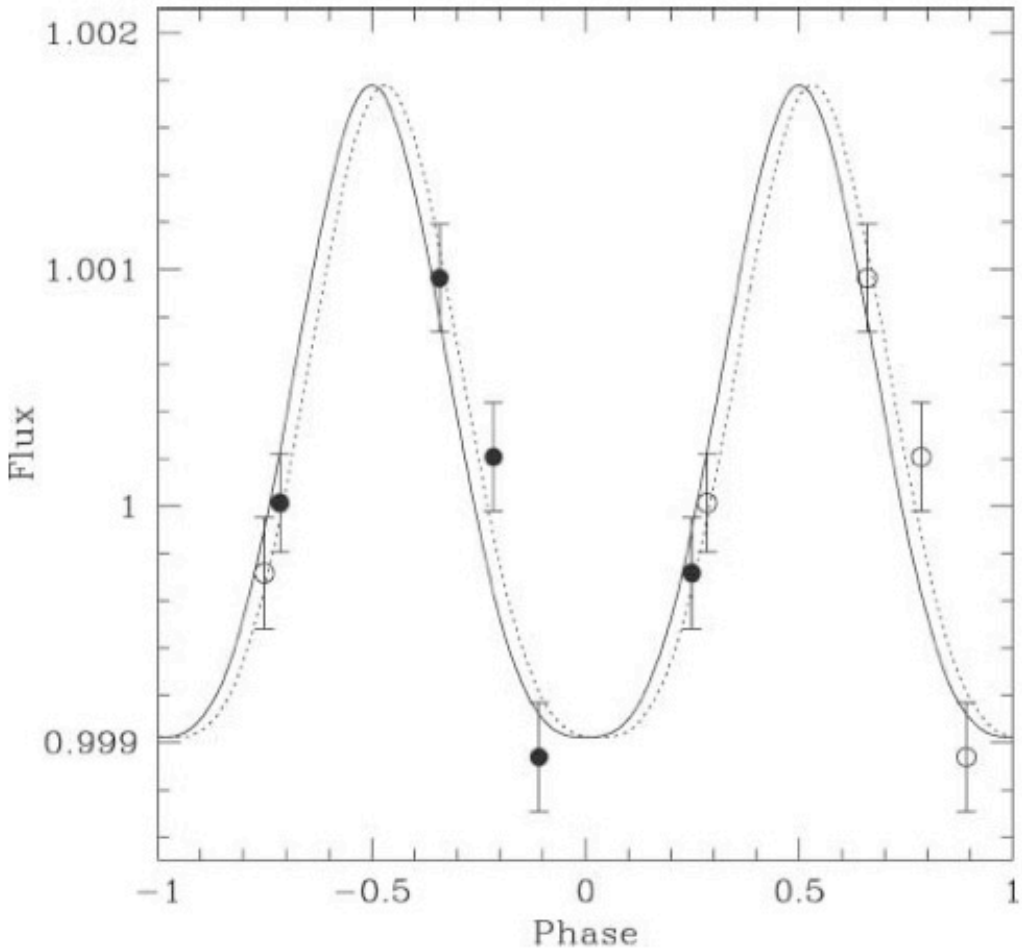
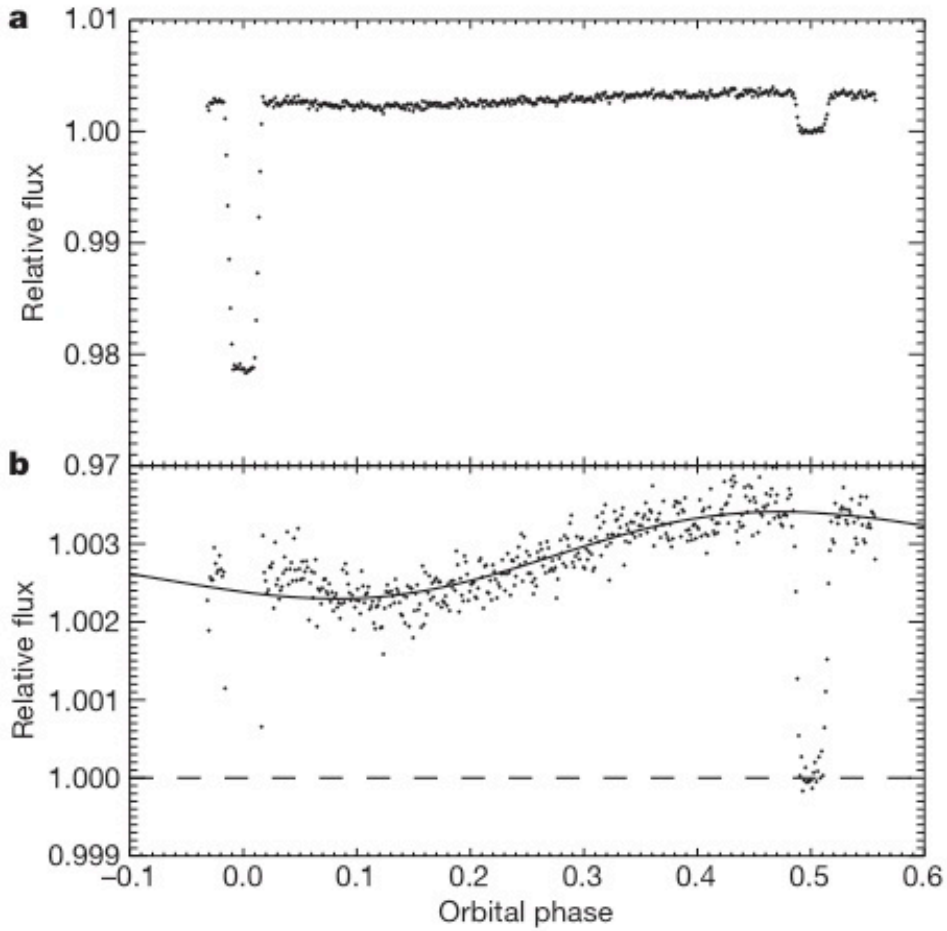



Knutson et al (2006) - HD 189733
weak day night contrast, phase offset - ***large-scale transport***



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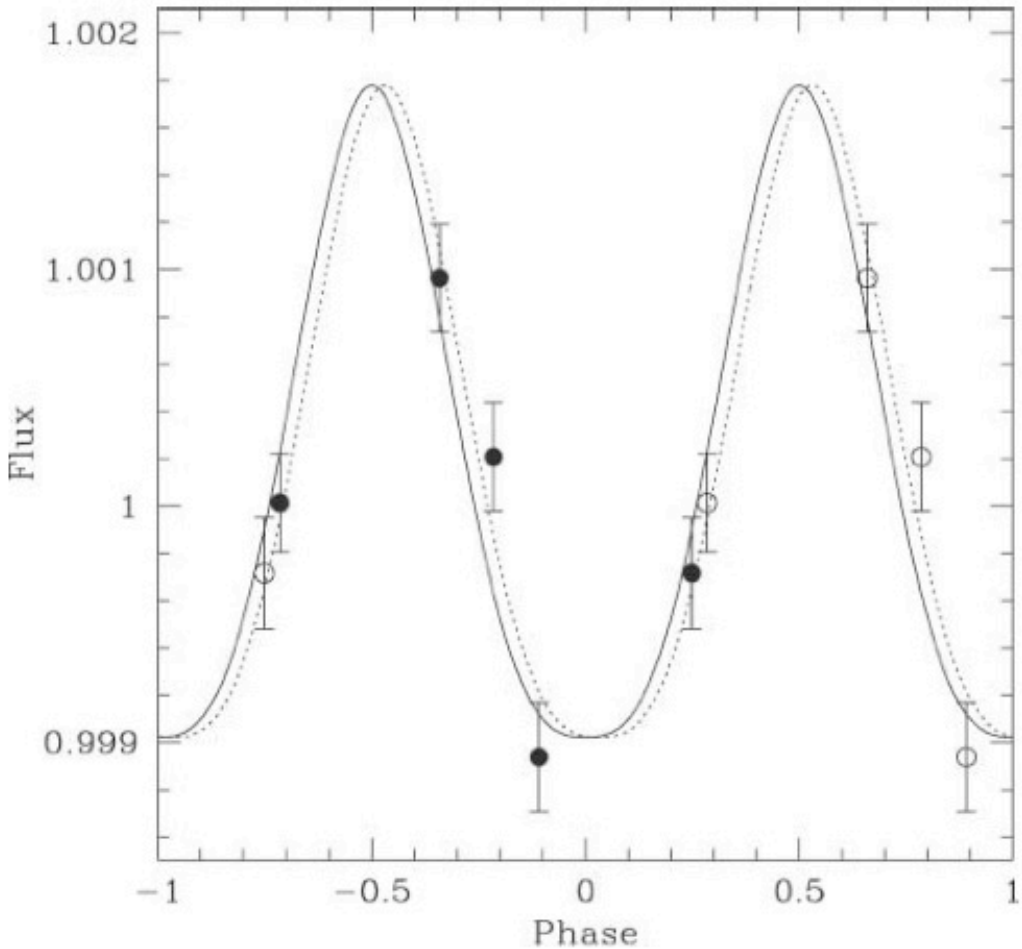


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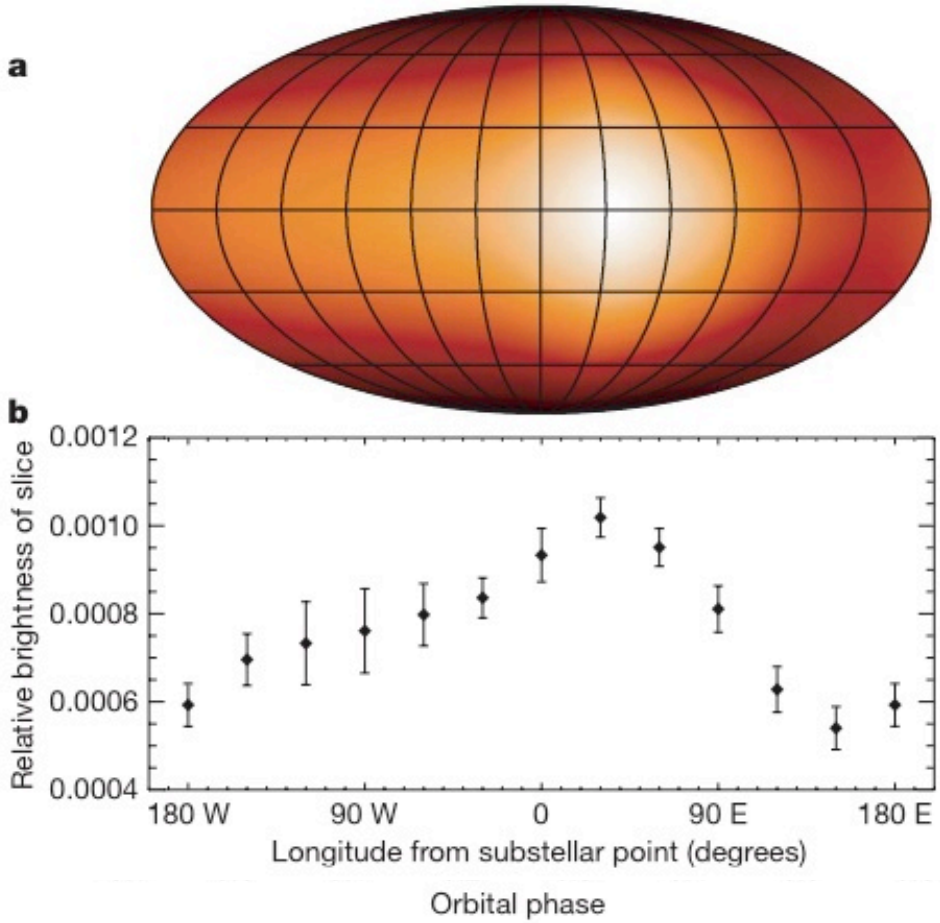


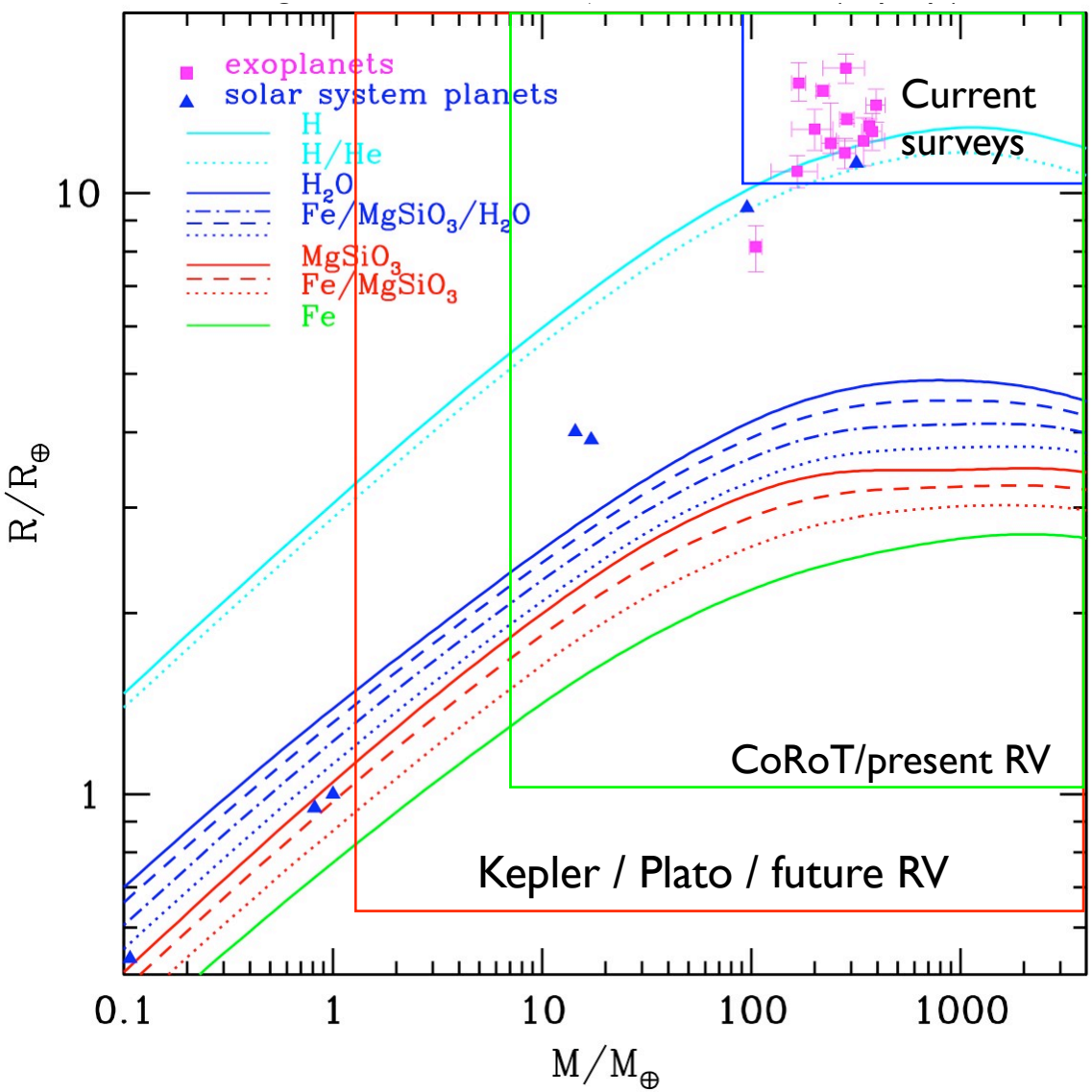
# Why build CoRoT?

## 2. space = terrestrial planets + more physics

# Reaching the terrestrial and habitable regimes

Space means **higher precision**, less correlated noise, and long, **uninterrupted time-series**: detect shallower and rarer transits, i.e. ***smaller and colder planets***.

Seager et al. (2007) - simple hydrostatic structure calculations




A word of caution: the mass - radius relation is degenerate for ocean and terrestrial planets (Adams et al. 2008, Baraffe et al. 2008)

At best, CoRoT is expected to reach ~2 Earth radii, i.e. 3-4 Earth masses, for very short period orbits, and larger planets out to weeks or months.

# Improving statistics

**Over 120,000 stars** will be monitored for months.

Fressin et al (2007): **planet catch simulations** based on pre-launch simulated data, known properties of the RV planet population and realistic Galactic stellar population model:

Over the lifetime of the mission, simultations suggest that CoRoT should detect **60-70 Jupiter- or Saturn-mass** planets and **20-25 Neptune-mass planets or super-Earths**.

The simulations are being recalibrated to incorporate the actual properties of the data as we speak.

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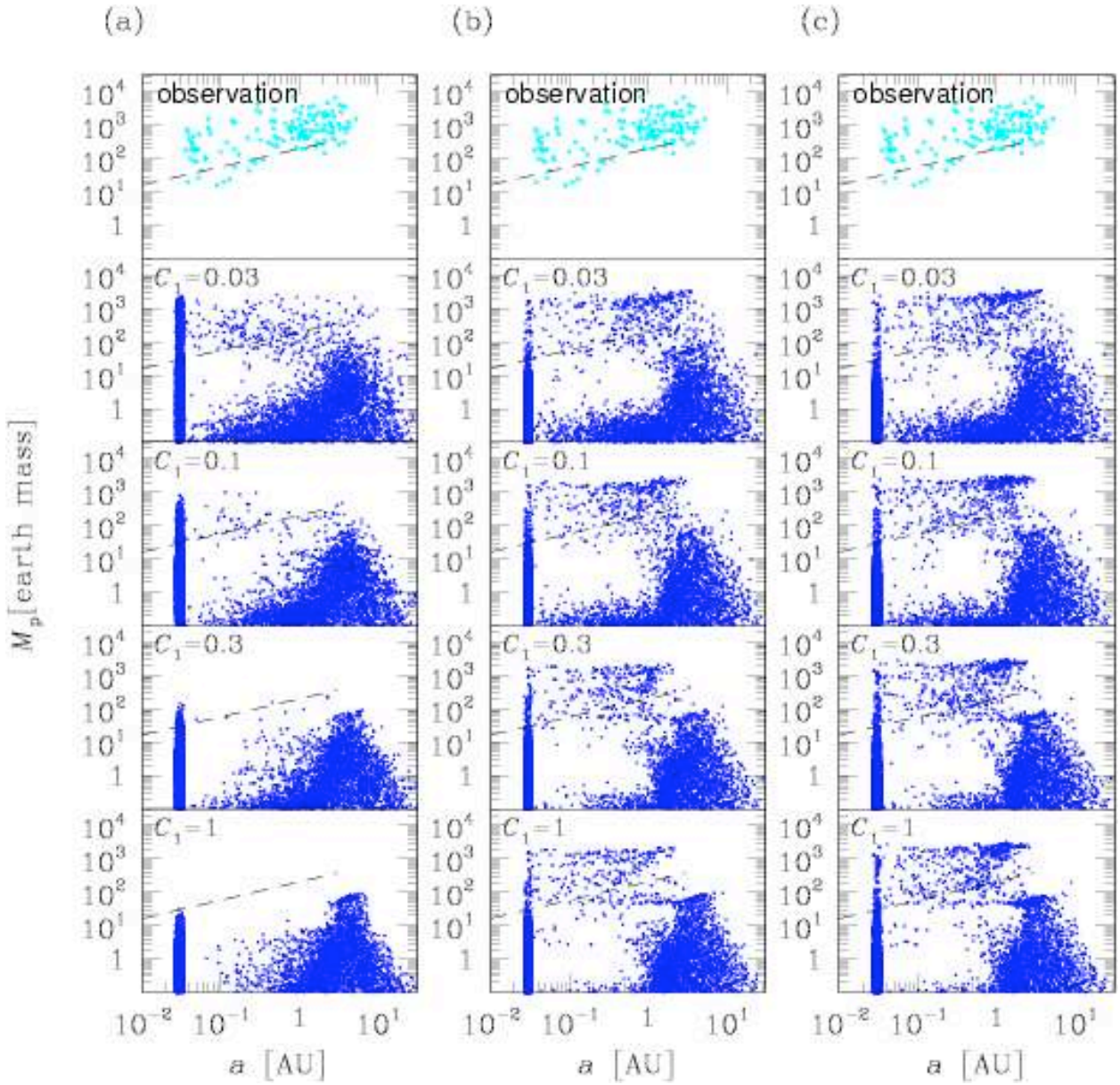
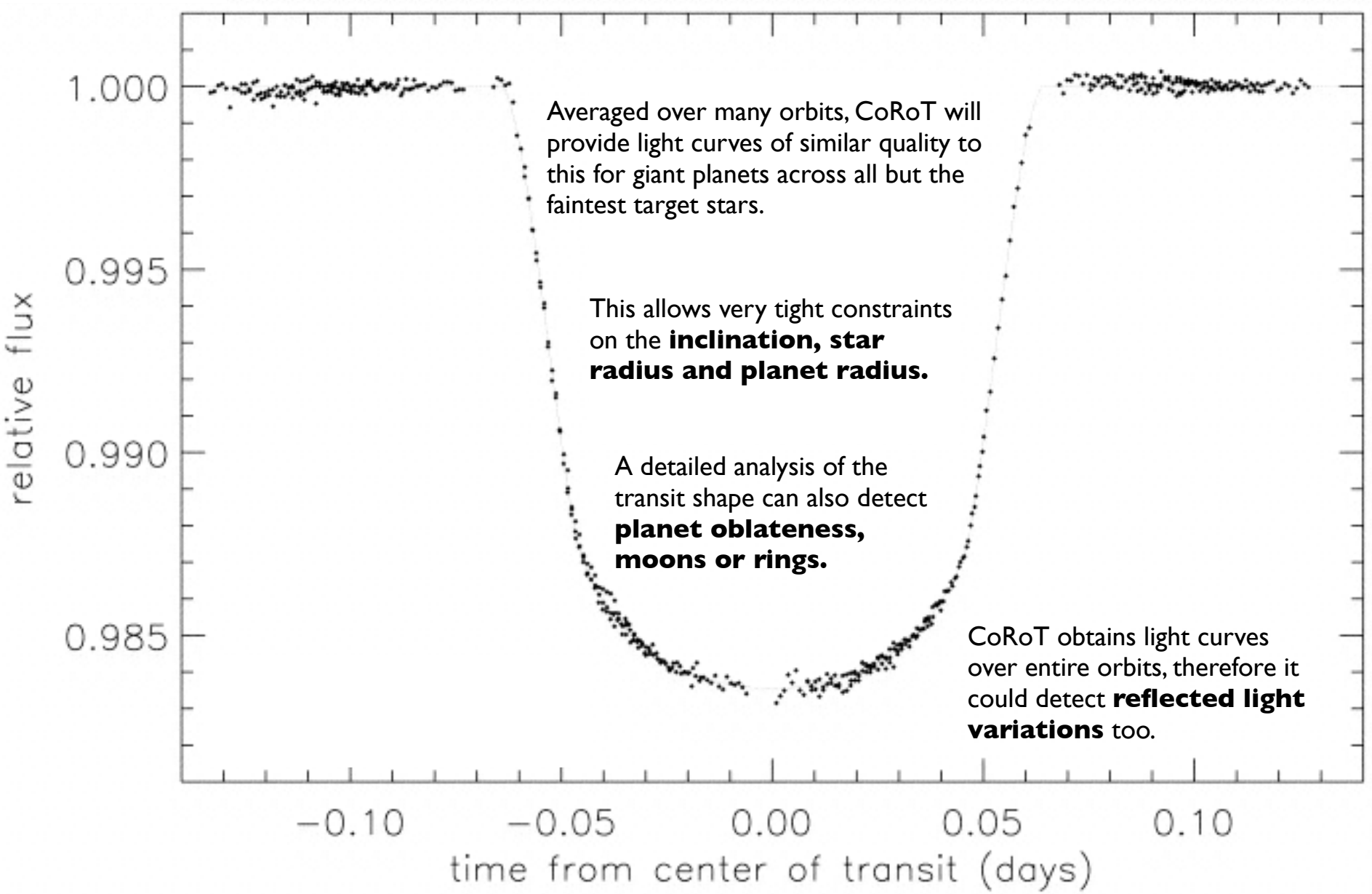
Simulated planet populations (Ida & Lin 2008)



# Ultraprecise light curves

HD209458b with HST (Brown et al. 2000)



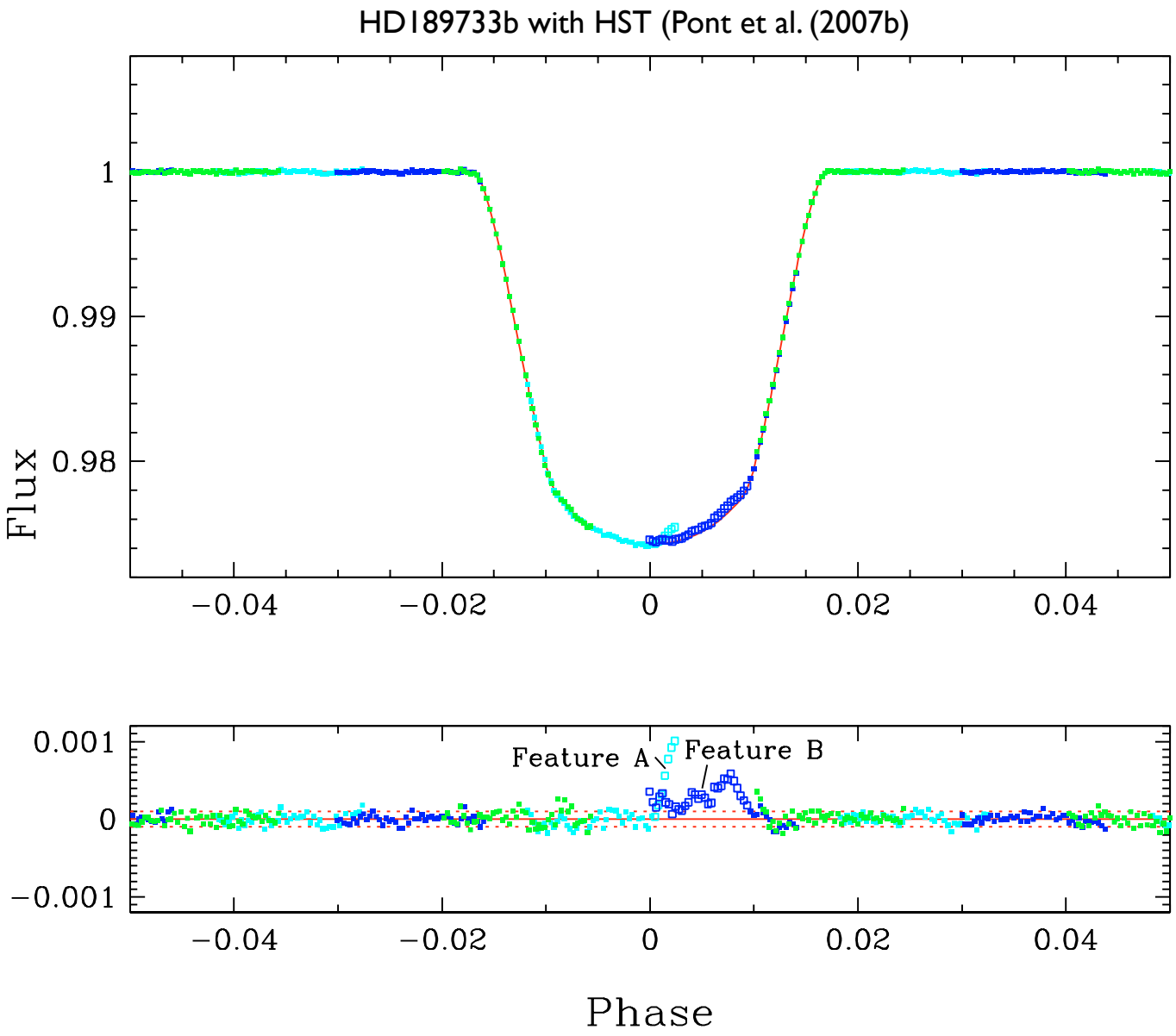

Averaged over many orbits, CoRoT will provide light curves of similar quality to this for giant planets across all but the faintest target stars.

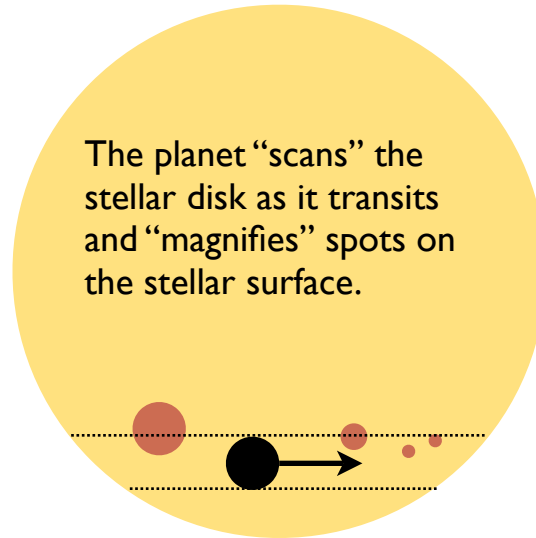
This allows very tight constraints on the **inclination, star radius and planet radius.**

A detailed analysis of the transit shape can also detect **planet oblateness, moons or rings.**

CoRoT obtains light curves over entire orbits, therefore it could detect **reflected light variations** too.

# Ultraprecise light curves



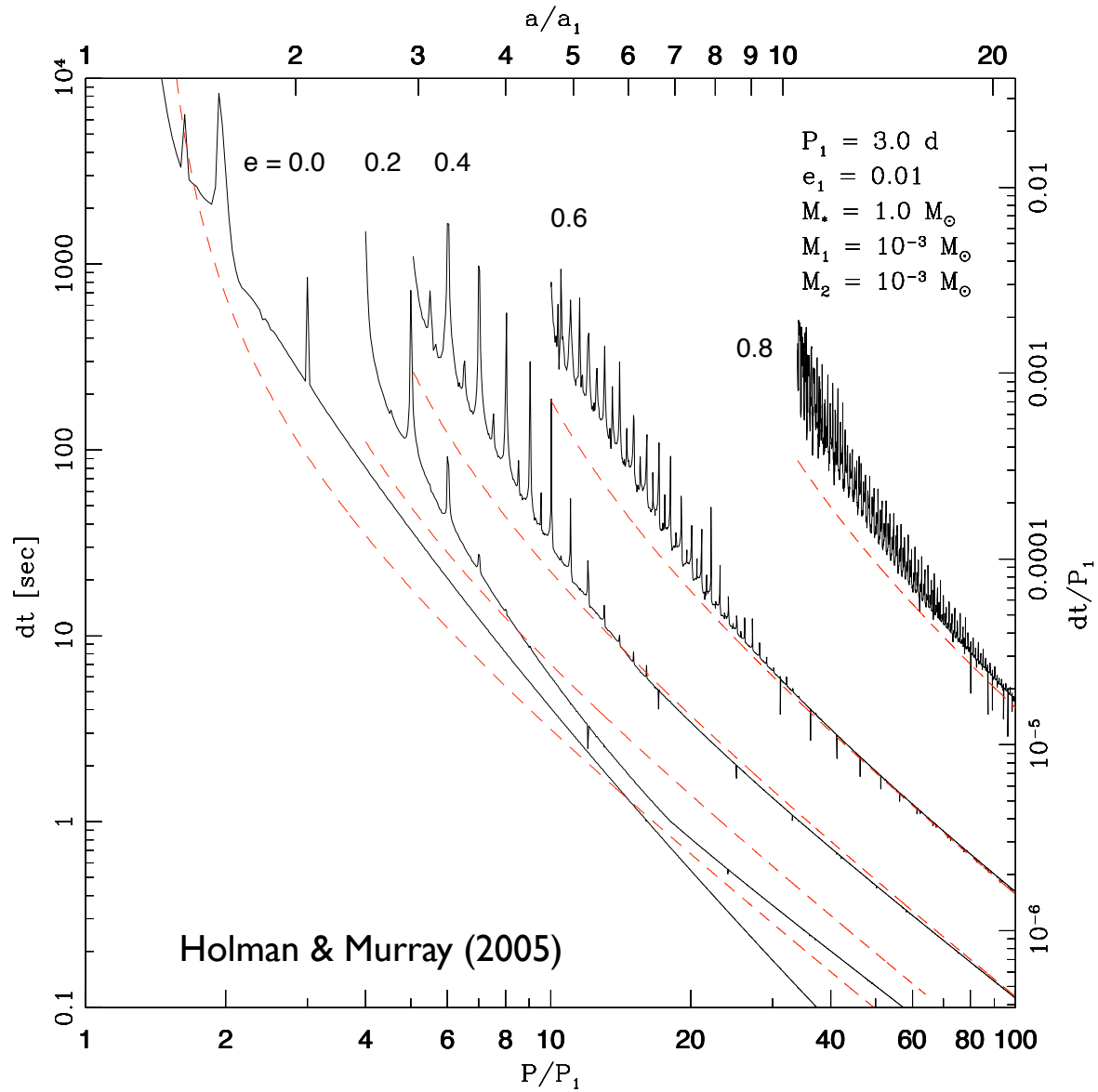




Potentially, this can be a tracer of **star-planet magnetic interaction** - as can the out-of-transit variability if it is synchronous with the planet's orbit.

# Transit timing variations

If there are **other planets** in addition to the one whose transits have been detected, they will **dynamically perturb** the transiting planet's orbit, causing small deviations in from strict periodicity

This can potentially be used to detect Earth mass planets in systems containing giant planets

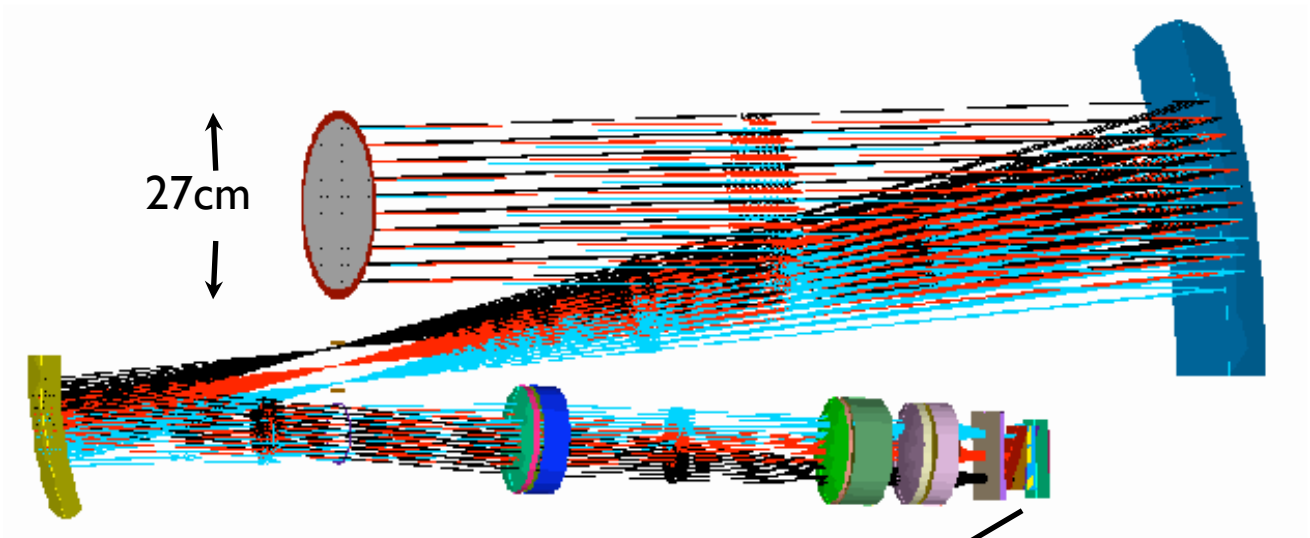


# How does CoRoT work?

# The satellite

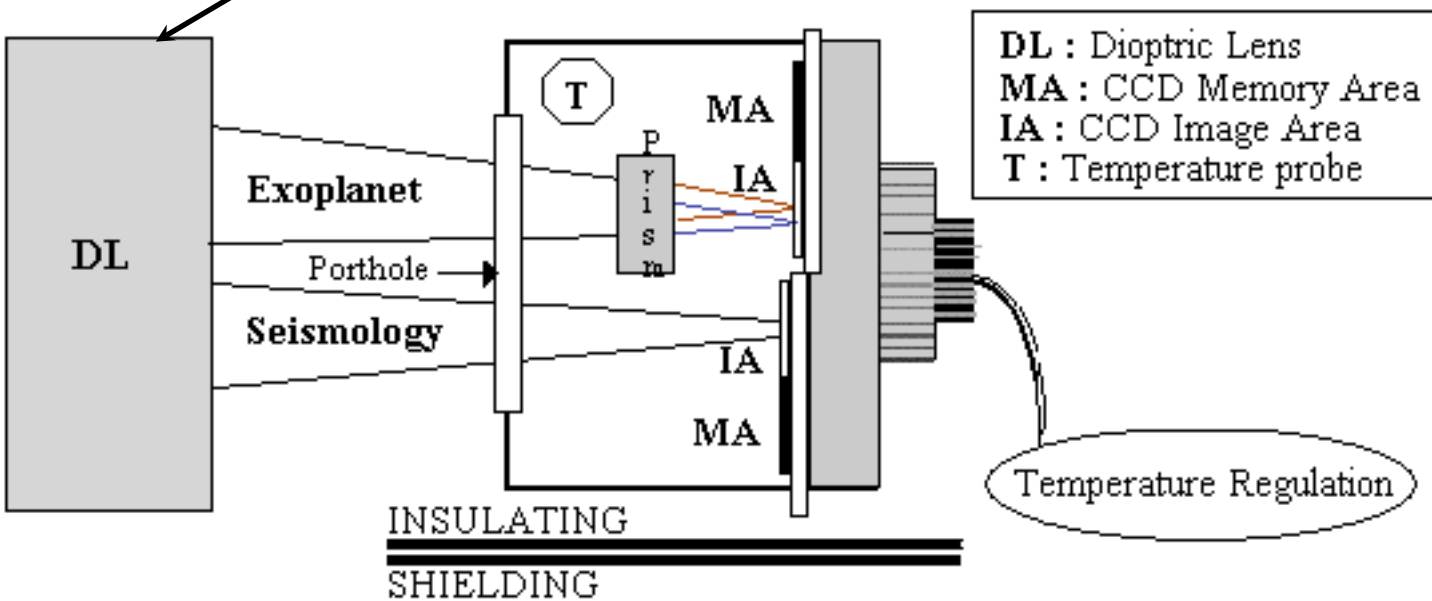
- PI: Annie Baglin, LESIA, Meudon
- CNES PROTEUS bus
- 27cm aperture telescope
- Soyuz II-1b launcher from Baikonour
- Polar orbit
- 2.5 year minimum lifetime

# Payload




telescope layout

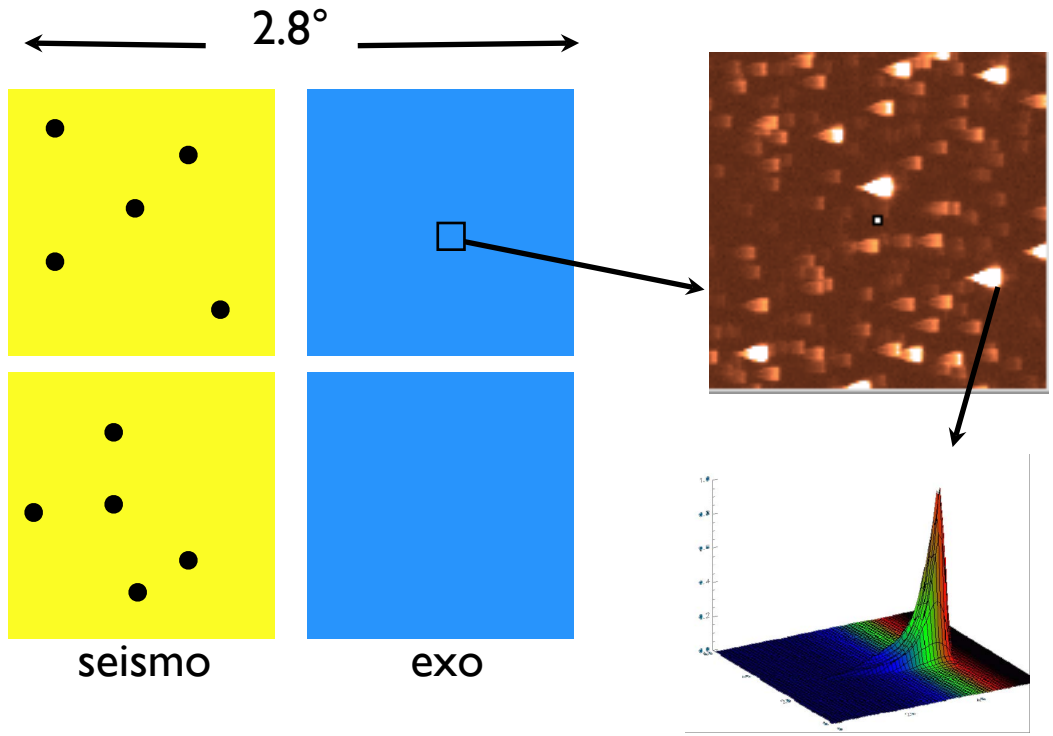
focal box

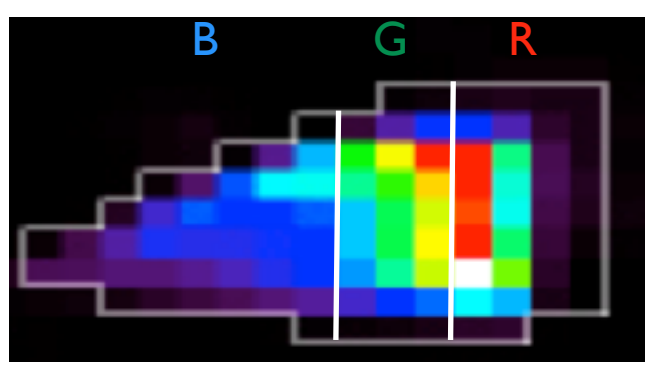



27 December 2006

# Exo field

- Exo field
  - up to 6000 LCs / CCD
  - $11.5 < m_V < 16$
  - 512s sampling (32s for 500 objects / CCD)
  - 3 colours for ~ 4500 objects / CCD with $m_V < 15$
  - some small background windows
  - up to 40 10x15 pixel windows
  - on-board aperture photometry using mask selected form 256 templates based on one initial long integration image



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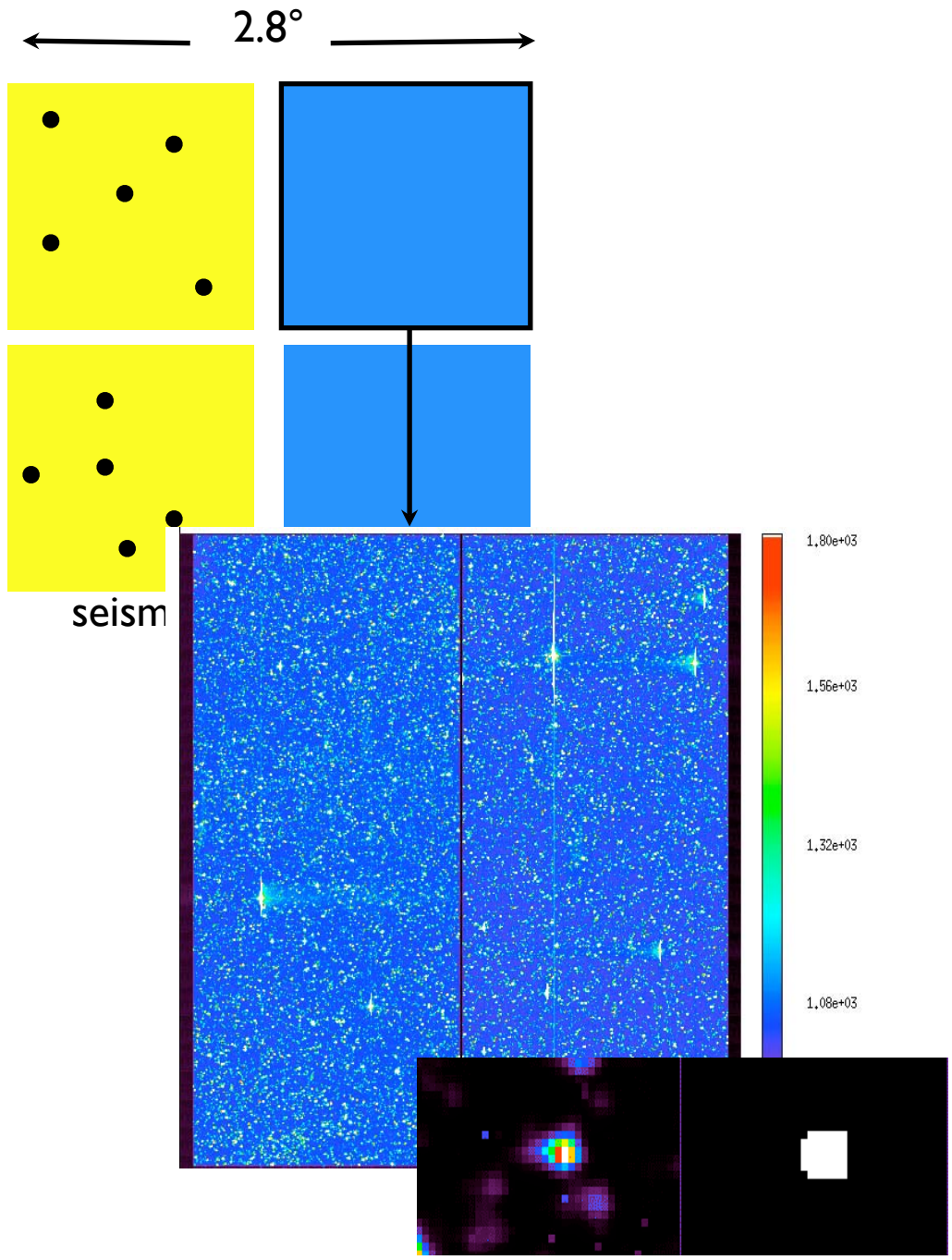
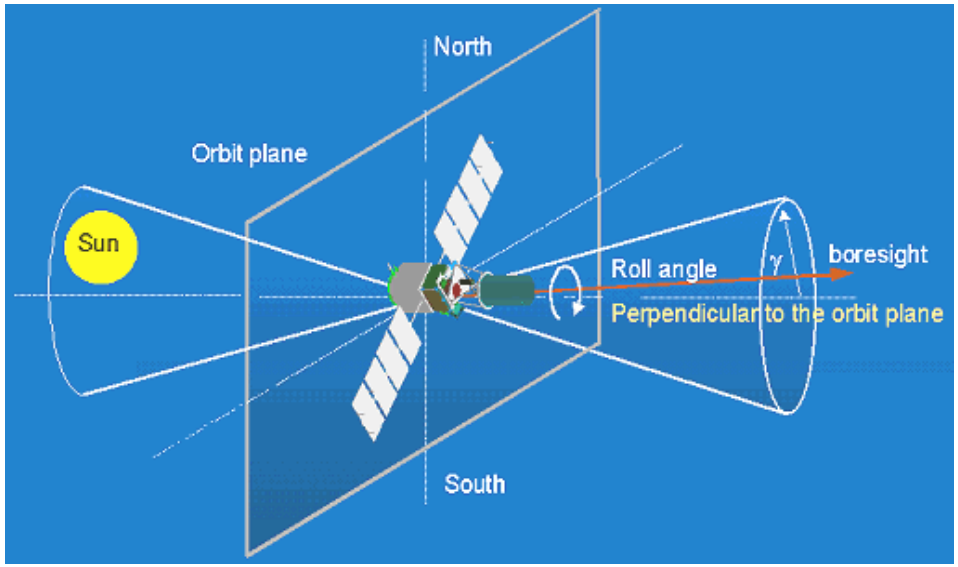
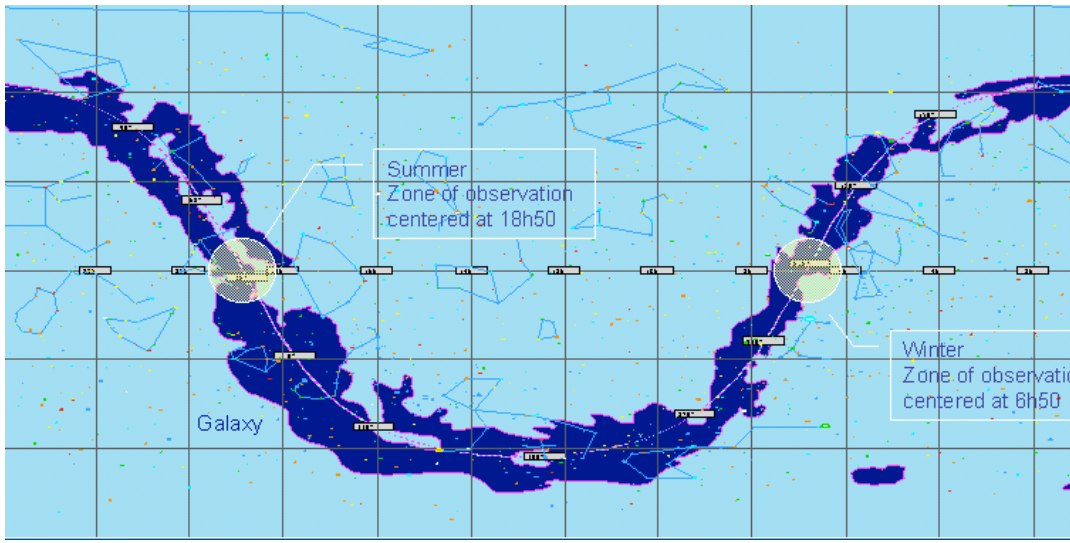


# Observing strategy

- Sequence:
  - ~1 month commissioning
  - 1 initial run (early science, ~50d)
  - then 5 x (150d long run + 21d short run)
  - rotate satellite every 6 months
  - Currently doing 2nd long run
- Visibility zone
  - sun angle constraints imply 2 'CoRoT eyes'
  - 10° diameter, small drift over 2.5 yr lifetime
  - intersection of ecliptic & Galactic planes
  - field selection = compromise



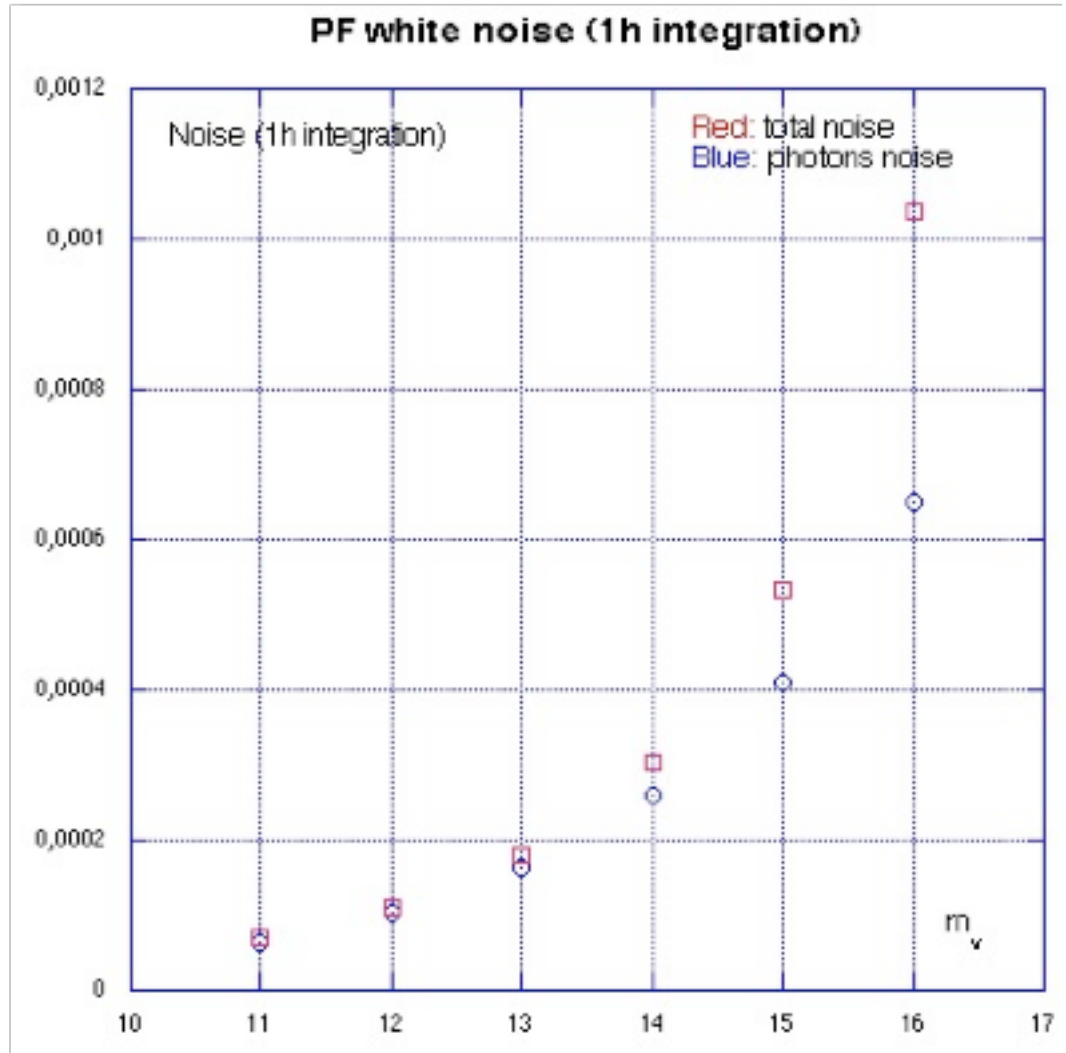




| Field | Dur. (d) | RA | Dec | Rot* (°) |
|---|---|---|---|---|
| IR1 | ~60 | 06:50:25 | -01:42:00 | +14.96 |
| LRc1 | 150 | 19:23:28.8 | +00:28:48 | +19.0 |
| LRa1 | 150 | 06:46:48.0 | -00:11:24 | +7.3 |

*N-S direction: Rot = -5° in centre, +5° in anticentre

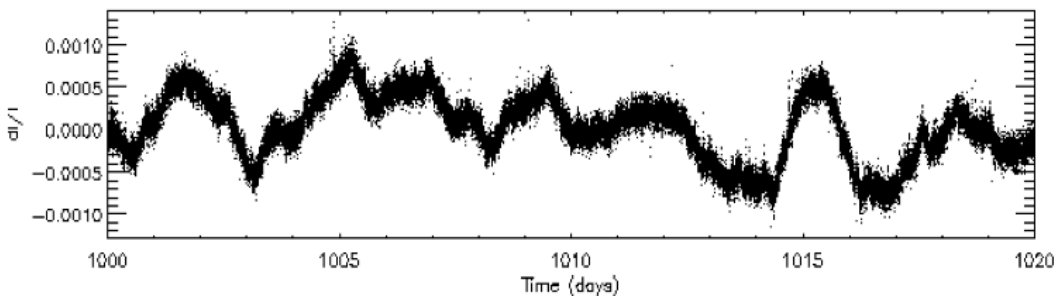
# Exoplanet noise budget

- Nominal noise budget
  - white noise
    - readout, background, jitter
    - see plot
  - orbital period (6174s)
    - jitter, temperature, residual straylight
    - 120 ppm
- Stellar variability
  - few tens of ppm over transit timescale
- Correlated noise?
  - Blind test light curves contain 0.5 mmag red noise after detrending

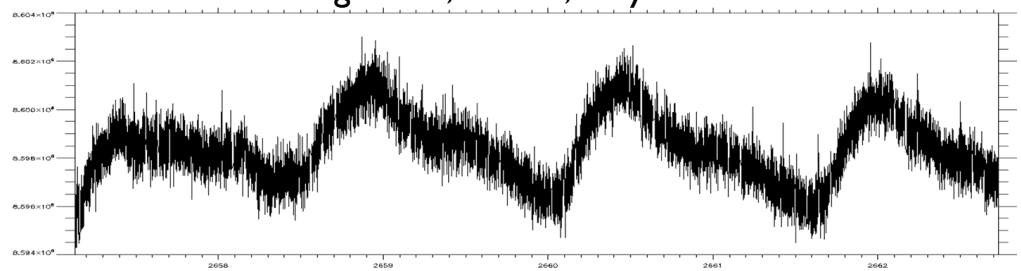


# Example light curves from the seismo field

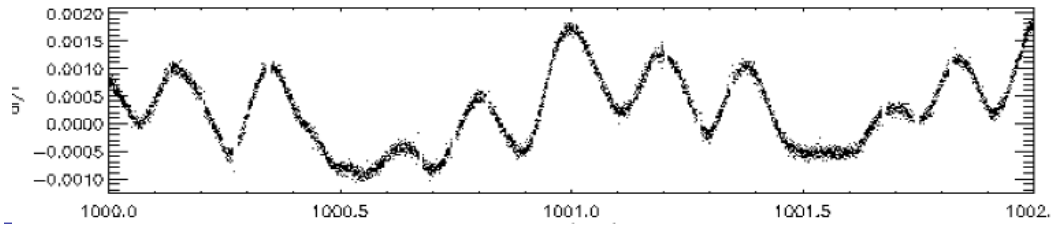
6th magnitude, F-type star, daily time-scales, few $10^{-3}$



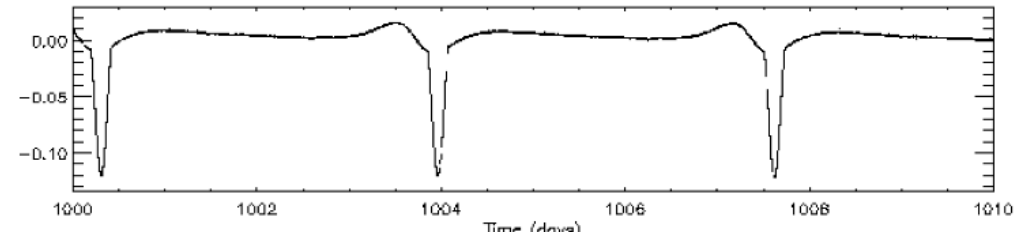

6th magnitude, Be star, daily time-scales



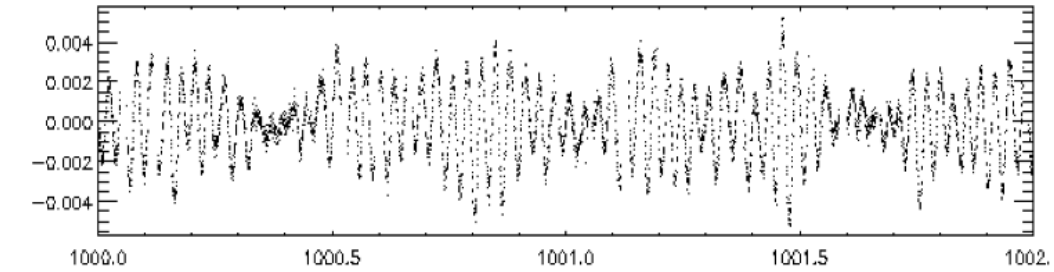
6th magnitude, few hours time-scales, few $10^{-3}$



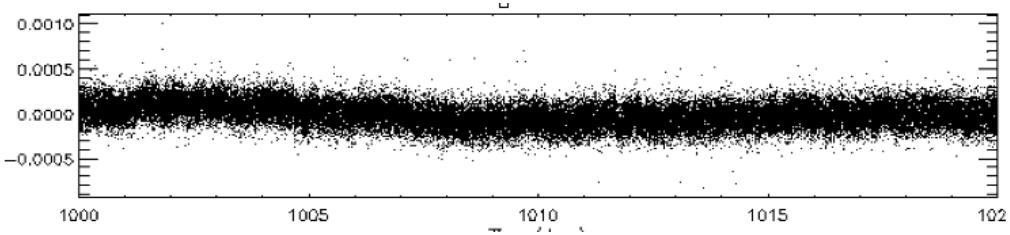

8th magnitude, B star, eclipsing binary




9th magnitude, suspected δ Scuti, few hours time-scales, few $10^{-3}$




7th magnitude, F-type giant, few $10^{-4}$



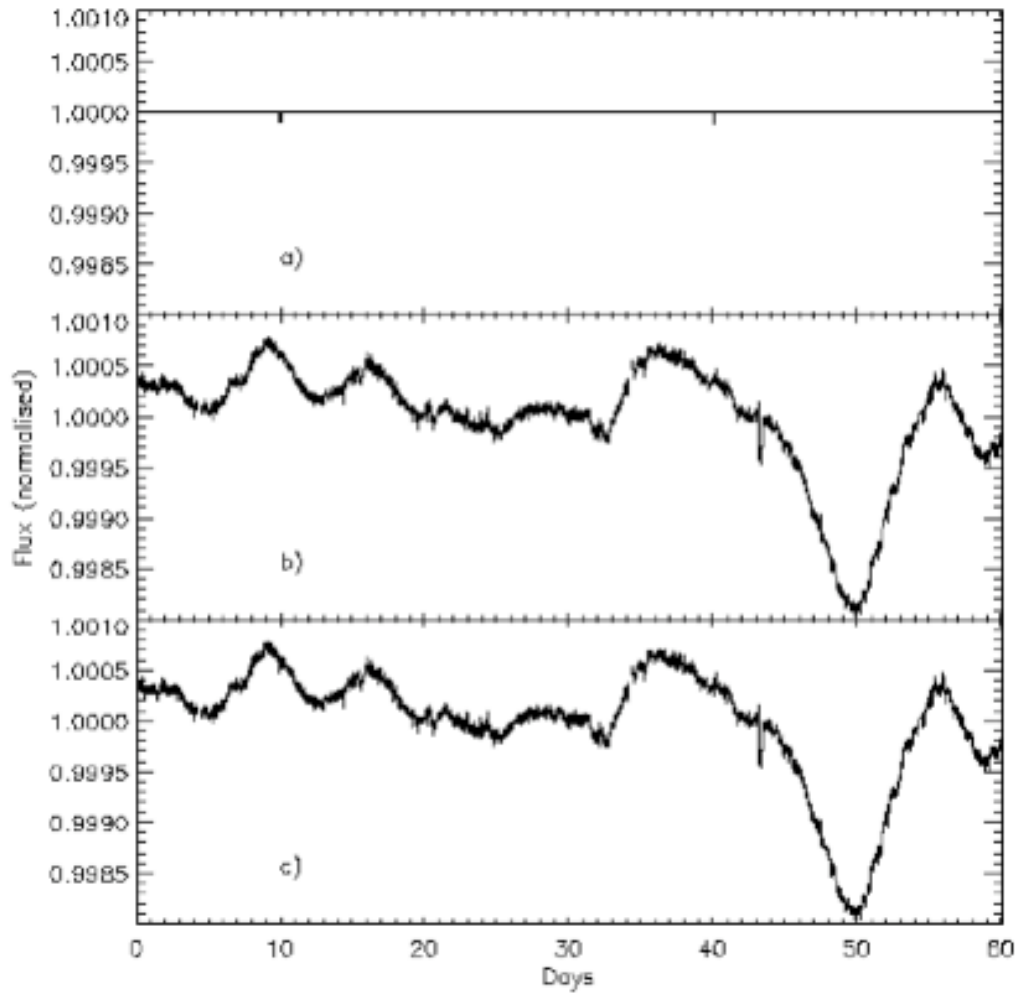
# Detecting the planets

# Steps in the detection process

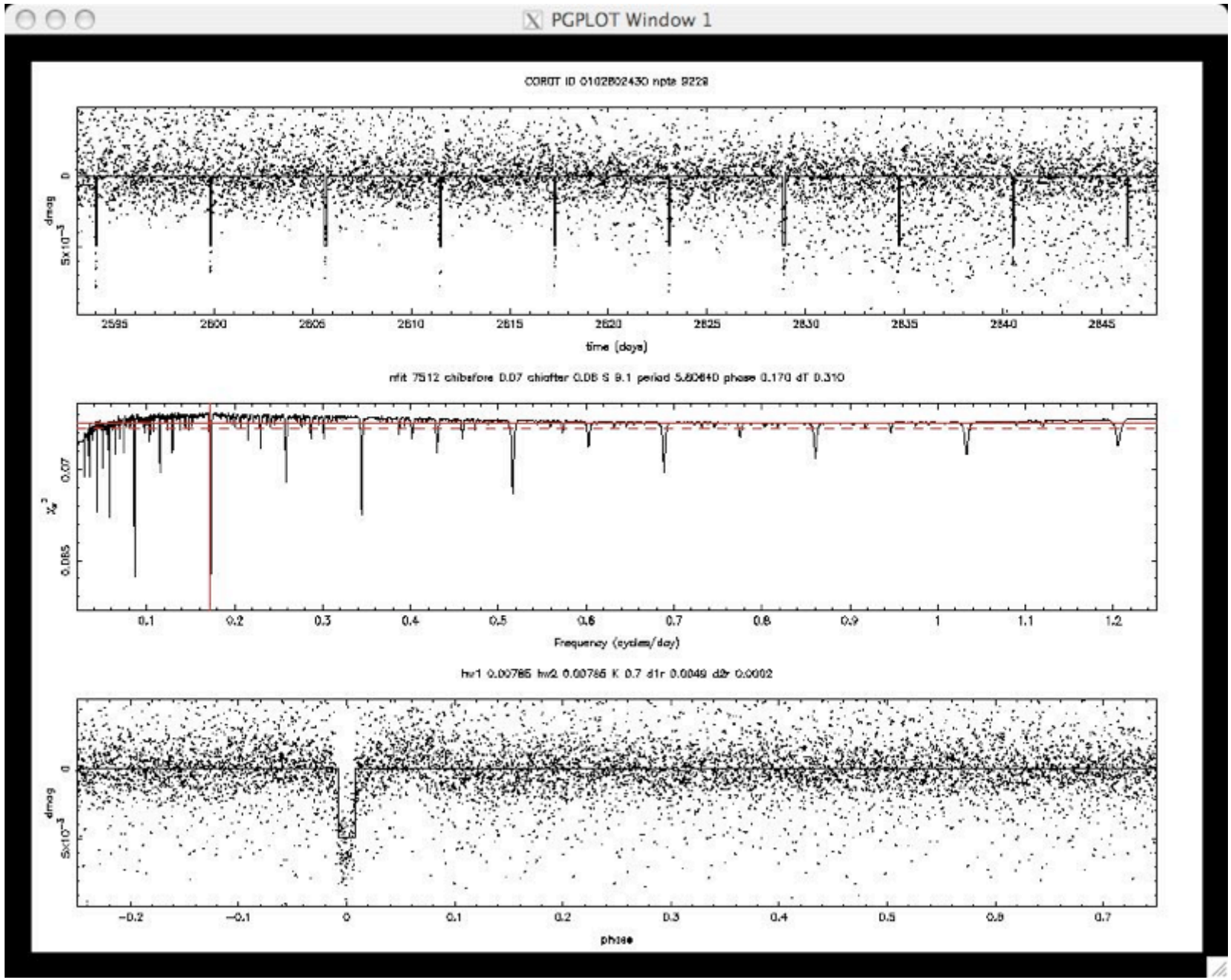
- Preprocessing
  - Identify and remove outliers
  - Correct for scattered light (satellite orbital period and daily timescales)
  - Identify and remove hot pixels
  - Evaluate flux measurement uncertainties
- Detection
  - Filter out stellar variability
  - Run transit search (most commonly using variants of the BLS agorithm of Kovacs, Zucker & Mazeh 2002)
  - Prioritise candidates
- Ground-based follow-up

# Stellar micro-variability

- Rotational modulation & intrinsic evolution of surface structures (spots, faculae, granules)
  - Roughly 1/f noise spectrum
- Very ill characterised in stars other than the Sun
  - Attempts at predicting micro-variability for other stars (Aigrain, Favata & Gilmore 2004, Lanza et al. 2005)
  - Major ancillary science goal
- The main noise source for terrestrial transit detection from space
- Temporal signature different from transits
  - Exploit to construct filters
  - Moutou et al. (2005): CoRoT detection limits in the presence of variability



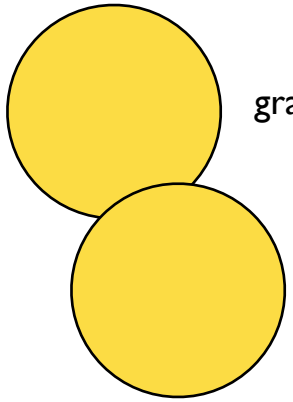
# Transit detection




Algorithm of Aigrain & Irwin (2004) modified to allow secondaries and trapezoidal eclipses

# Transit mimics

# Transit mimics



grazing eclipsing binary

close inspection of light curve
SB2 spectrum
pair of RV measurements

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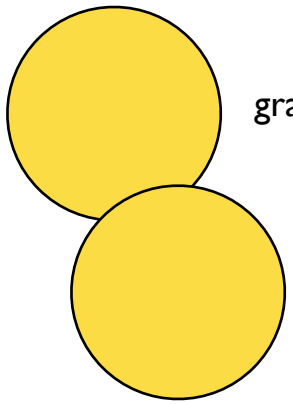

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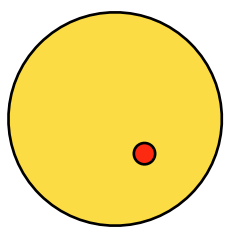
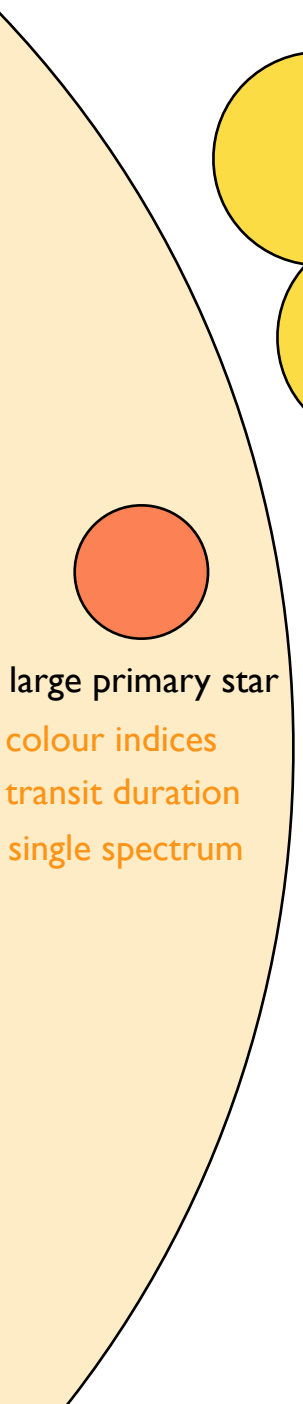


small secondary star

pair of RV measurements

# Transit mimics



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pair of RV measurements

large primary star

colour indices
transit duration
single spectrum

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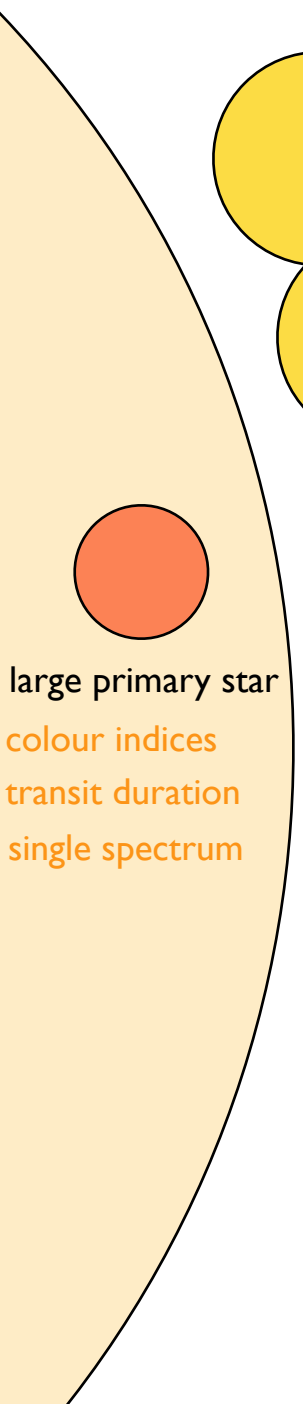

large primary star

colour indices

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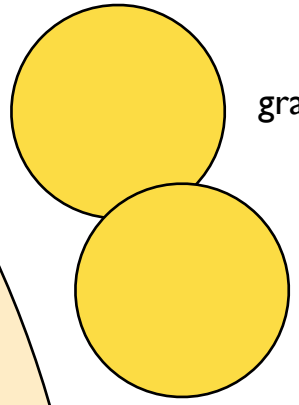
single spectrum



grazing eclipsing binary

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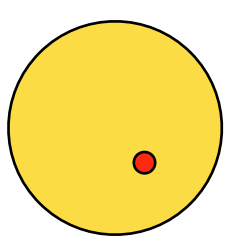
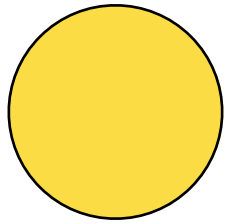


small secondary star

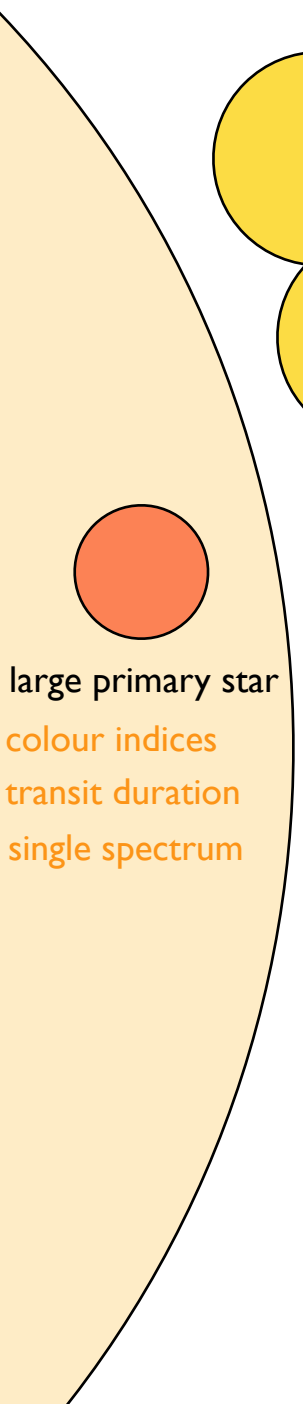
pair of RV measurements



nothing (false detection)

expensive!

# Transit mimics

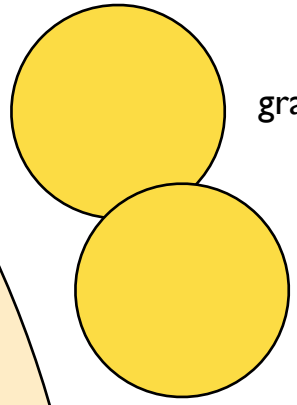


large primary star

colour indices

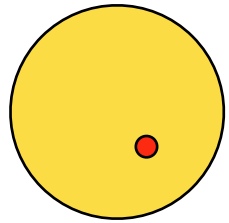
transit duration

single spectrum



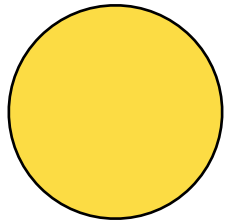
grazing eclipsing binary

close inspection of light curve
SB2 spectrum
pair of RV measurements



small secondary star

pair of RV measurements



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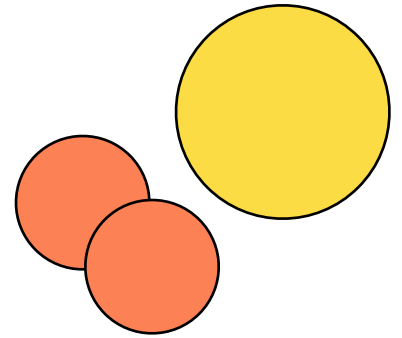
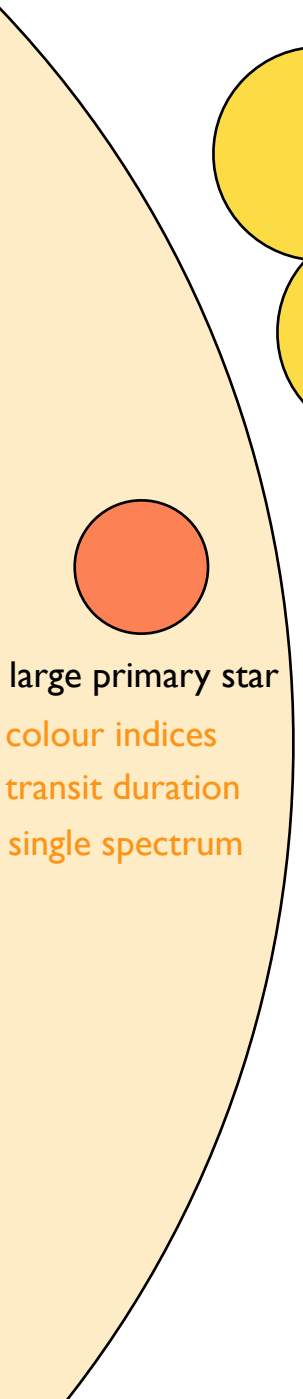
expensive!



blended eclipsing binary
(triple system or chance alignment)

high spatial resolution lightcurve
can mimic planet's RV
line bissector analysis

# Transit mimics

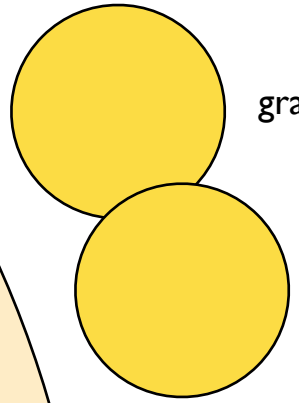


large primary star

colour indices

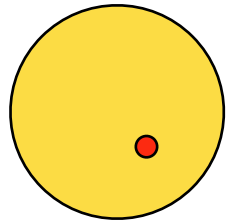
transit duration

single spectrum



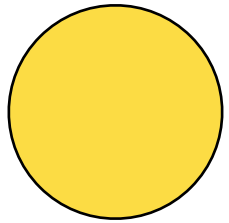
grazing eclipsing binary

close inspection of light curve
SB2 spectrum
pair of RV measurements



small secondary star

pair of RV measurements



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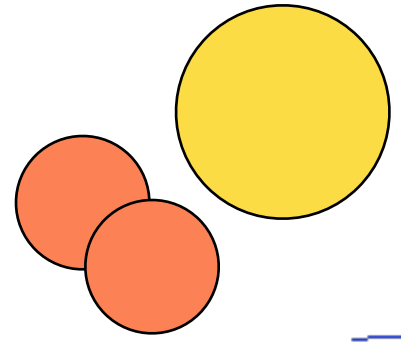

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(triple system or chance alignment)

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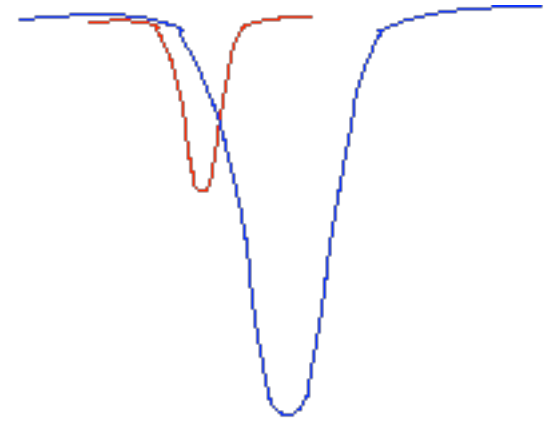
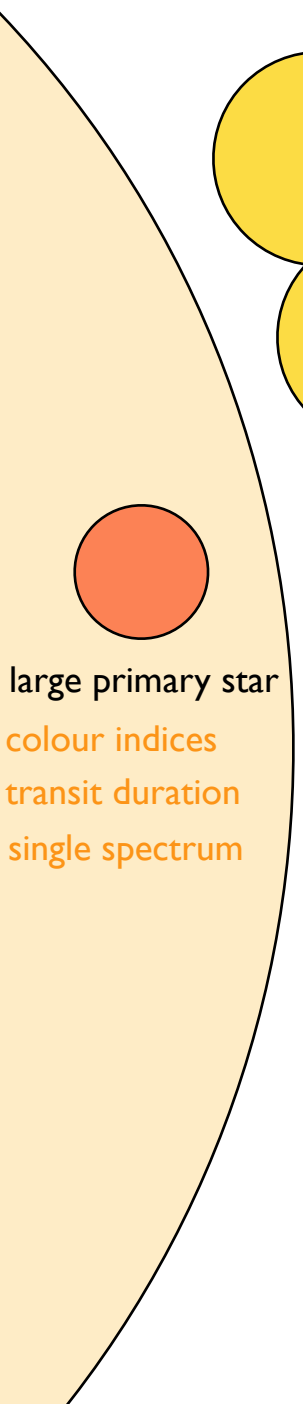


# Transit mimics

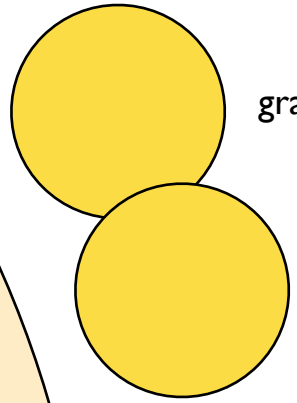


large primary star

colour indices

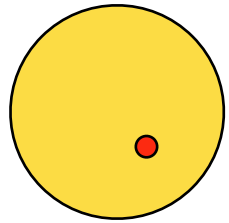
transit duration

single spectrum



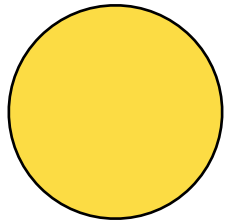
grazing eclipsing binary

close inspection of light curve
SB2 spectrum
pair of RV measurements



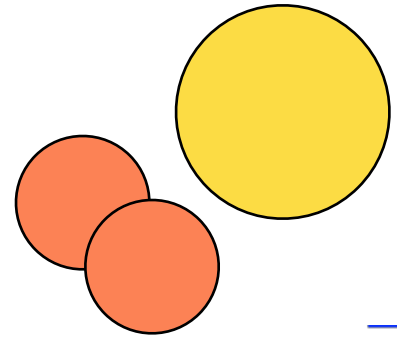
small secondary star

pair of RV measurements



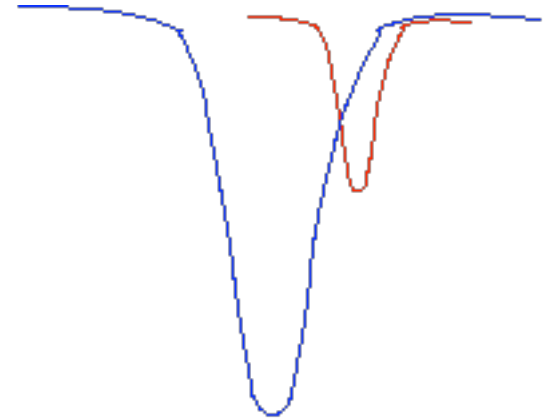
nothing (false detection)

expensive!

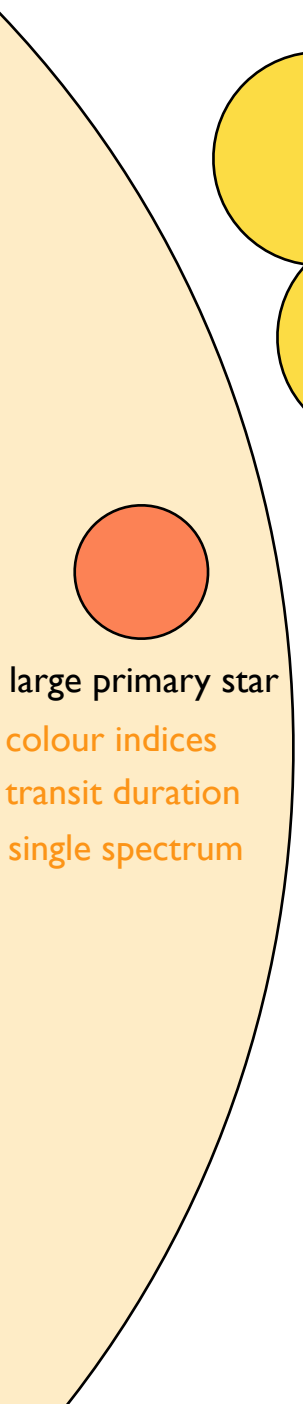


blended eclipsing binary
(triple system or chance alignment)

high spatial resolution lightcurve
can mimic planet's RV
line bissector analysis



# Transit mimics

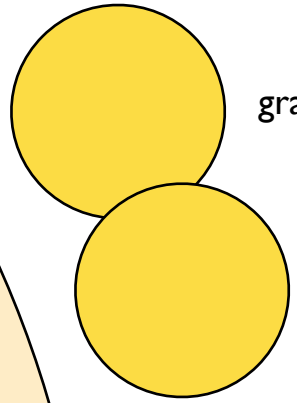


large primary star

colour indices

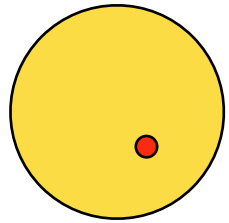
transit duration

single spectrum



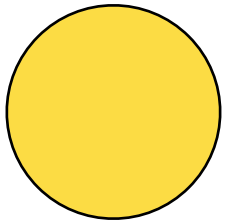
grazing eclipsing binary

close inspection of light curve
SB2 spectrum
pair of RV measurements



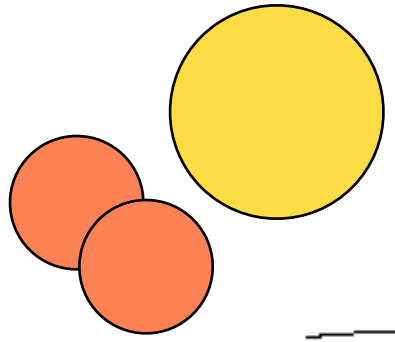
small secondary star

pair of RV measurements



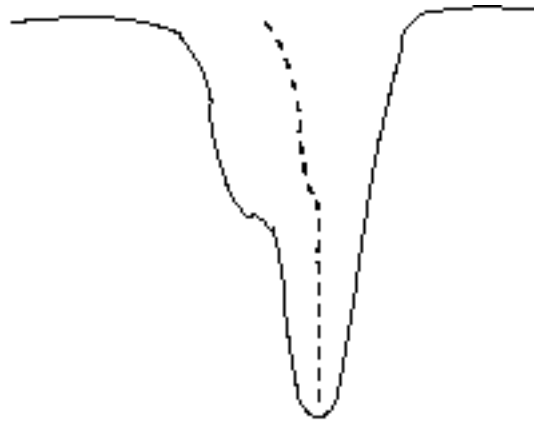
nothing (false detection)

expensive!



blended eclipsing binary
(triple system or chance alignment)

high spatial resolution lightcurve
can mimic planet's RV
line bissector analysis



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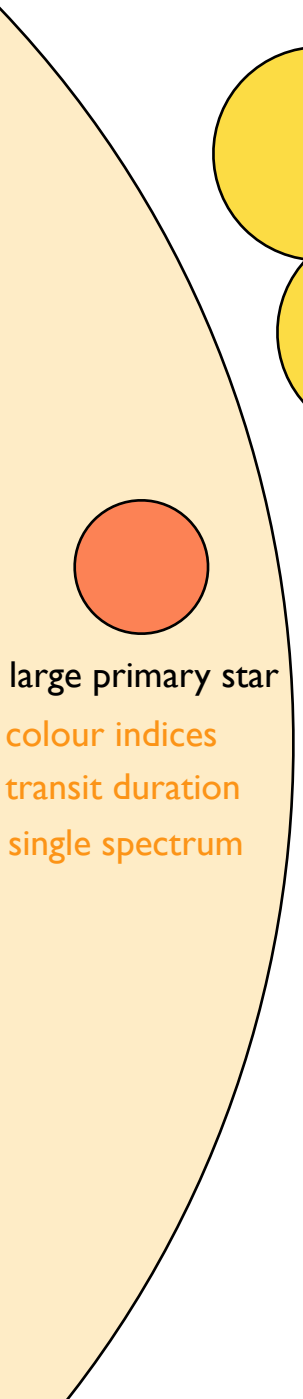
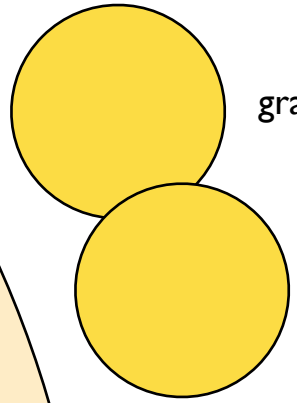


large primary star

colour indices

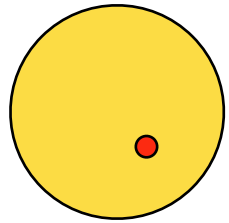
transit duration

single spectrum



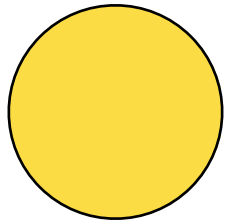
grazing eclipsing binary

close inspection of light curve
SB2 spectrum
pair of RV measurements



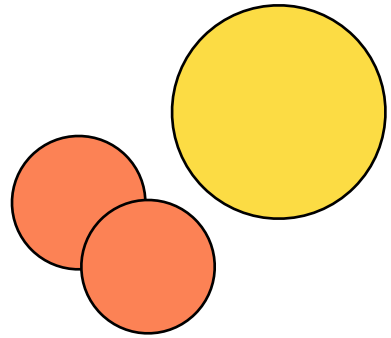
small secondary star

pair of RV measurements



nothing (false detection)

expensive!



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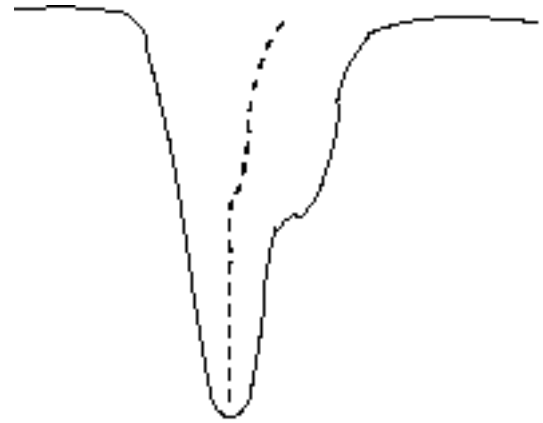
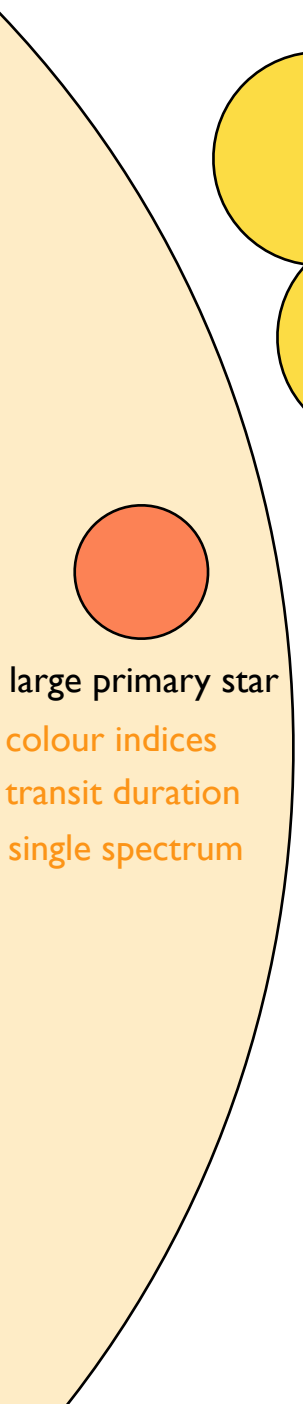


# Transit mimics

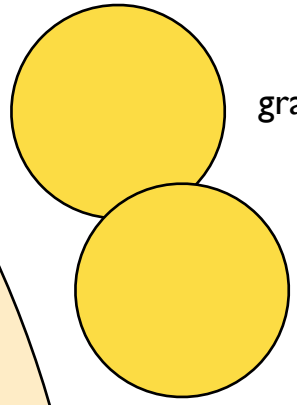


large primary star

colour indices

transit duration

single spectrum



grazing eclipsing binary

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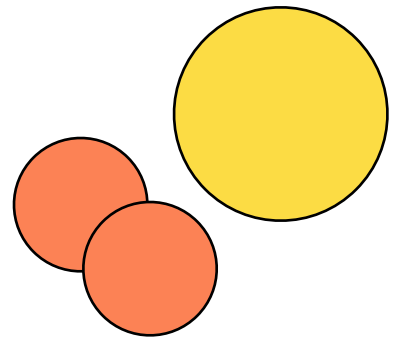

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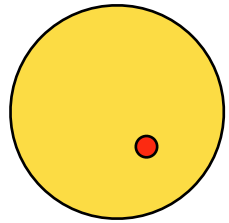
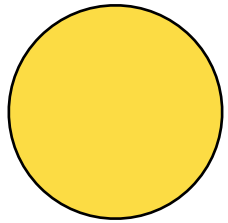


small secondary star

pair of RV measurements



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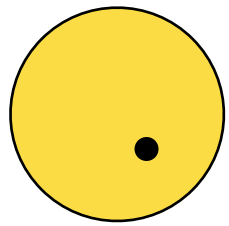
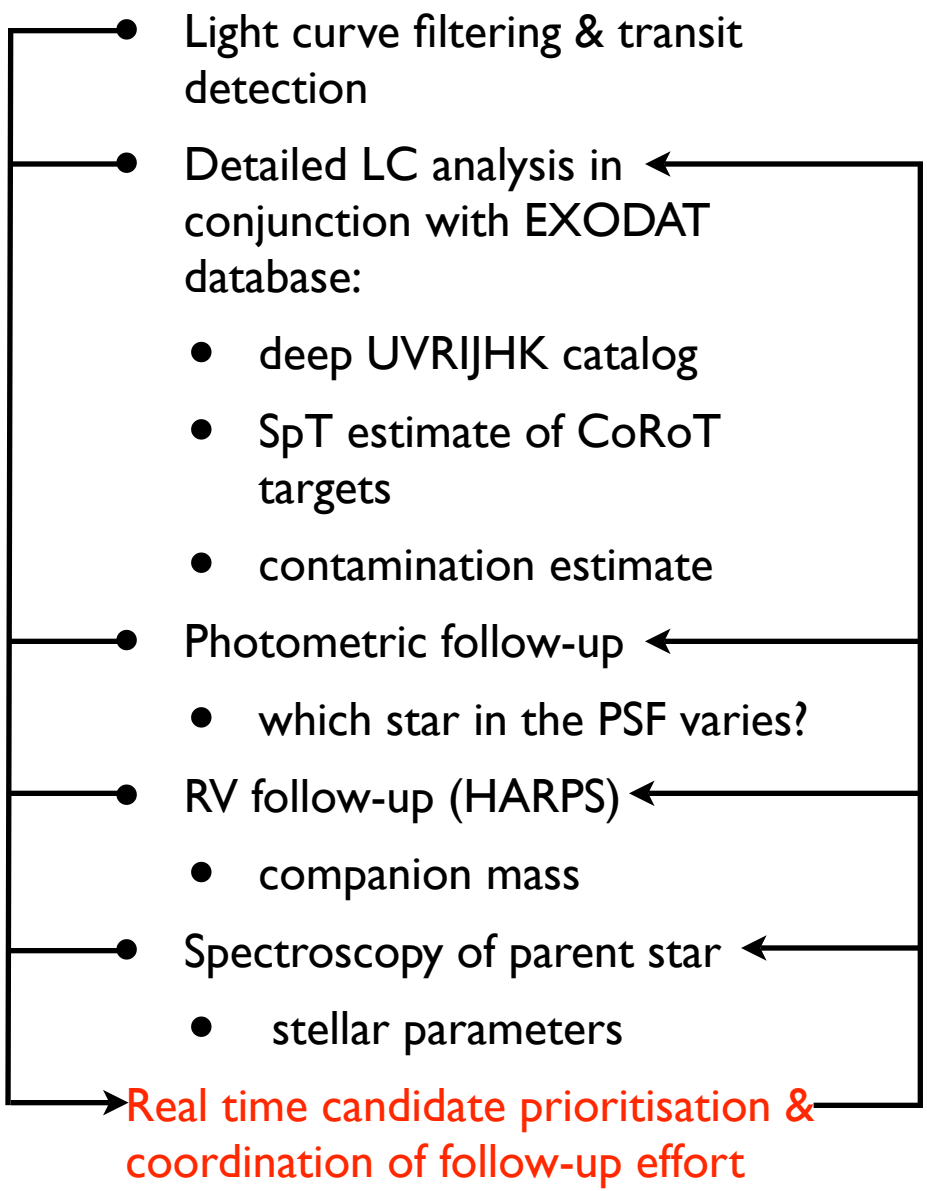
expensive!



star + planet

high precision repeat RV

# Follow-up

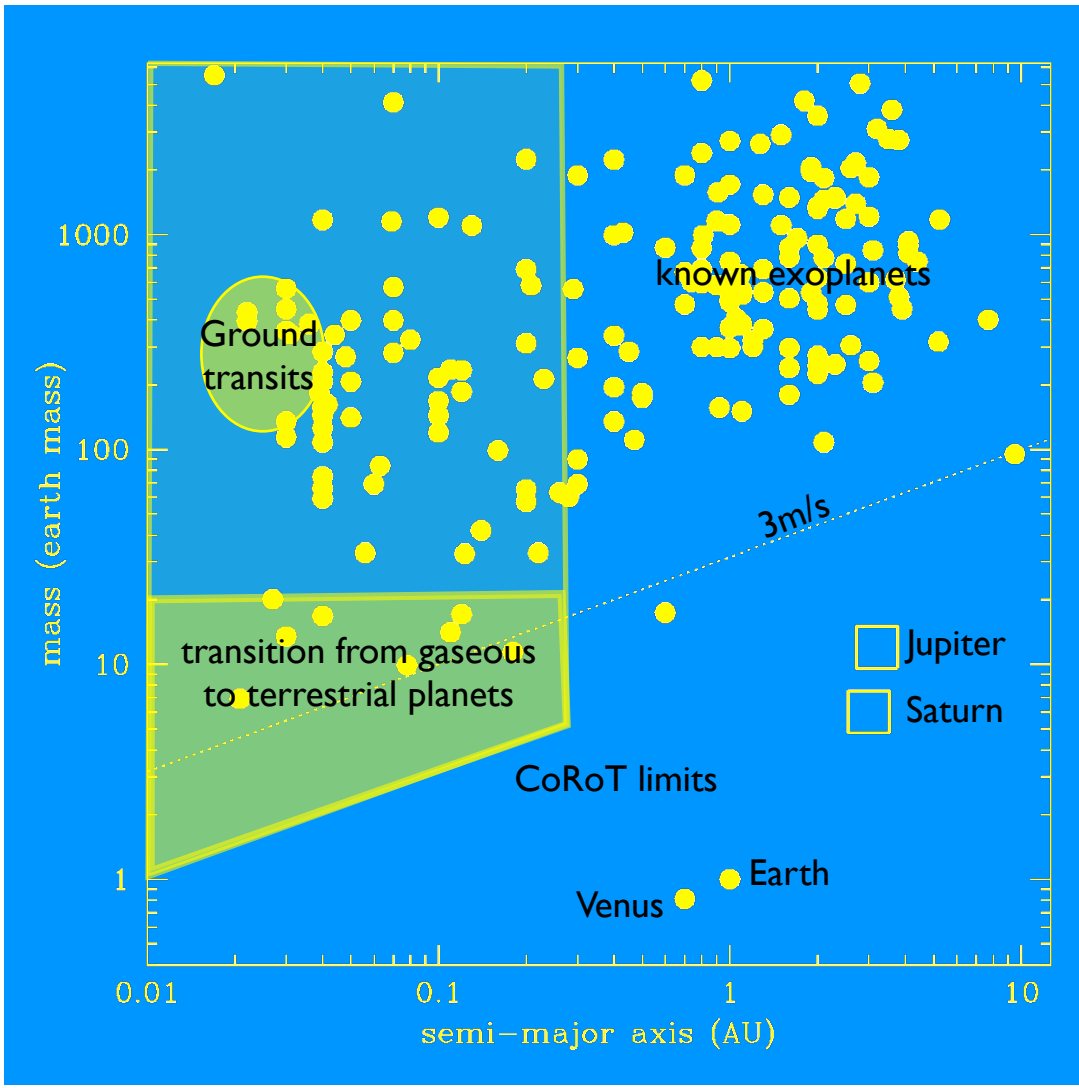

Light curve filtering & transit detection
Detailed LC analysis in conjunction with EXODAT database:
deep UVRIJHK catalog
SpT estimate of CoRoT targets
contamination estimate
Photometric follow-up
which star in the PSF varies?
RV follow-up (HARPS)
companion mass
Spectroscopy of parent star
stellar parameters
Real time candidate prioritisation & coordination of follow-up effort

# Follow-up

- Light curve filtering & transit detection
- Detailed LC analysis in conjunction with EXODAT database:
  - deep UVRIJHK catalog
  - SpT estimate of CoRoT targets
  - contamination estimate
- Photometric follow-up
  - which star in the PSF varies?
- RV follow-up (HARPS)
  - companion mass
- Spectroscopy of parent star
  - stellar parameters

Real time candidate prioritisation & coordination of follow-up effort

COROT is well matched to current RV facilities



# CoRoT-exo-1b

## a low density short-period planet around a G0V star

### Barge et al. (2008, A&A submitted)

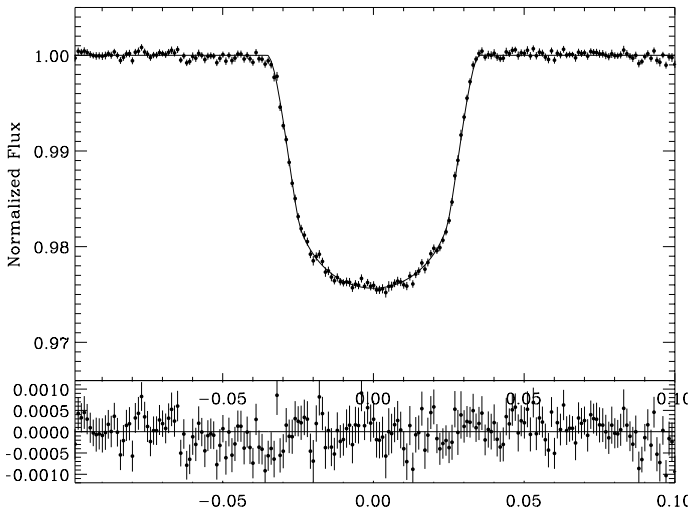



**Fig. 1.** Normalized and phase folded light curve of 36 transits of CoRoT-Exo-1b, and the residuals from the best-fit model. The bin size corresponds to 2.17$min$, and the 2$\sigma$ error bars have been estimated from the dispersion of the data points inside each bin.

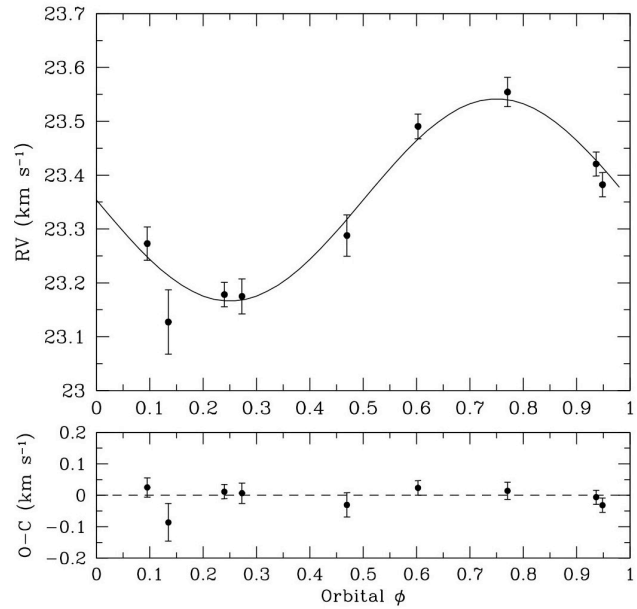



**Fig. 2.** Radial-velocity variations of CoRoT-Exo-1b versus phase from CoRoT's ephemeris. Top: the data fitted with a Keplerian circular orbit of semi-amplitude K=188 m s$^{-1}$ and a drift of 1.02 m s$^{-1}$ per day; bottom: the O-C residuals to the fit

# CoRoT-exo-1b

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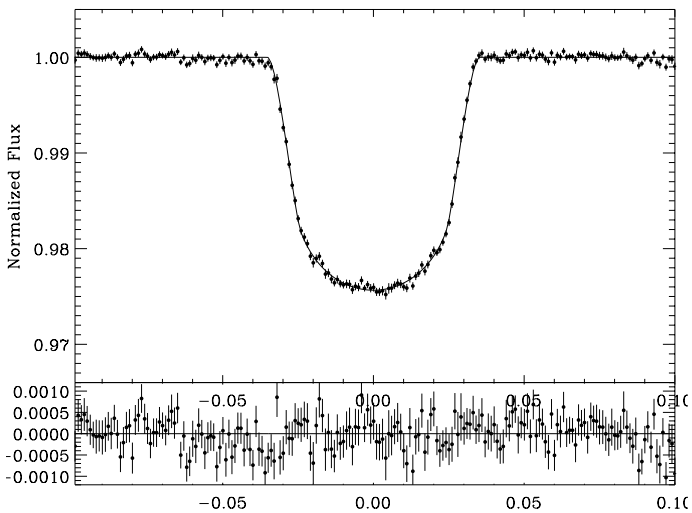


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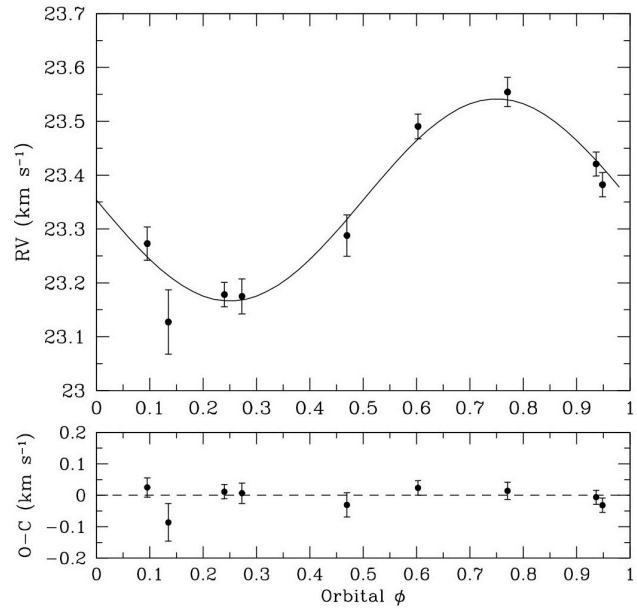


**Fig. 2.** Radial-velocity variations of CoRoT-Exo-1b versus phase from CoRoT's ephemeris. Top: the data fitted with a Keplerian circular orbit of semi-amplitude K=188 m s$^{-1}$ and a drift of 1.02 m s$^{-1}$ per day; bottom: the O-C residuals to the fit

| | |
|---|---|
| Orbital period (d) | 1.5089557 (± 0.0000064) |
| Transit center (d) | 2454159.4532 (± 0.0001) - HJD |
| $V_0$ (km/s) | 23.354 ±0.008 |
| K (m/s) | 188 ±11 |
| $M_\star$: star mass ($M_\odot$) | 0.9 (±0.1) |
| $R_\star$: star radius ($R_\odot$) | 1.09 (±0.04) |
| $M_P$: planet mass ($M_{\rm Jup}$) | 0.99 (±0.09) |
| $R_P$: planet radius ($R_{\rm Jup}$ ) | 1.47 (±0.06) |
| Planet mean density (g.cm$^{-3}$) | 0.35 (±0.06) |

# CoRoT-exo-2b

## a low transiting plant around a and active G star

Alonso et al., Bouchy et al (2008, A&A submitted)

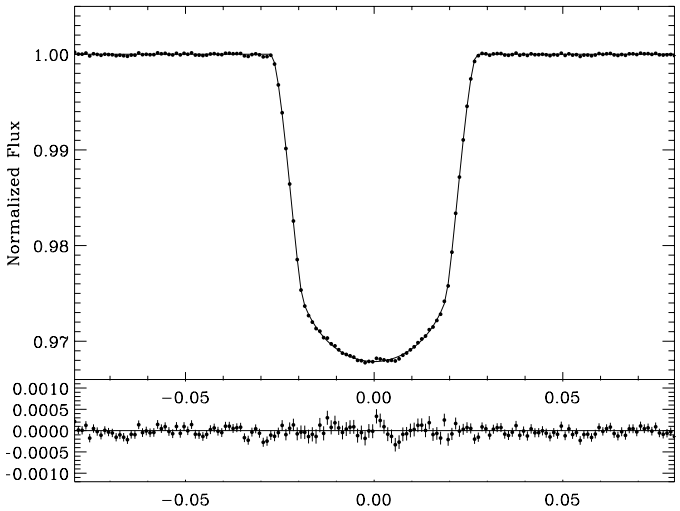


**Fig. 2.** Normalized and phase folded light curve of 78 transits of CoRoT-Exo-2b (top), and the residuals from the best-fit model (bottom). The bin size corresponds to 2.5 min, and the 1-sigma error bars have been estimated from the dispersion of the points inside each bin. The residuals of the in-transit points are larger due to the effect of succesive planet occultations of stellar active regions.

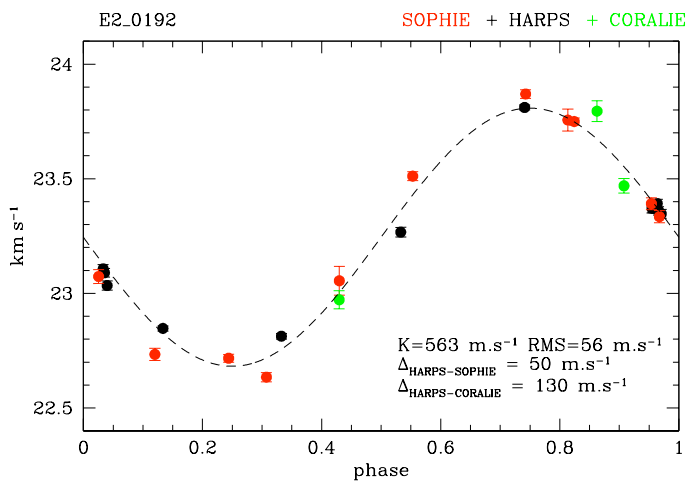


**Fig. 3.** Phase folded radial velocity measurements of CoRoT-Exo-2, together with the final fitted semi-amplitude ($K$) and the applied offsets between the instruments. Red points: SOPHIE, black points: HARPS, green points: CORALIE.

# CoRoT-exo-2b

## a low transiting plant around a and active G star

### Alonso et al., Bouchy et al (2008, A&A submitted)

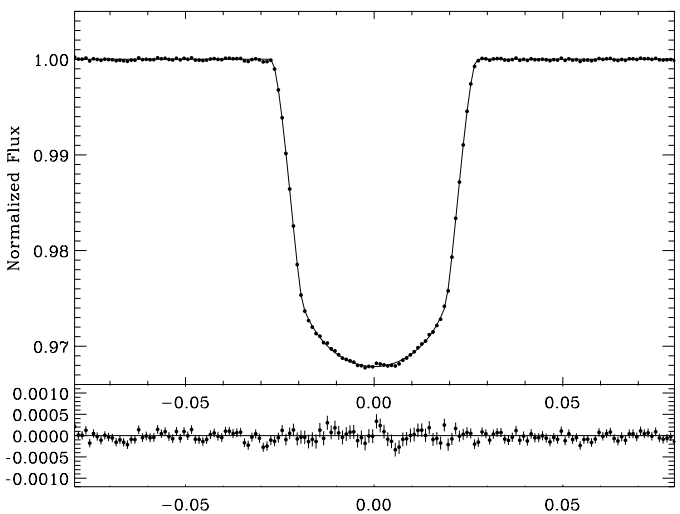


**Fig. 2.** Normalized and phase folded light curve of 78 transits of CoRoT-Exo-2b (top), and the residuals from the best-fit model (bottom). The bin size corresponds to 2.5 min, and the 1-sigma error bars have been estimated from the dispersion of the points inside each bin. The residuals of the in-transit points are larger due to the effect of succesive planet occultations of stellar active regions.

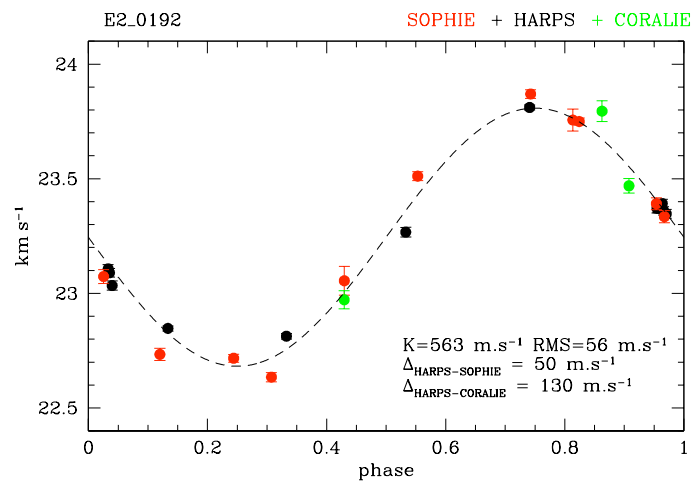


**Fig. 3.** Phase folded radial velocity measurements of CoRoT-Exo-2, together with the final fitted semi-amplitude ($K$) and the applied offsets between the instruments. Red points: SOPHIE, black points: HARPS, green points: CORALIE.

| | Value | Error |
|---|---|---|
| $P$ [d] | 1.7429964 | 0.0000017 |
| $T_c$ [d] | 2454237.53562 | 0.00014 |
| $V_0$ [km/s] | 23.245 | 0.010 |
| $K$ [km/s] | 0.563 | 0.014 |
| $e$ | 0 | (fixed) |
| $M_s$ [$M_\odot$] | 0.97 | 0.06 |
| $R_s$ [$R_\odot$] | 0.902 | 0.018 |
| $M_p$ [$M_{\rm Jup}$] | 3.31 | 0.16 |
| $R_p$ [$R_{\rm Jup}$] | 1.465 | 0.029 |
| $\rho_p$ [g/cm$^3$] | 1.31 | 0.04 |

# CoRoT-exo-2b

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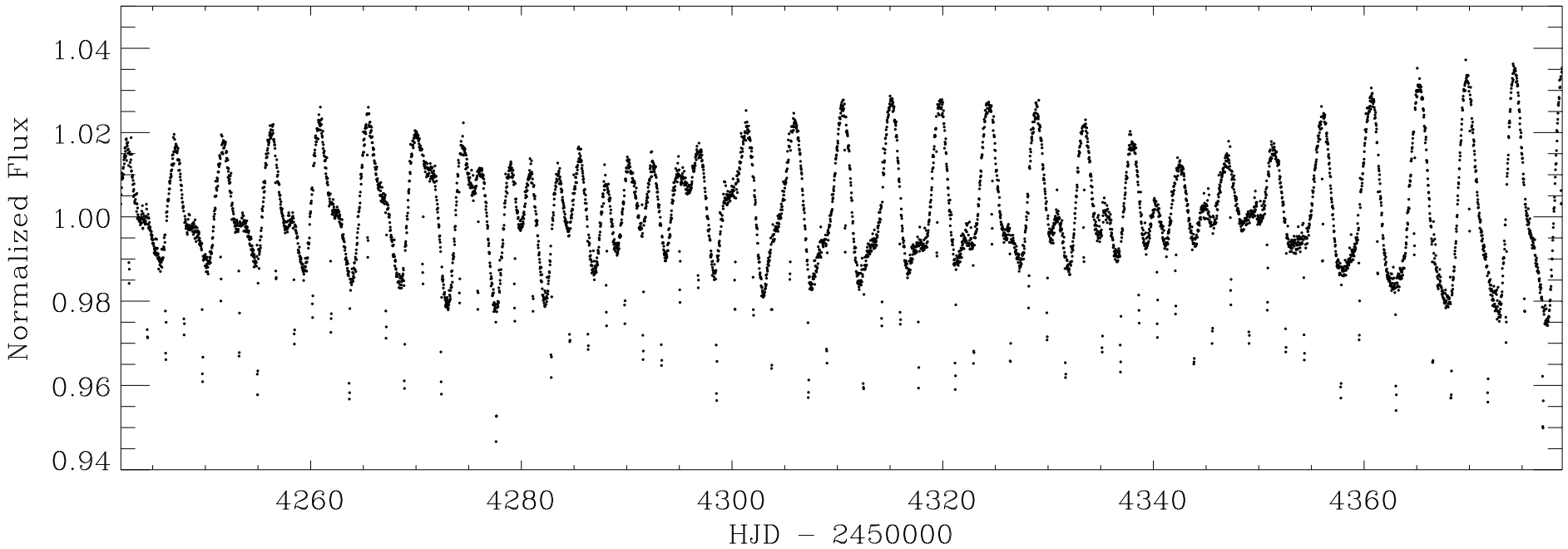


**Fig. 1.** Normalized flux of the CoRoT-Exo-2 star, showing a low frequency modulation due to the presence of spots on the stellar surface, and the 78 transits used to build the phase-folded transit of the Figure 2. For clarity purposes, data have been combined in 64-points bins.

# CoRoT-exo-2b

## a low transiting planet around a and active G star

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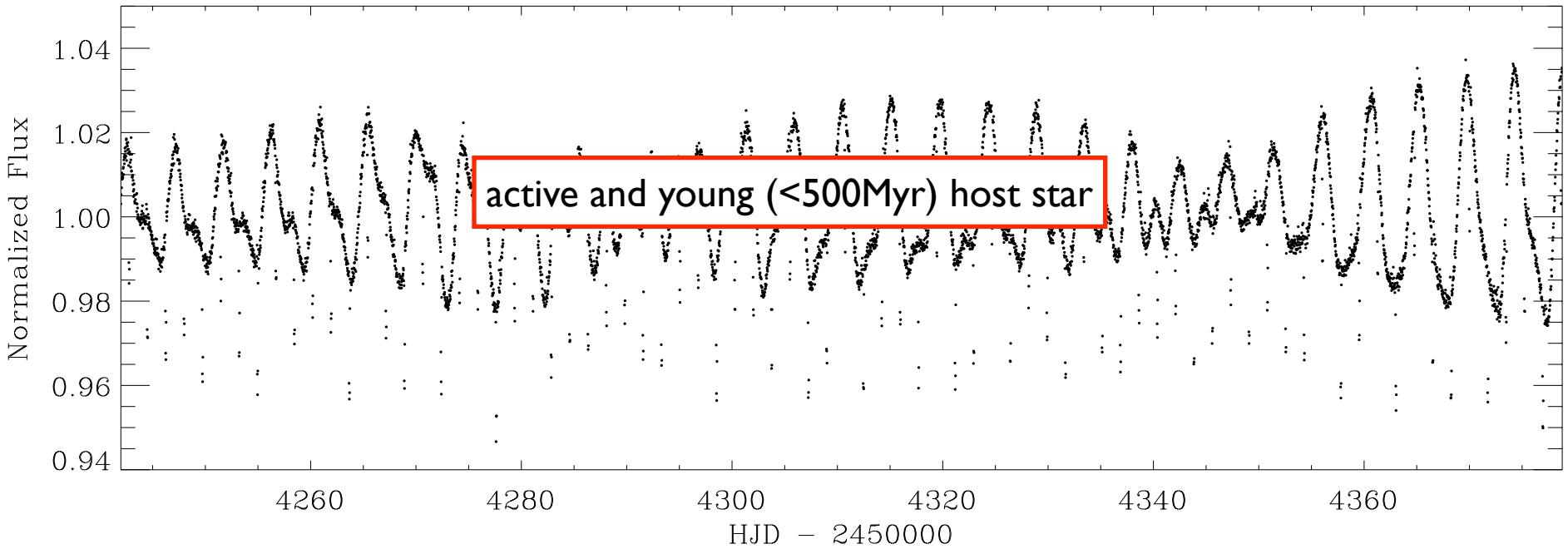


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# CoRoT-exo-2b

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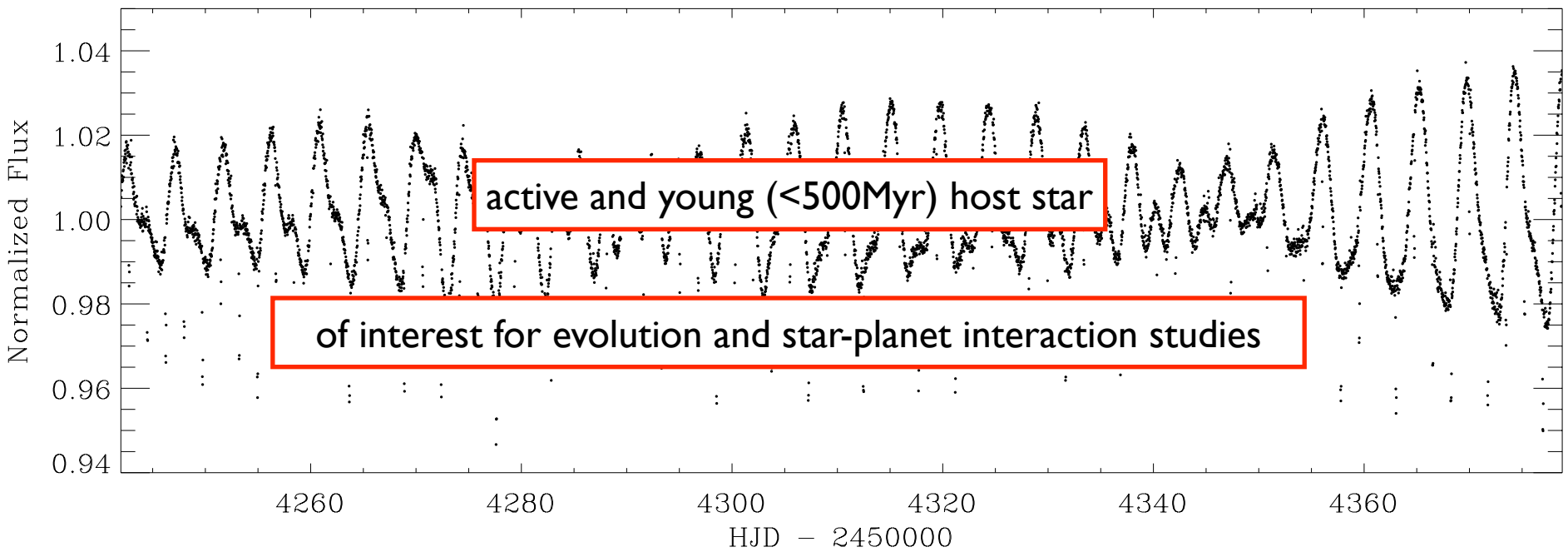


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# CoRoT-exo-2b

## spectroscopic transit with SOPHIE & HARPS

Bouchy et al. (2008, A&A submitted)

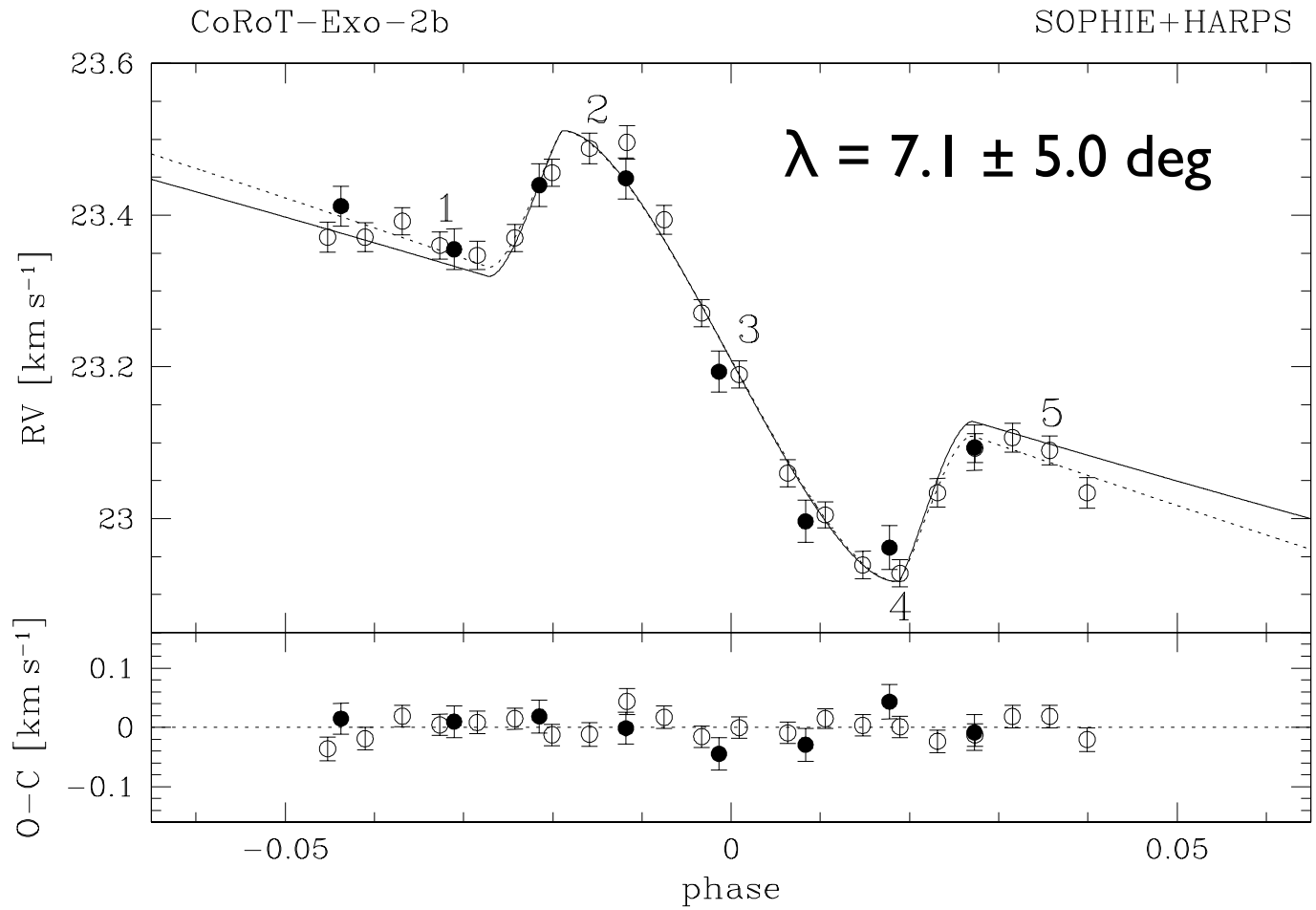
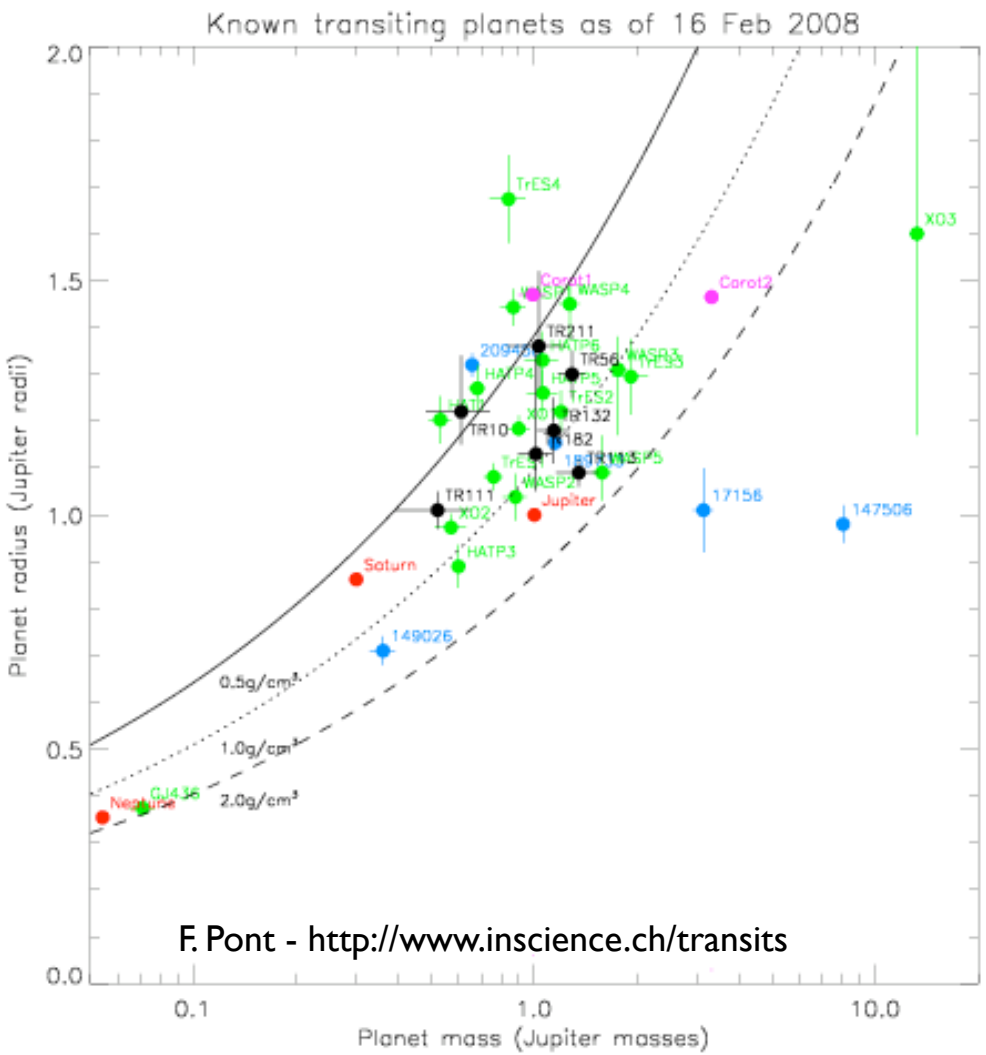
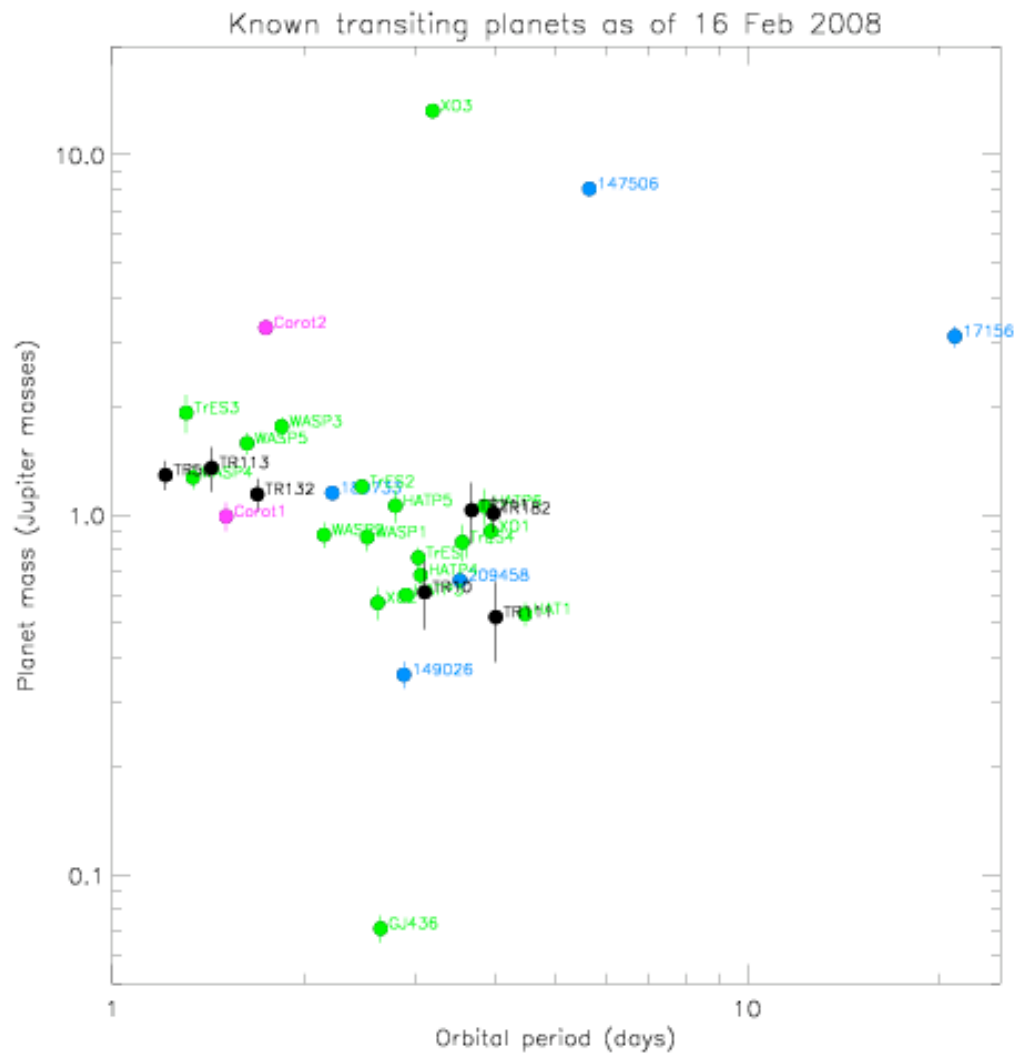



**Fig. 1.** Phase-folded radial velocity measurements of CoRoT-Exo-2 during the transit of the planet with SOPHIE (dark circle) and HARPS (open circle). The solid line corresponds to the Rossiter-McLaughlin model ajusted to these data assuming the semi-amplitude $K$=563 m s$^{-1}$ from Alonso et al. (2008). The dotted line corresponds to the Rossiter-McLaughlin model with $K$ as free parameters.

# Mass-radius-period relations



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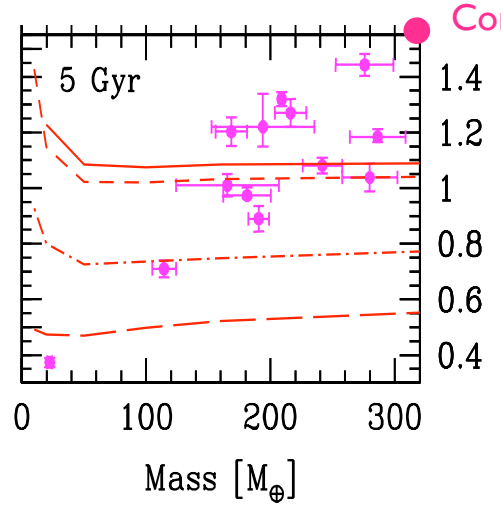


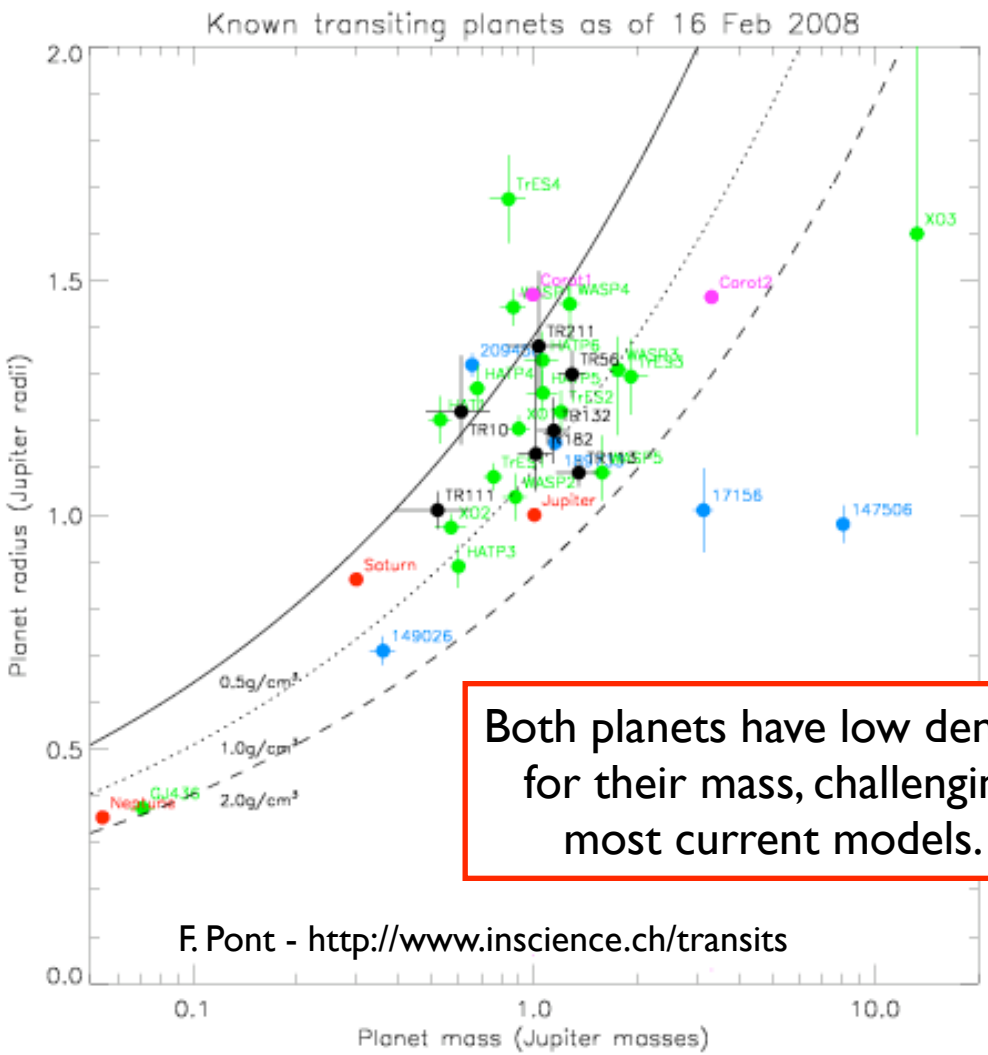


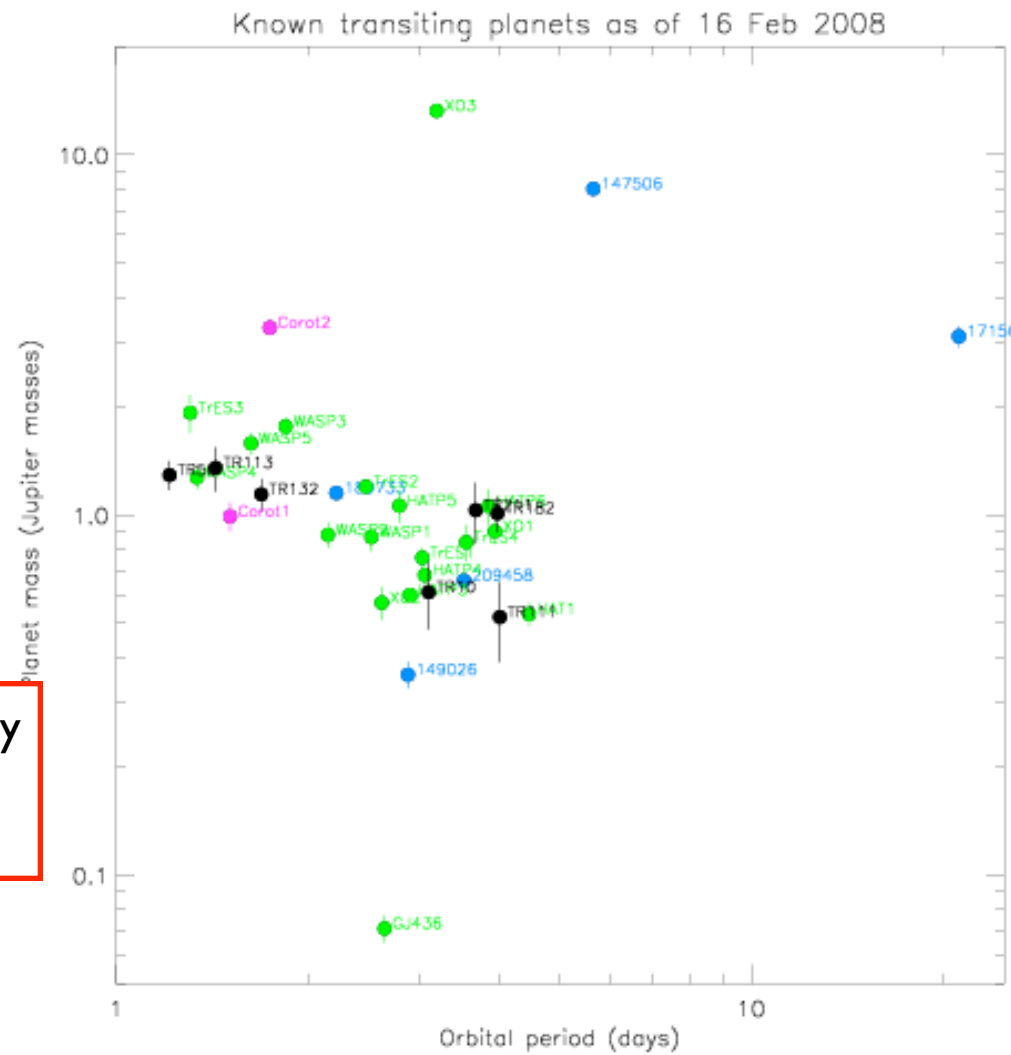


Both planets have low density for their mass, challenging most current models.

F. Pont - http://www.inscience.ch/transits

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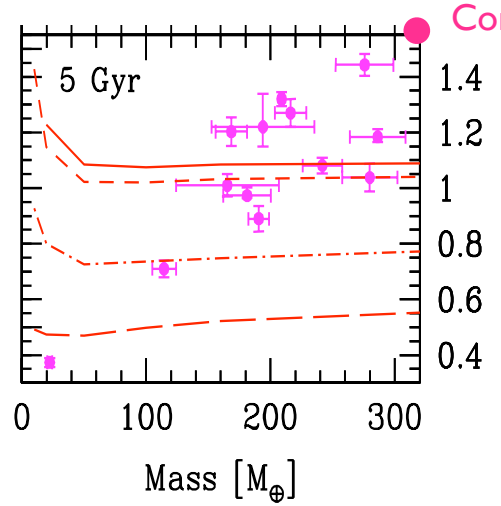


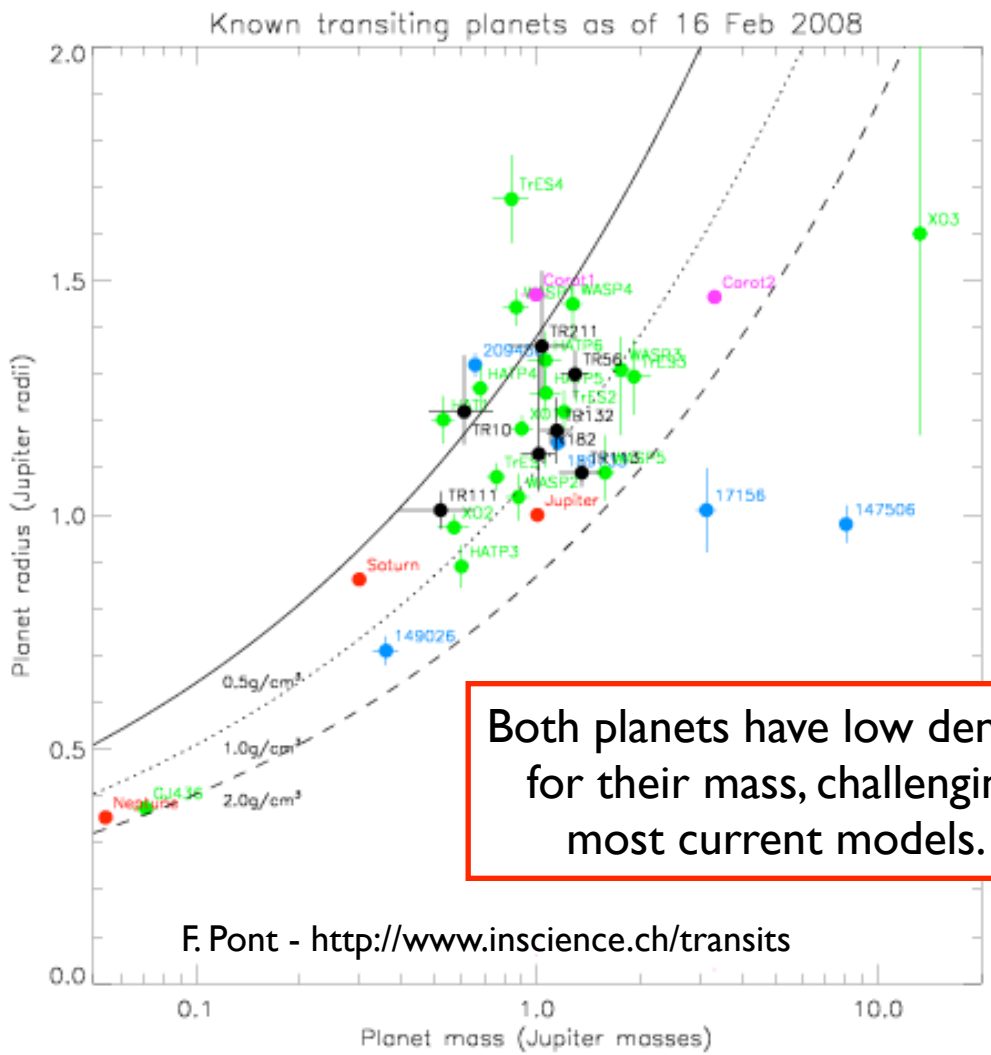


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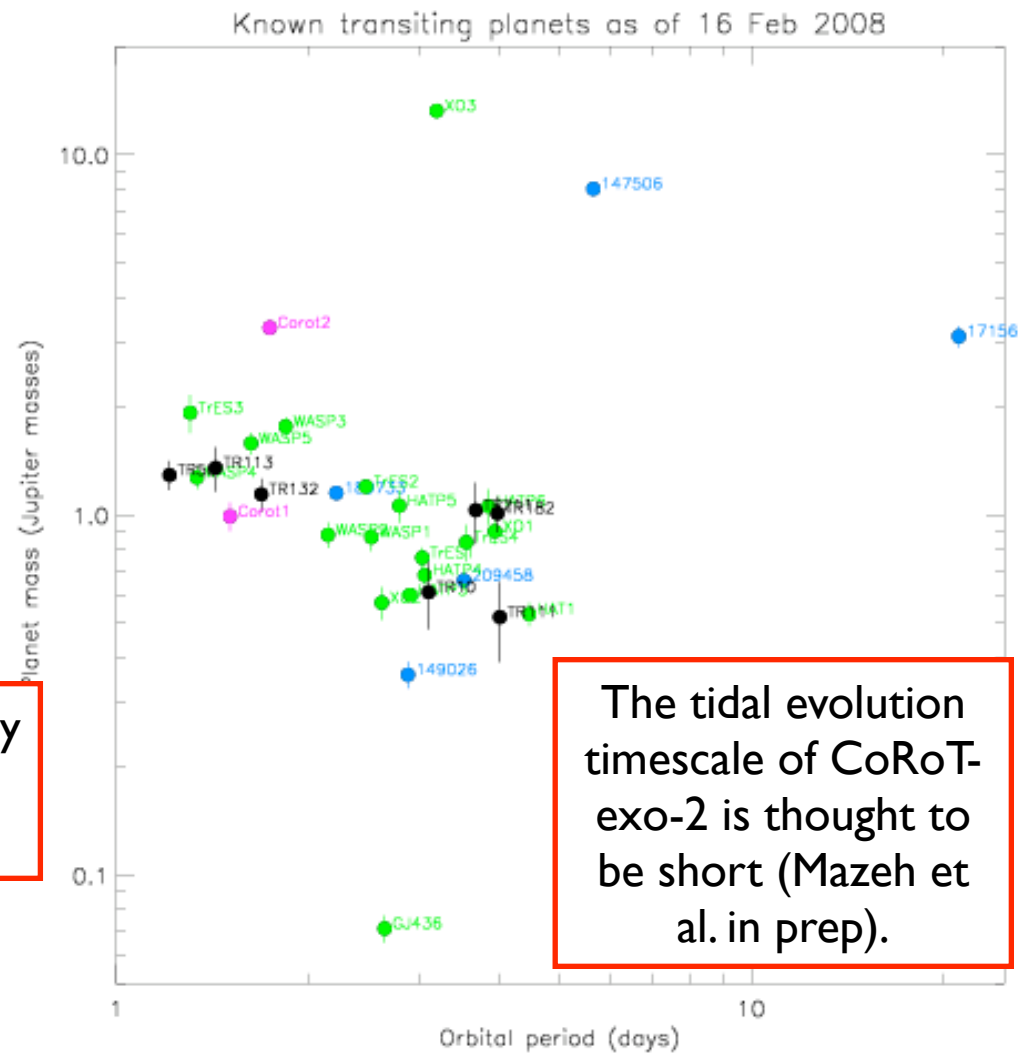


The tidal evolution timescale of CoRoT-exo-2 is thought to be short (Mazeh et al. in prep).