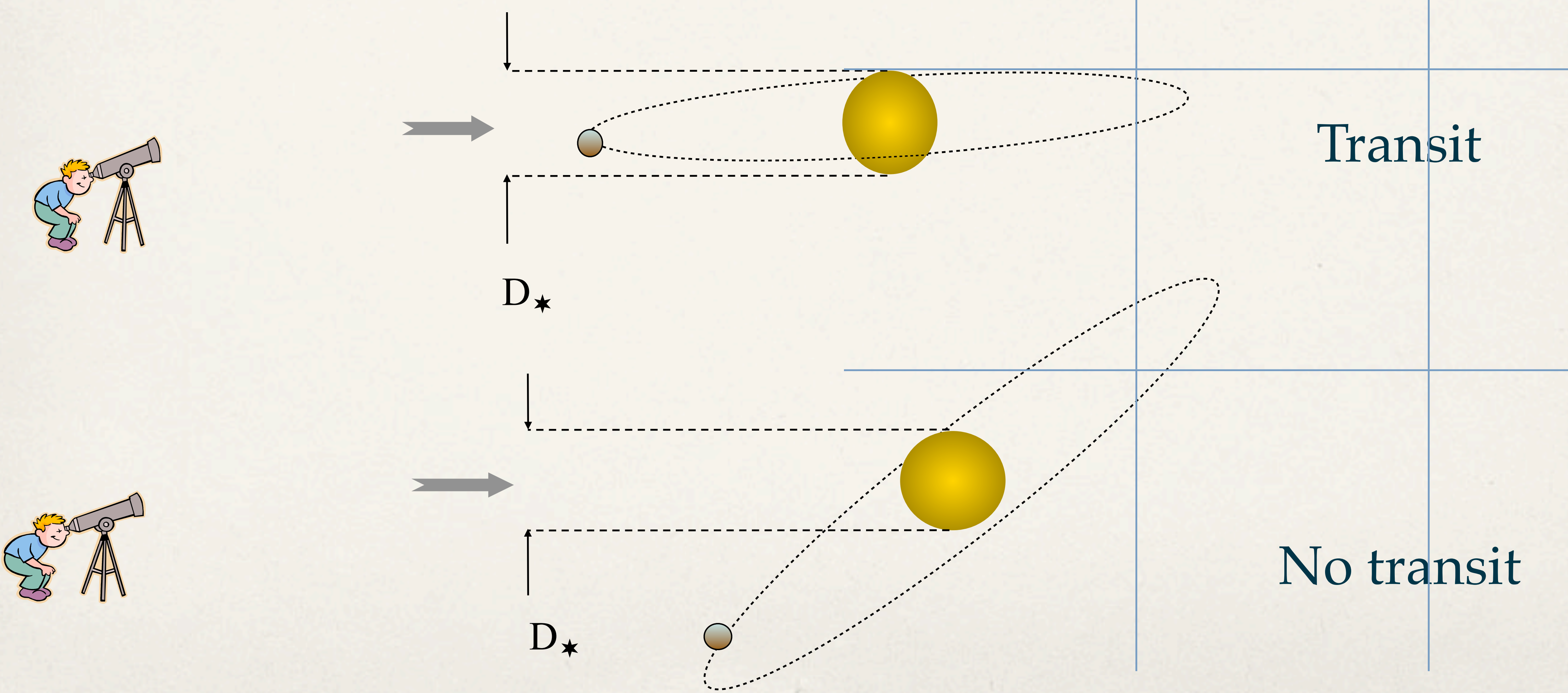
What is to expect from the transit method

M. Deleuil, Laboratoire d'Astrophysique de Marseille
Institut Universitaire de France

Transit - method

- Occurrence: only if the planet orbital plane is close to the observer's line of sight. The planet must cross over the diameter of the star as we watch it.



Transit - occurrence

- Probability of transit occurrence

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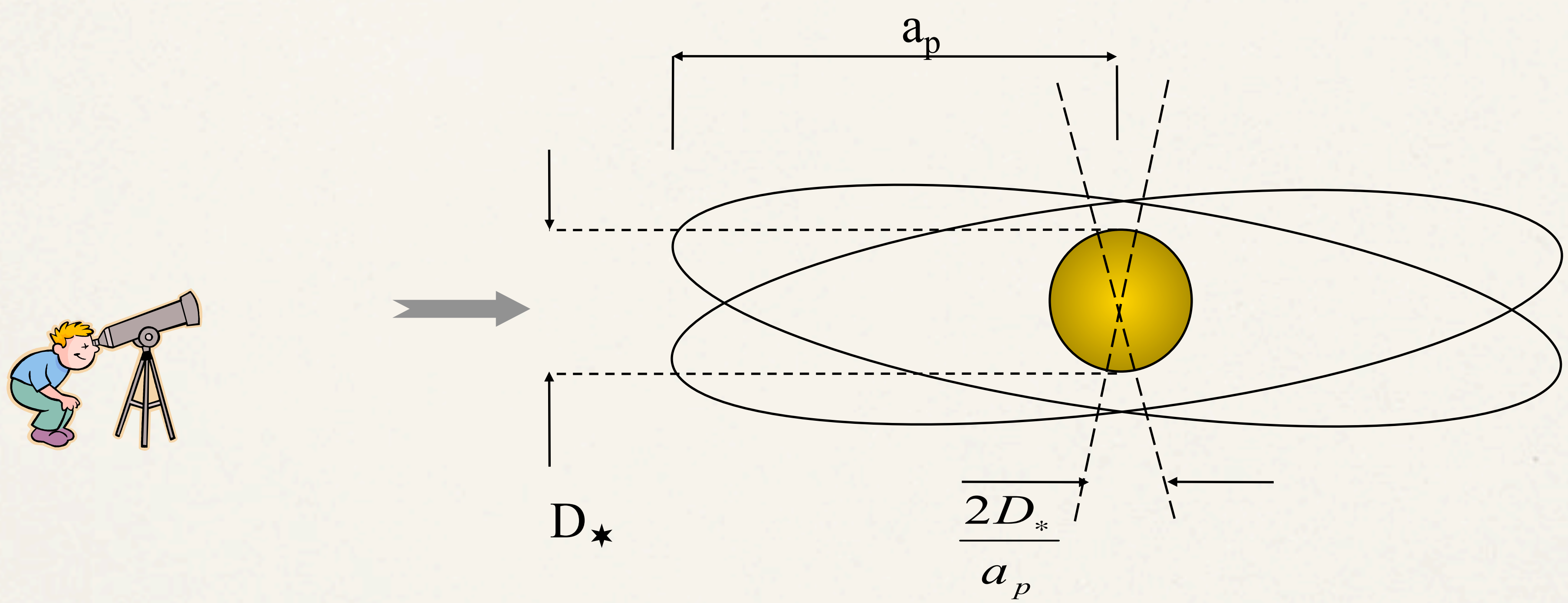

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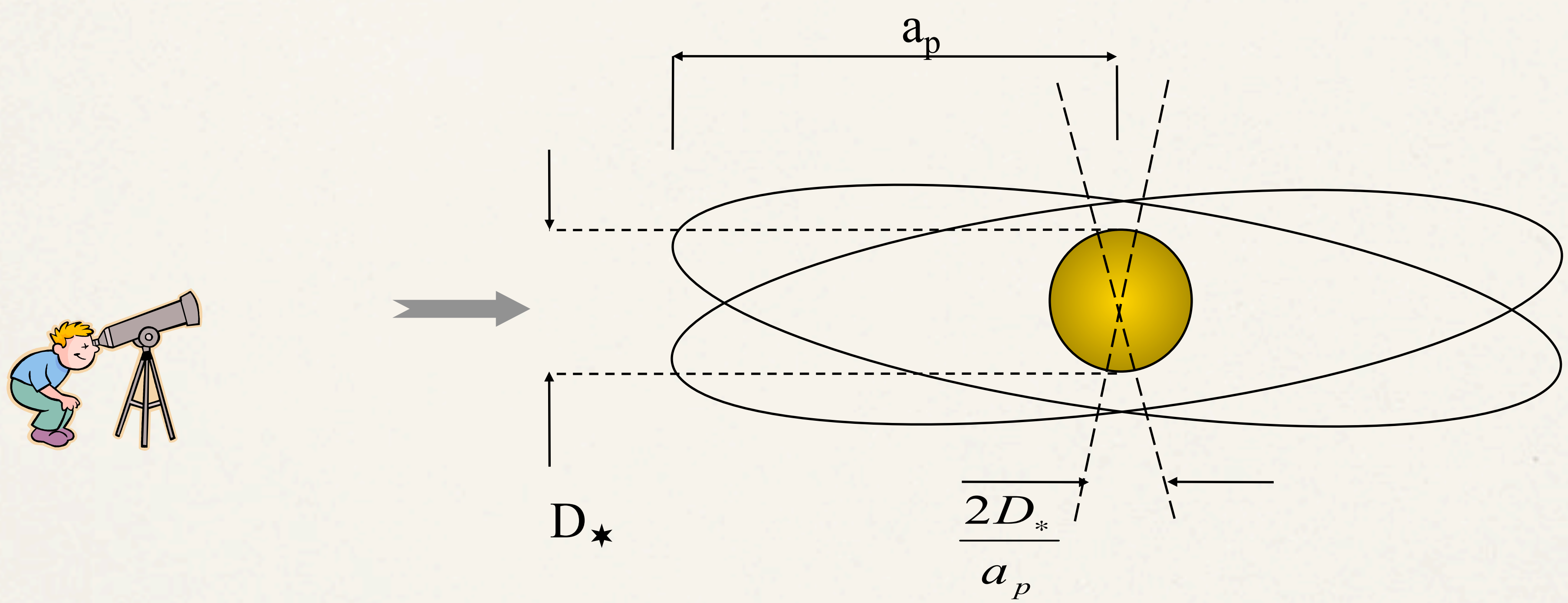
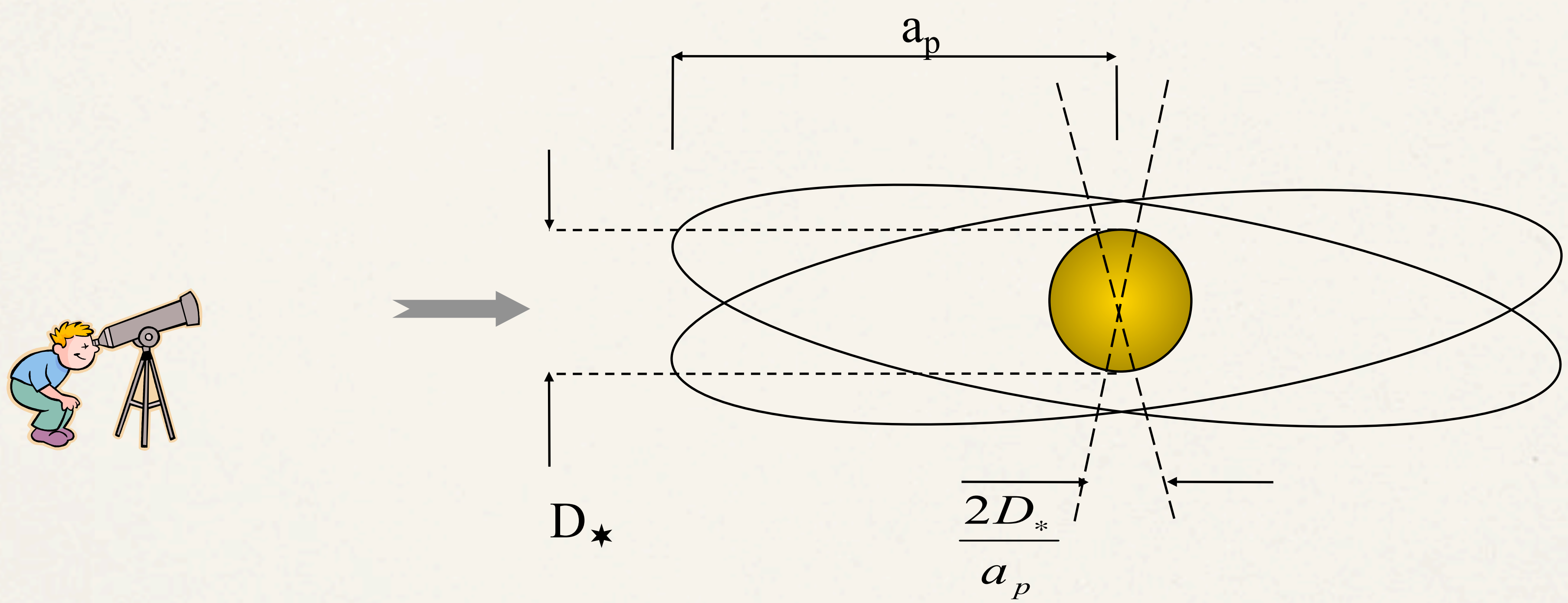


Range of solid angles under which a transit can be observed : $\frac{4\pi D_*}{a}$

Transit - occurrence

- Probability of transit occurrence

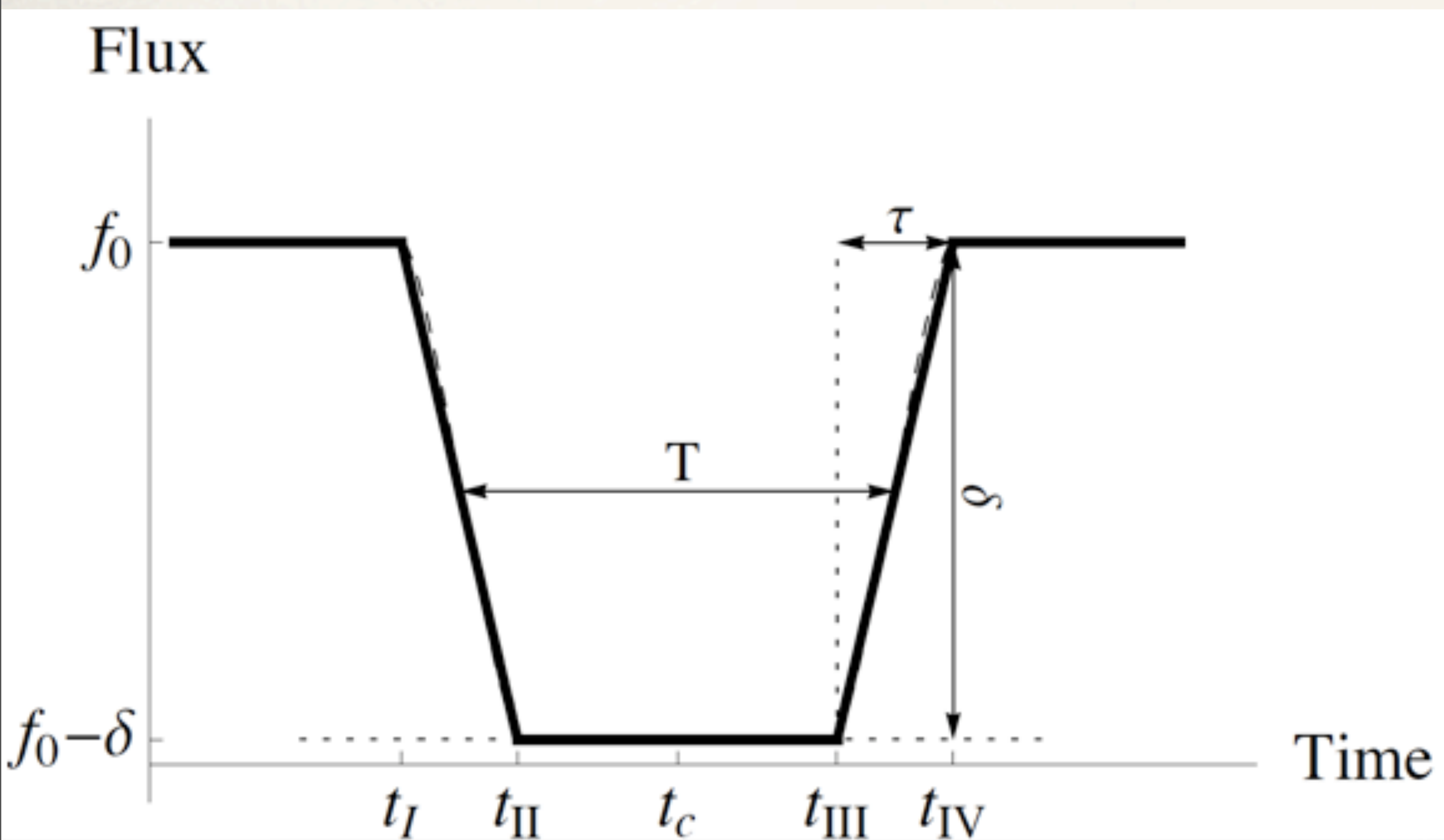


Range of solid angles under which a transit can be observed : $\frac{4\pi D_*}{a}$

Transit probability (geometric): $\mathrm{Pr} = \frac{R_*}{a_P}$

Transit -observables

Geometry is described by the transit depth, shape and duration



F_0 : out-of transit flux

t_c : mid transit time

$\delta = (F_0 - F_{transit}) / F_0$

flux of the photometric decrement during the full phase of the transit

$\Delta\tau$: duration of the ingress or egress

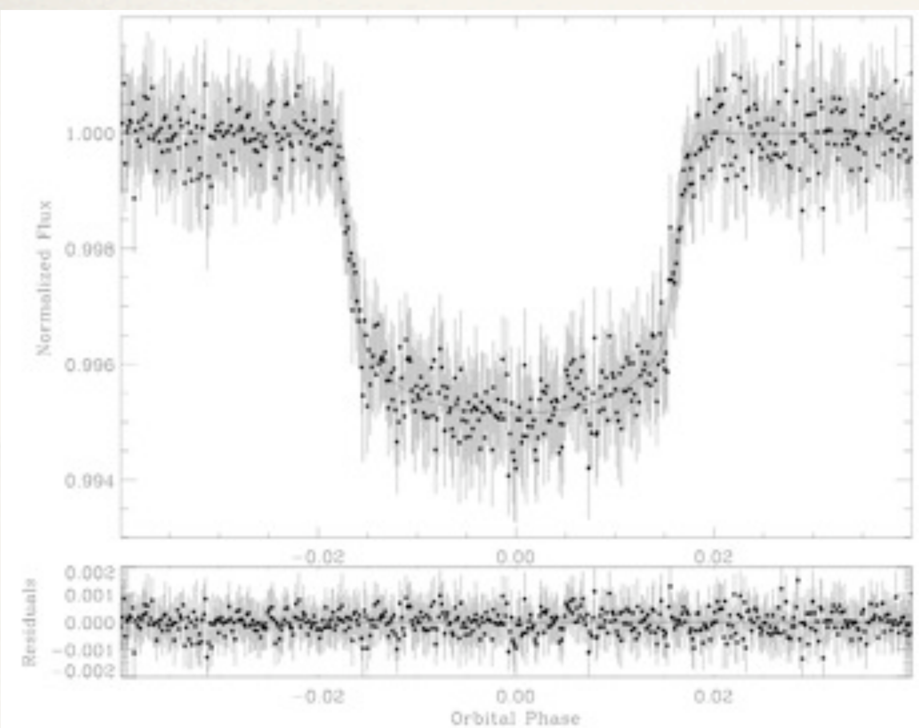
ΔT : total duration (between the mid point)

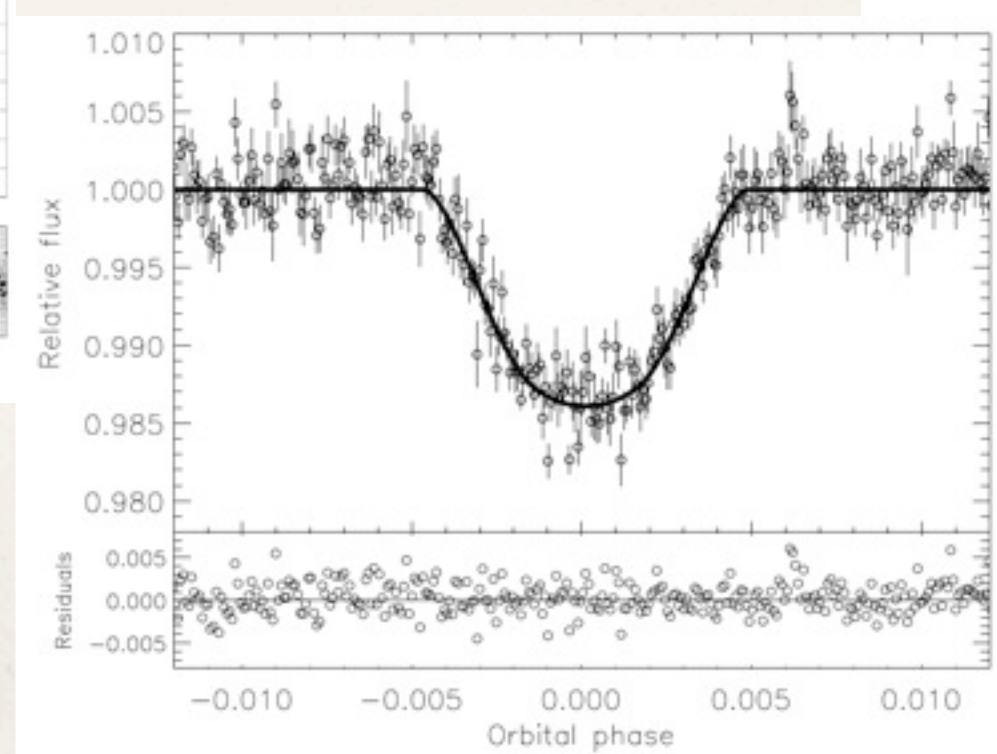
P : the period

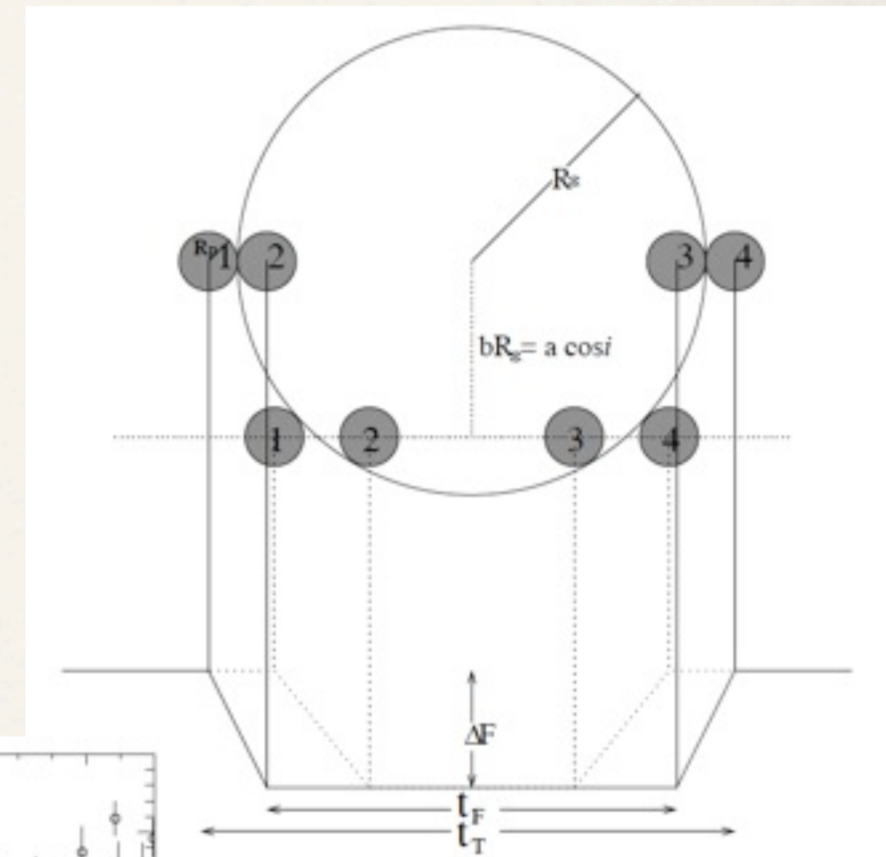
Transit - observables

The shape changes depending on the geometry of the star and the planet

➢ shorter duration for large impact parameter & V-shape







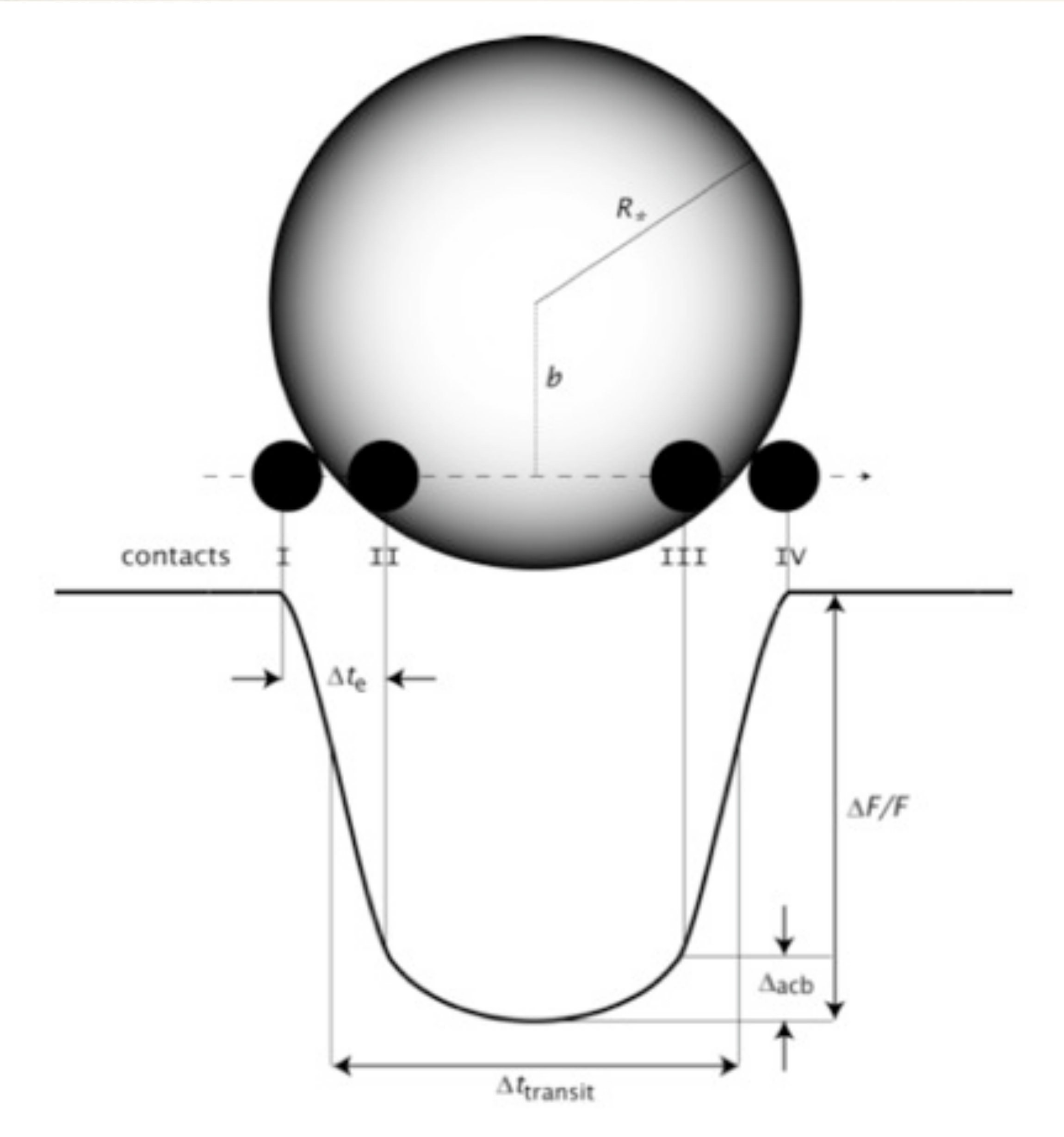
Transit -Physical parameters

Assuming :

- a circular orbit
- the planet is dark
- a single star
- the stellar mass-radius relation is known
- the transits have a flat bottoms
- the orbital period is known
  (2 transits at least)

Transit -Physical parameters

Physical parameters to be derived from the observables : $M_\star$, $R_\star$, a, i, R_p



Radii ratio $$\frac{R_p}{R_*} = \sqrt{\delta} = \sqrt{\frac{\Delta F}{F_0}}$$

Impact parameter: $$b = \frac{a_p \cos(i)}{R_*} = 1 - \sqrt{\delta}\,\frac{T}{\tau}$$

Scaled stellar radius : $$\frac{R_*}{a} \approx \frac{\pi\sqrt{T\,\tau}}{\delta^{1/4}\;P}\left(\frac{1 + e\sin\omega}{\sqrt{1-e^2}}\right)$$

e orbital eccentricity ; *ω* argument of pericenter

Seager & Mallen-Ornelas, ApJ 585, 2003; Carter et al., 2008

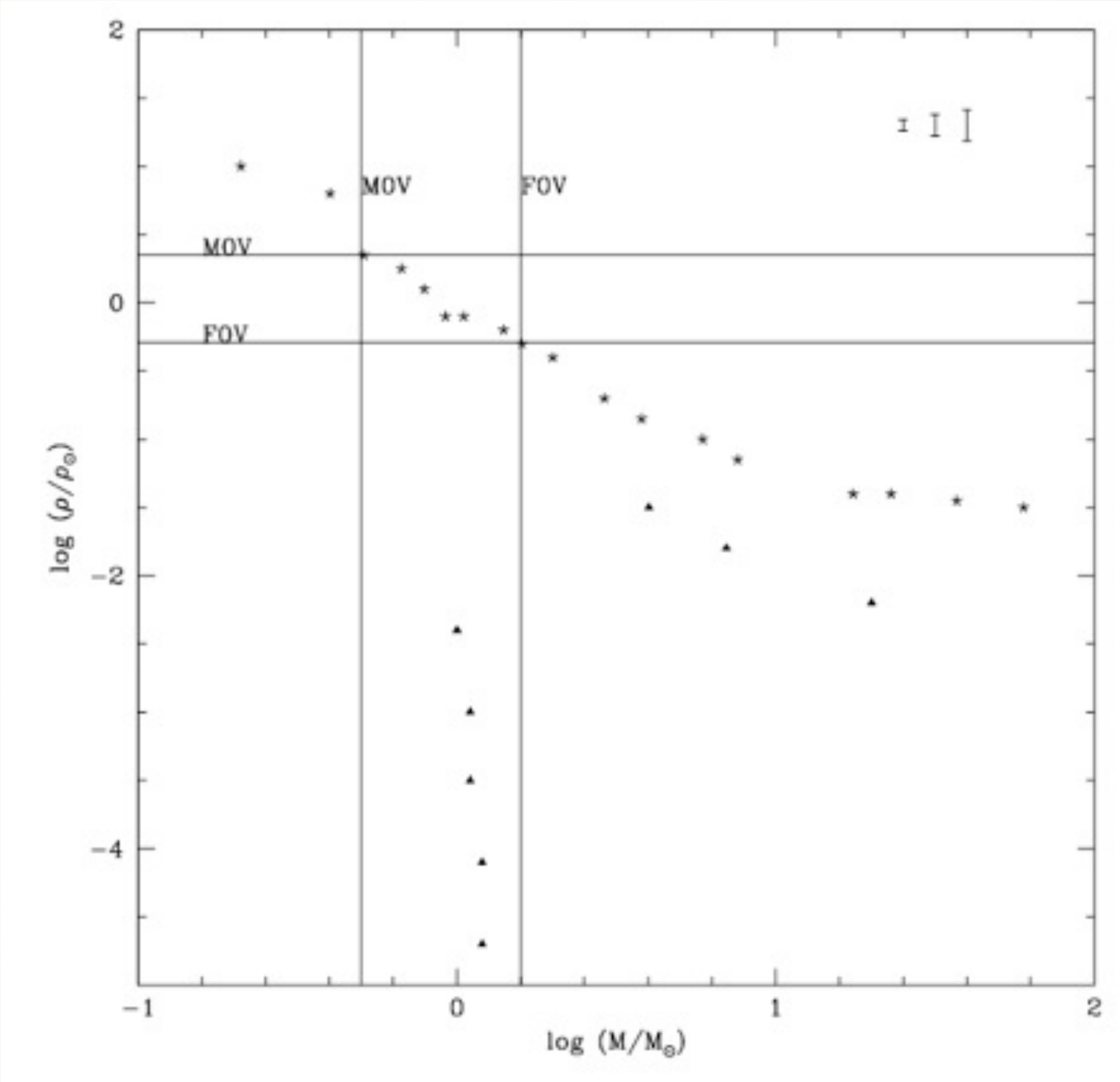
Transit -Physical parameters

Combined to Kepler's law

➙ mean stellar density

$$\rho_* \approx \frac{3P}{\pi^2 G}\left(\frac{\sqrt{\delta}}{T\tau}\right)^{3/2}\left[\frac{1-e^2}{(1+e\sin\omega)^2}\right]^{3/2}$$

➙ useful to help identifying blends and get the star's radius



▲ giant star ; ★ dwarf stars

Seager & Mallen-Ornelas, 2003 APJ 585, 1038;
Southworth et al., 2007, MNRAS 379

Transit - some numbers

Planet	ΔT (hour)	ΔF/F (%)	Pr (%)	Orbital Period (year)
Mercury	8.1	0.0012	1.19	0.241
The Earth	13	0.0084	0.47	1.0
Mars	16	0.0024	0.31	1.7
Jupiter	30	1.01	0.089	11.86

Requirements :

- to catch transits ➛ continuous observations - high duty cycle
- to detect small size planets ➛ high photometric precision
- to compete against the low geometric probability ➛ monitor a high number of targets

Transit : issues with the star

* the limb-darkening effect : the stellar disk is not uniform

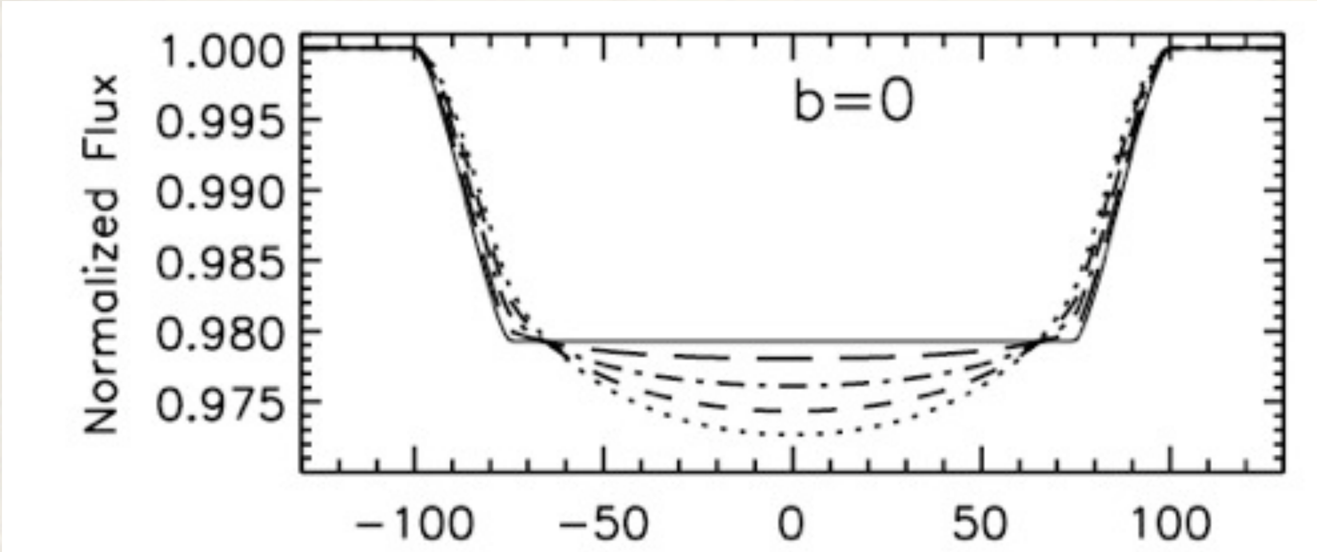
➛ affect the transit shape

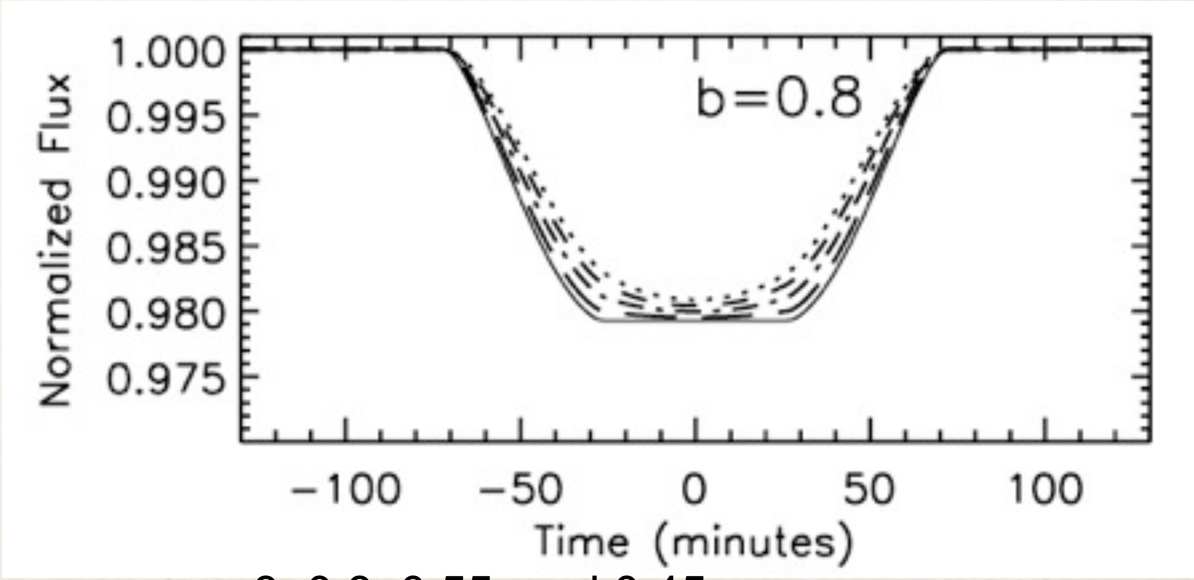
➛ depends on the star's physical parameters (Teff, logg) - color effect and on the photometric system

Narrow band-width ➛ large effects of stellar limb darkening

Smoother edges and U shape bottom ➛ large uncertainties on the transit's parameters

Smoother edges and U shape bottom





Seager & Mallen-Ornelas, ApJ 585, 2003 Pal, 2008

3, 0.8, 0.55, and 0.45μm

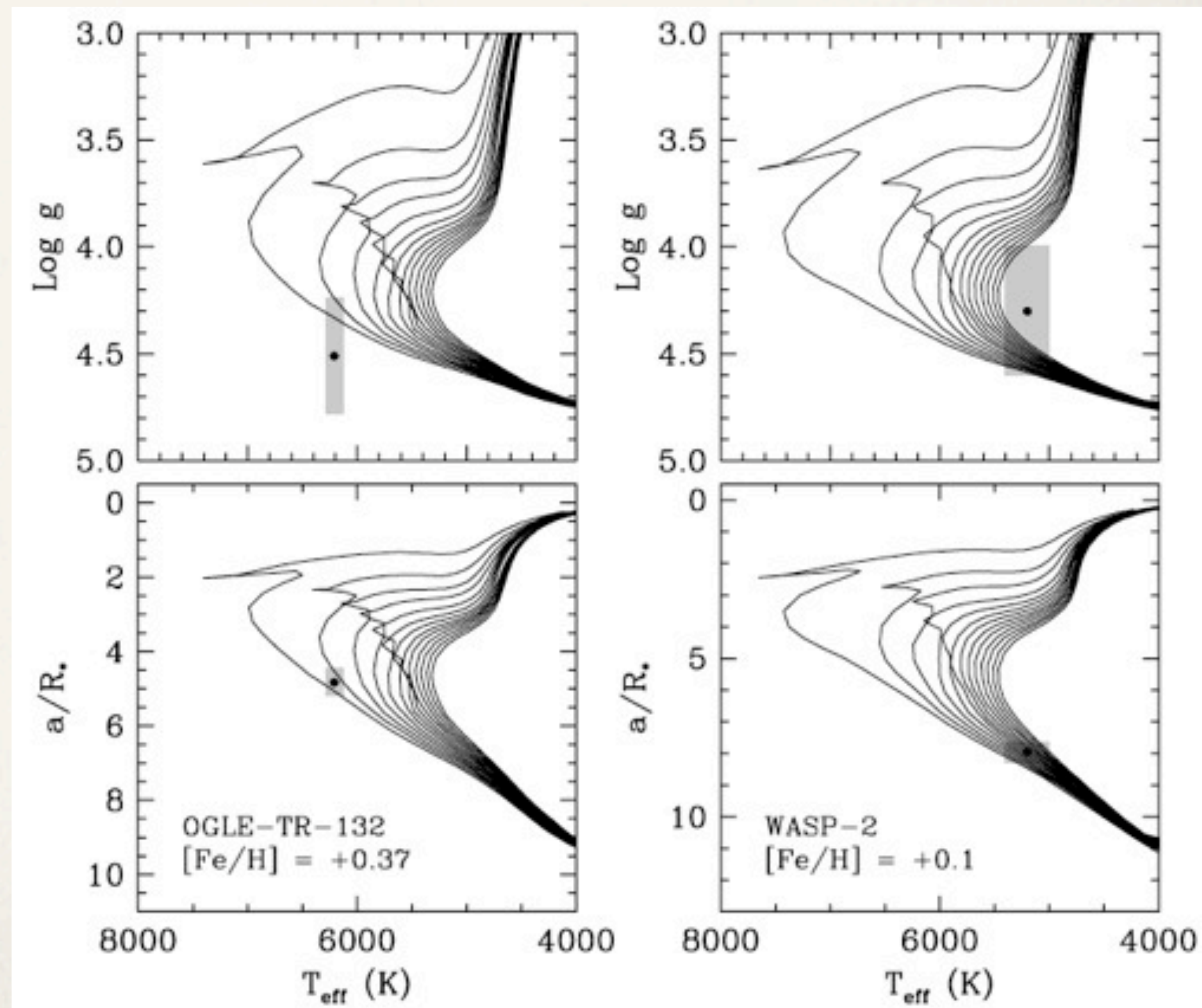
Transit : issue with the star (again!)

- the stars' fundamental parameters :

$R_\star$ but also Teff, [M/H] & age - could result in large uncertainties on the planet's parameters

$$\frac{\Delta F}{F} = \left(\frac{R_p}{R_*}\right)^2$$

$$k = \frac{28.4\ ms^{-1}}{\sqrt{1-e^2}} \frac{m_p \sin i}{M_{Jup}} \left(\frac{P}{1\ yr}\right)^{-1/3} \left(\frac{m_*}{1M_\odot}\right)^{-2/3}$$



Torres et al., 2008, ApJ 677

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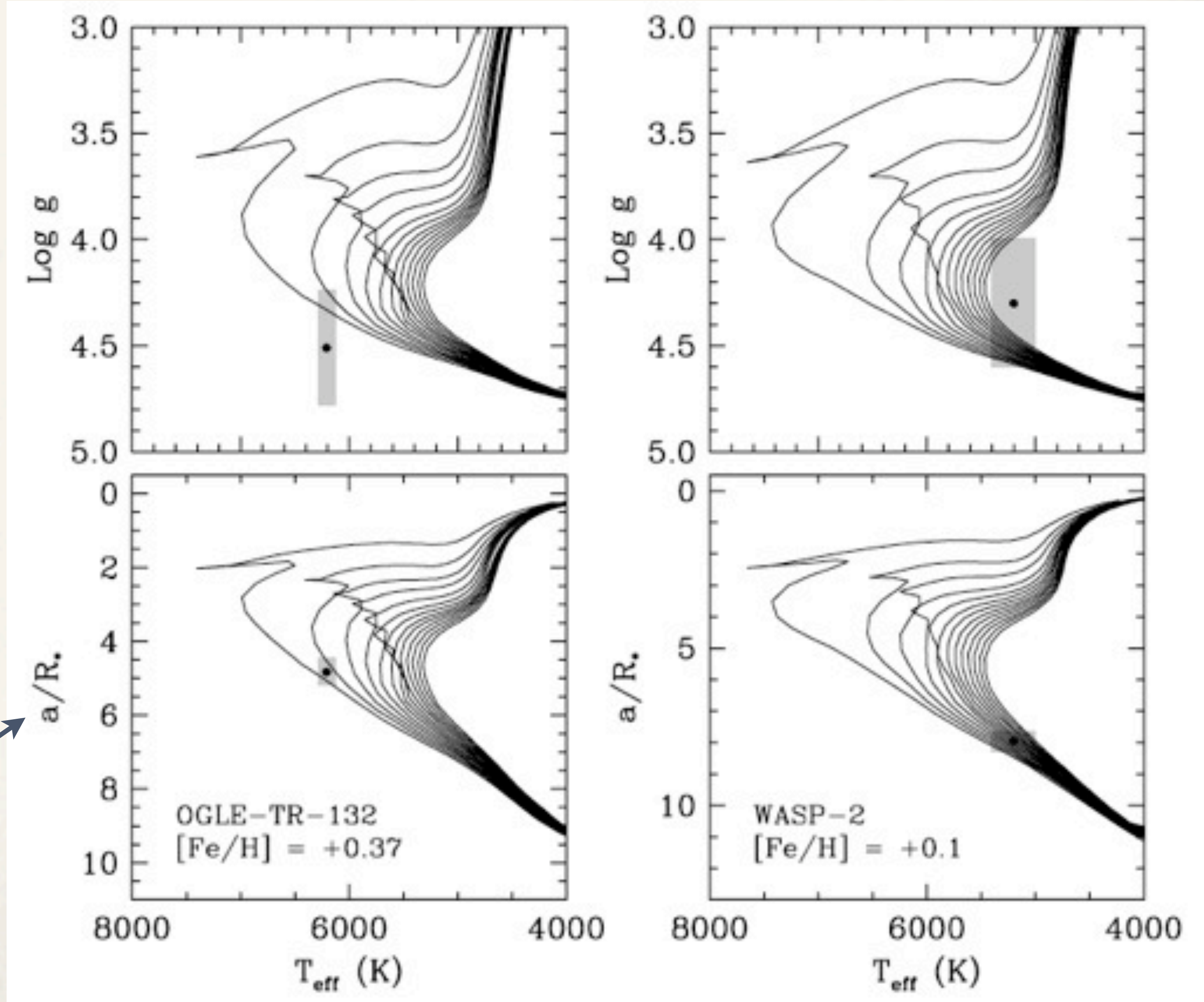
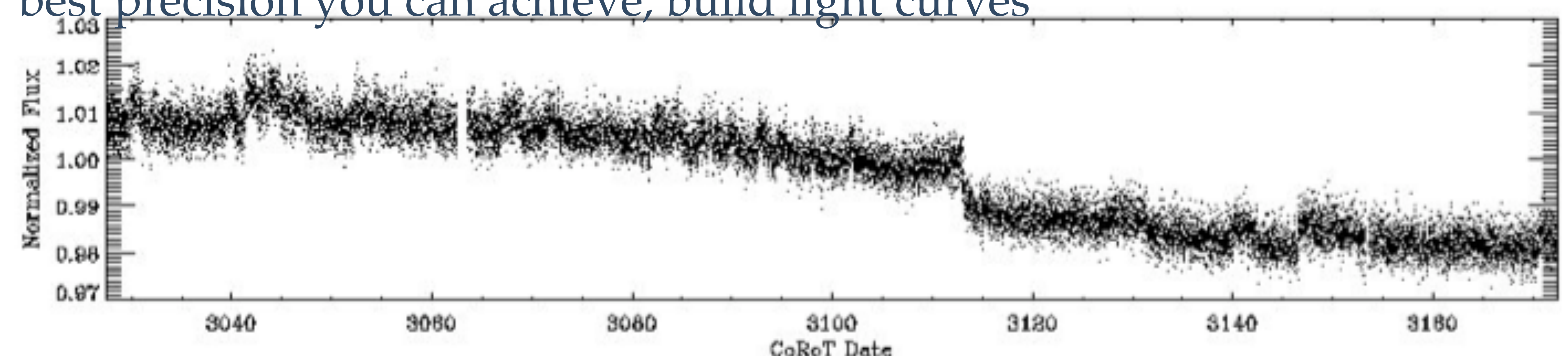


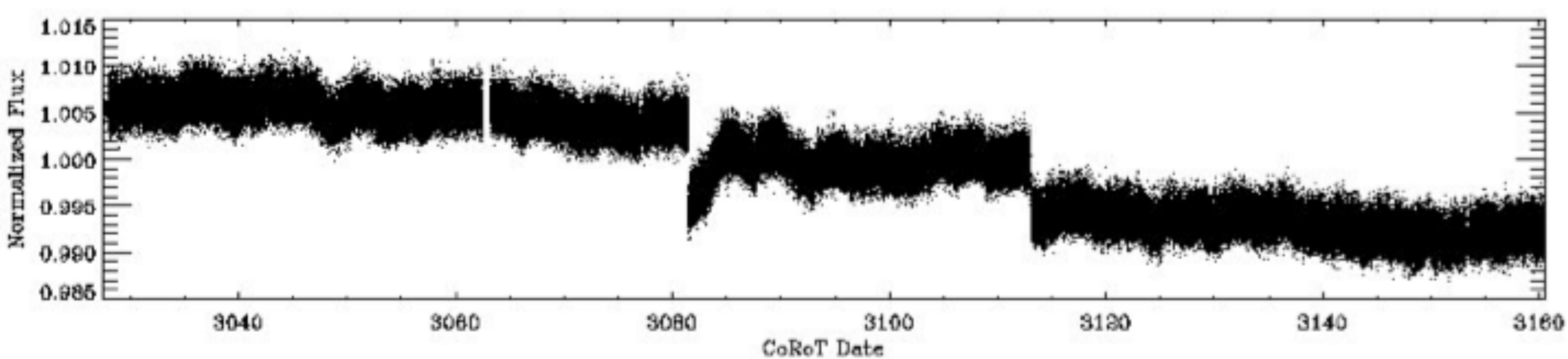
Derived from transit fit

Torres et al., 2008, ApJ 677

Transits in practice

Observe your stars over a long time lag, perform photometry with the best precision you can achieve, build light curves





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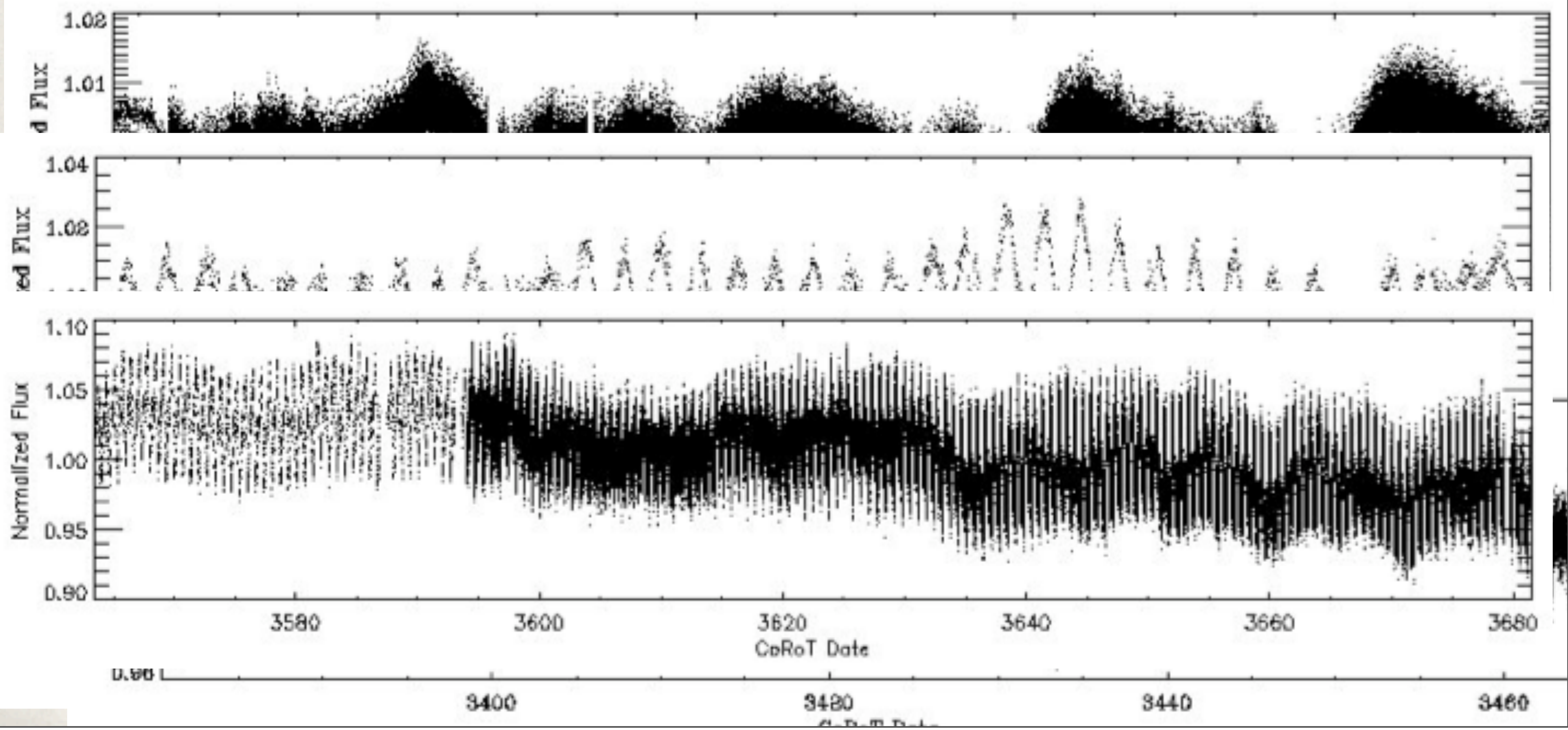
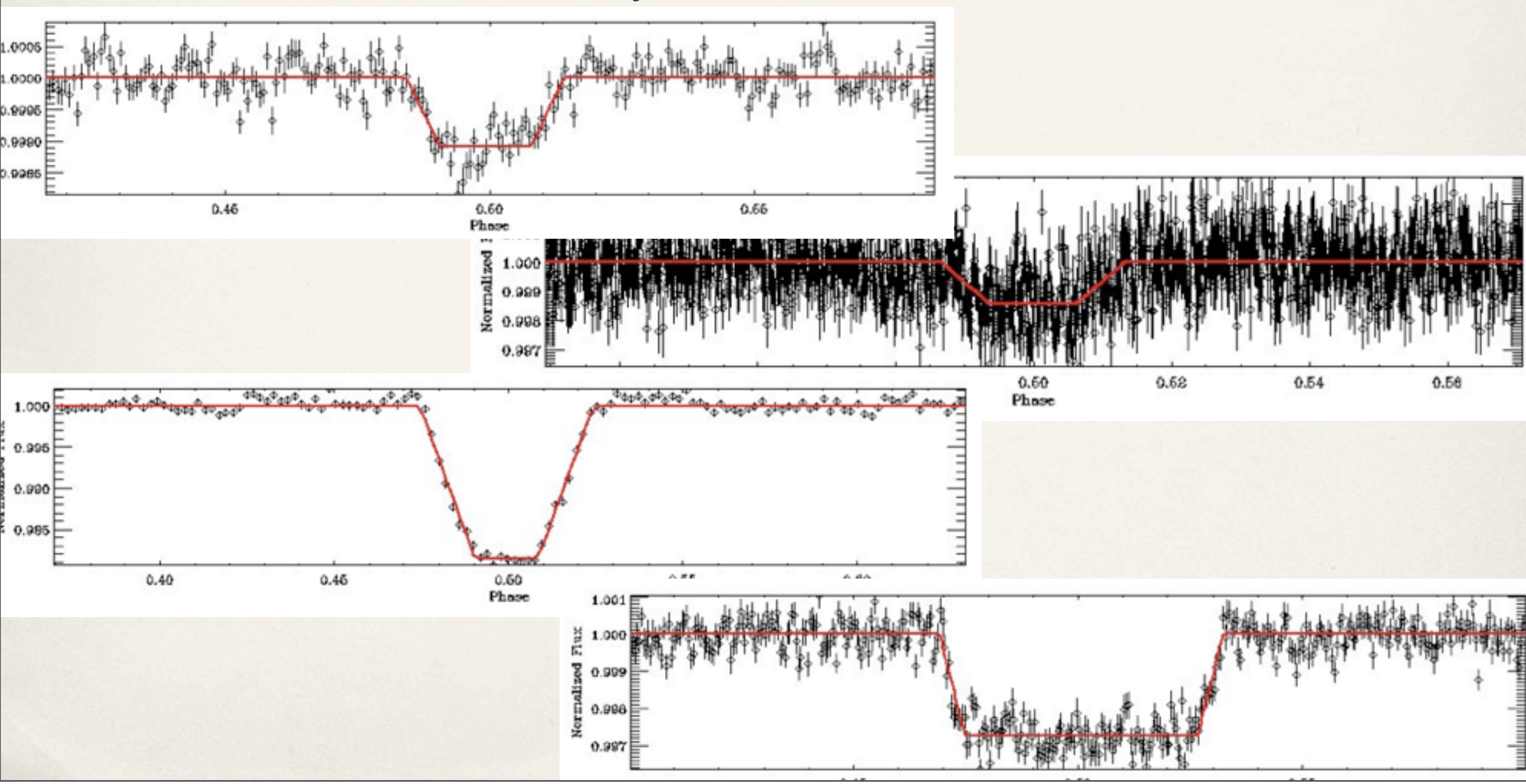


Monday, June 6, 2011

… get some transits

Perform transit detection with your favorite software



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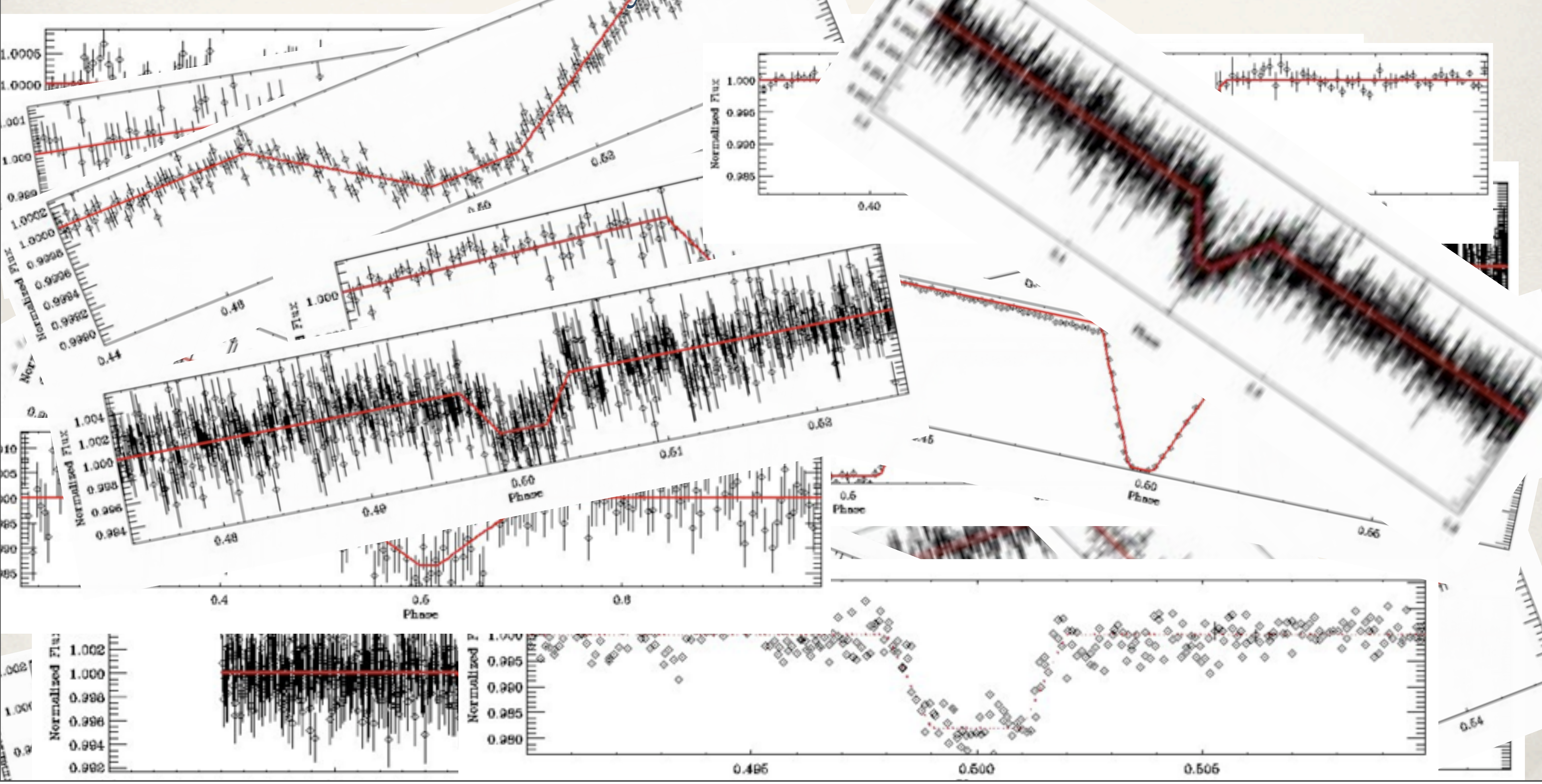
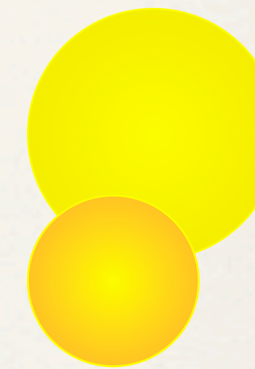


Transits : planet or stars?

Eclipsing binary



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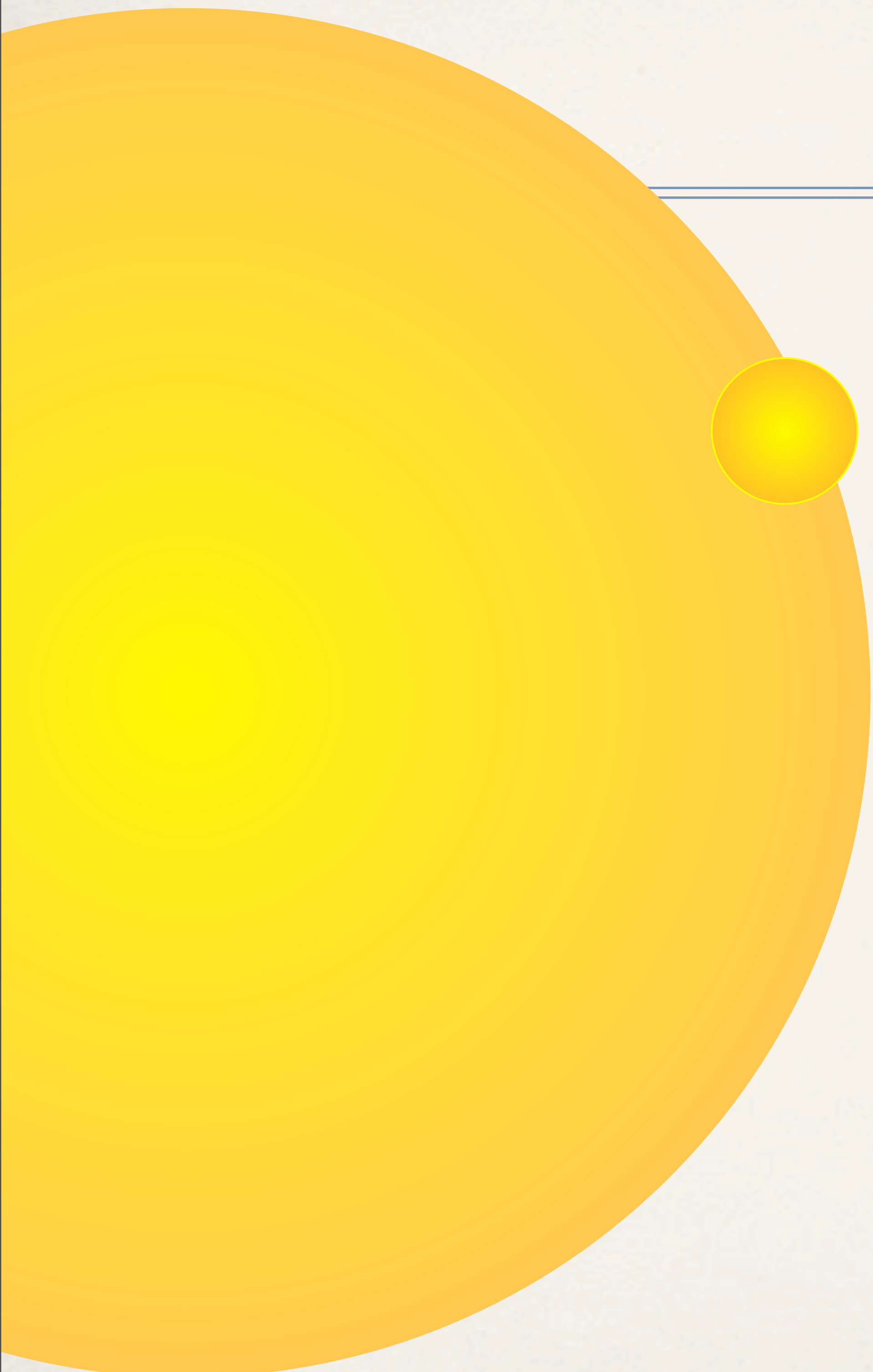

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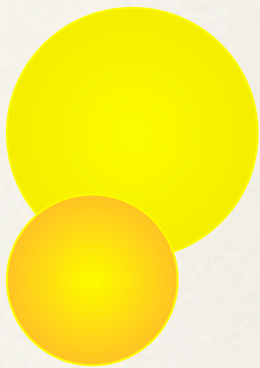

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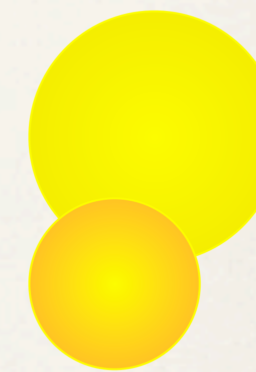

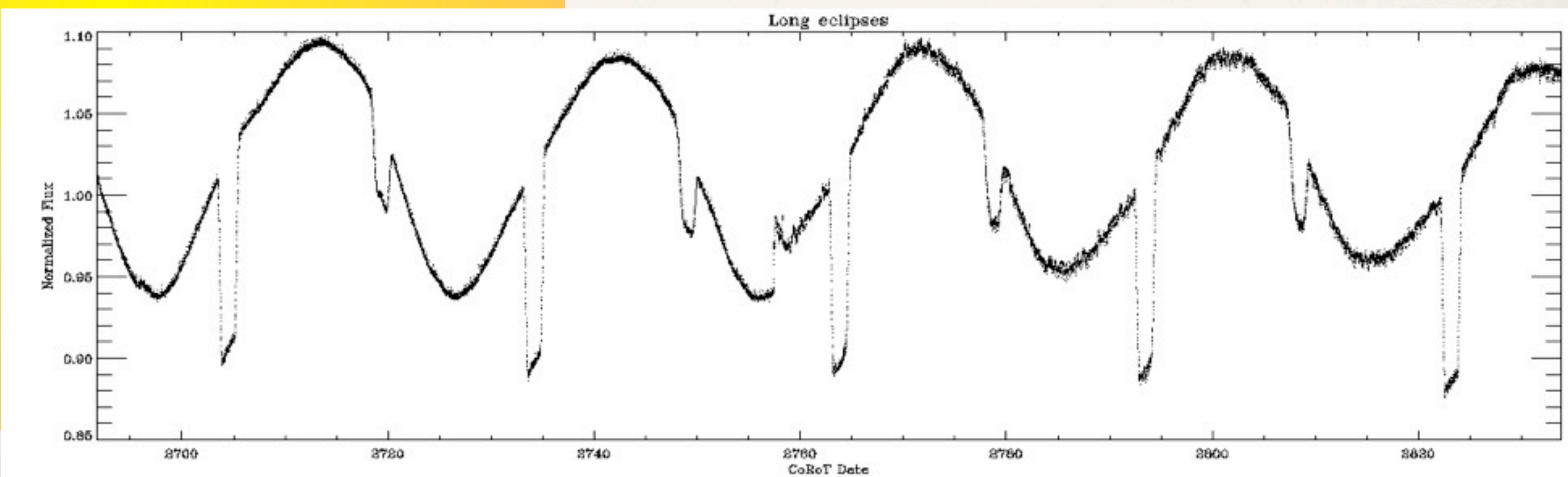

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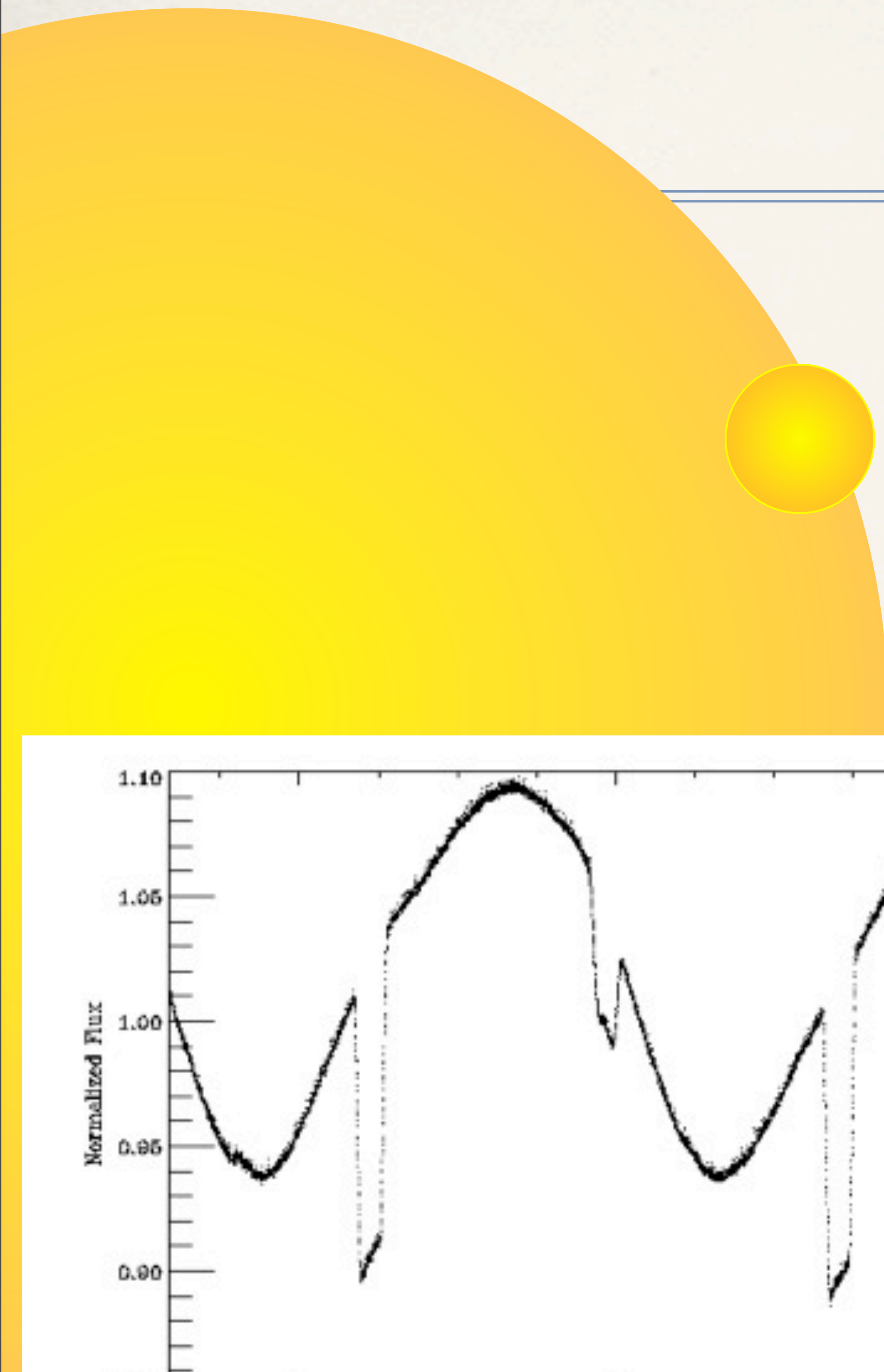

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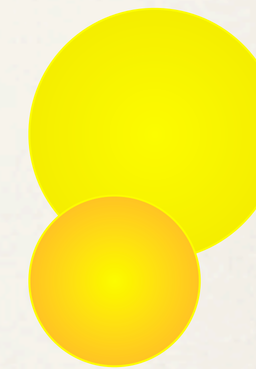
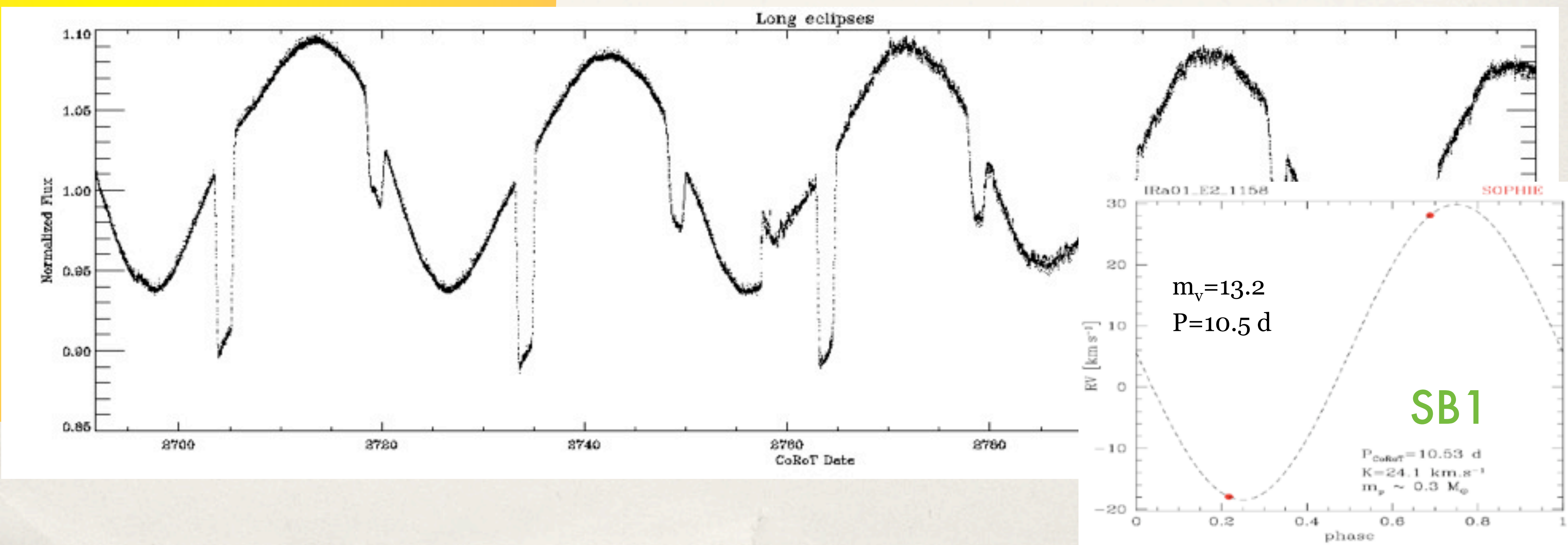
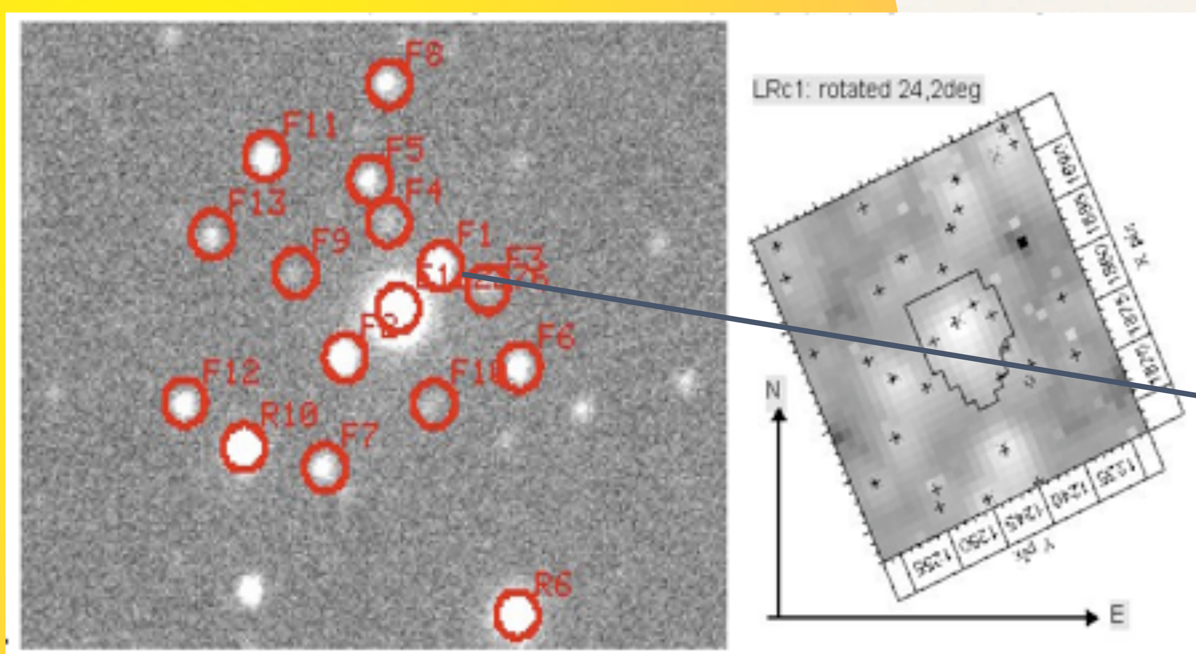
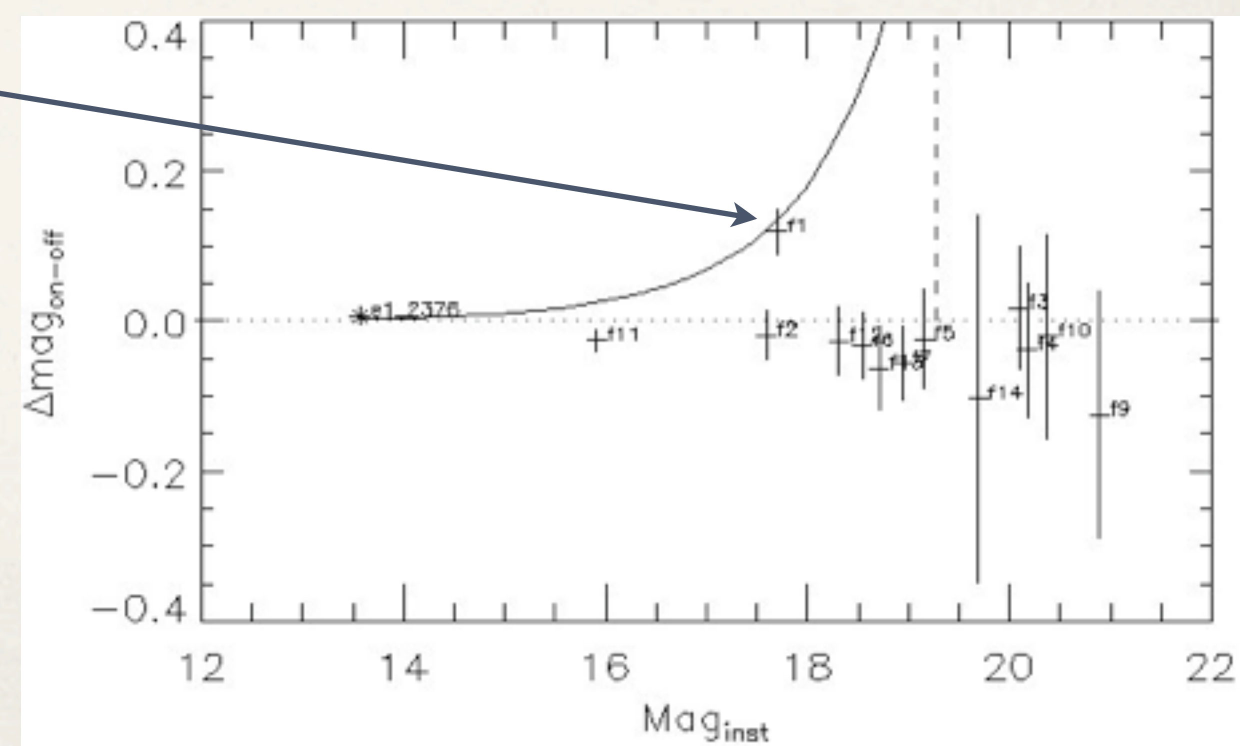




Transits : planet or stars?

blends

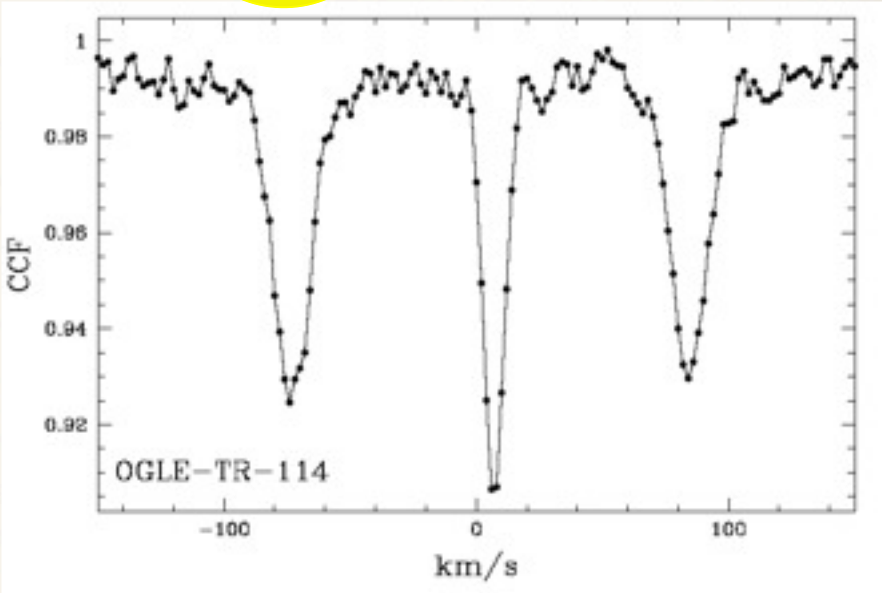




Check the photometric behavior of the nearby stars

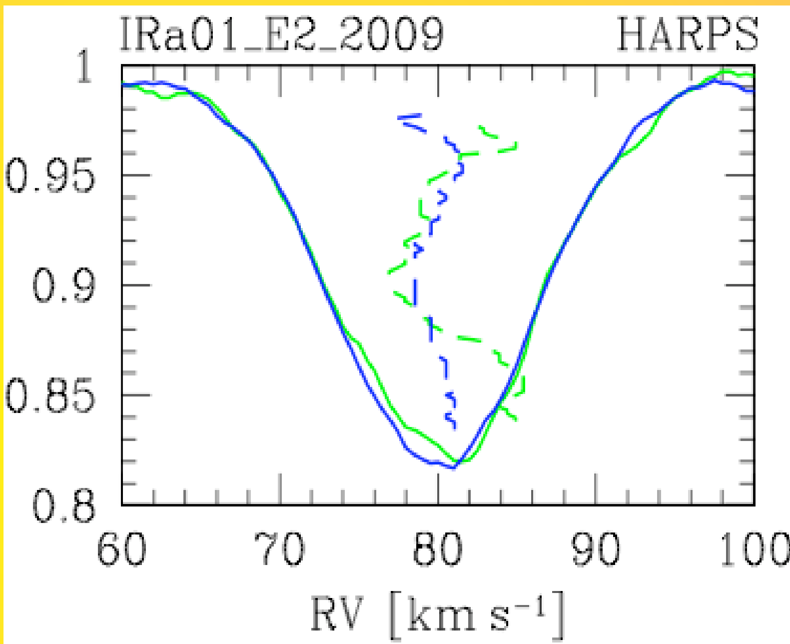
Transits : planet or stars?

blends inside the seeing :
spectroscopic check



Bisector Span

Transits : planet or stars?



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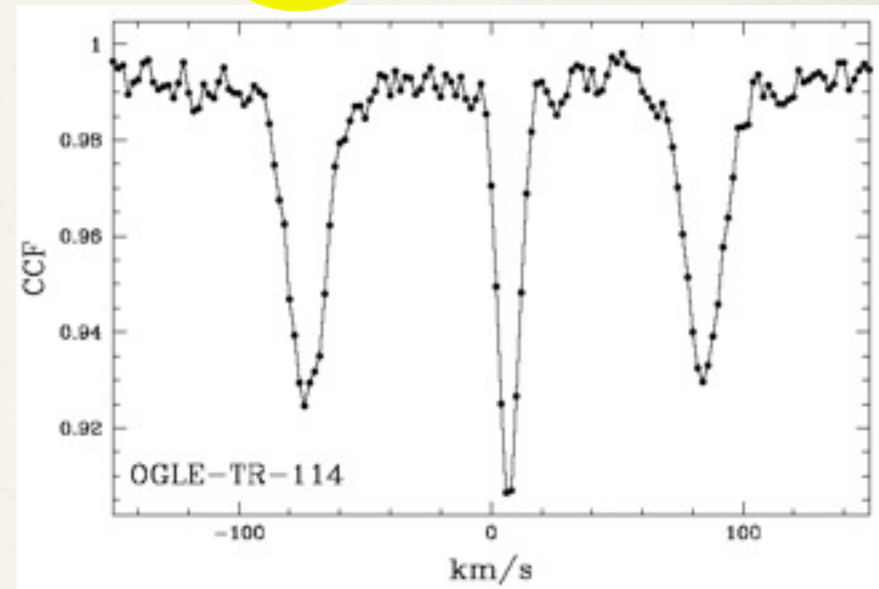

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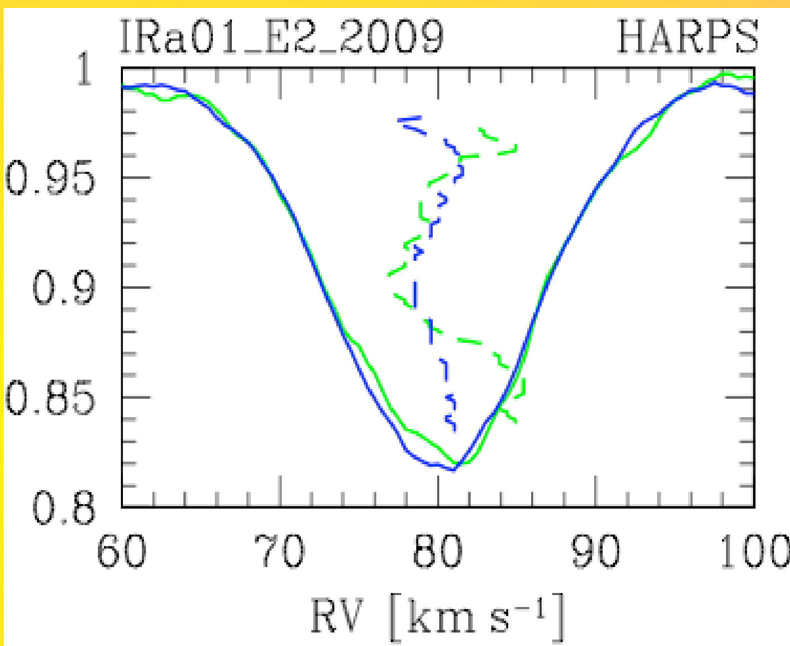

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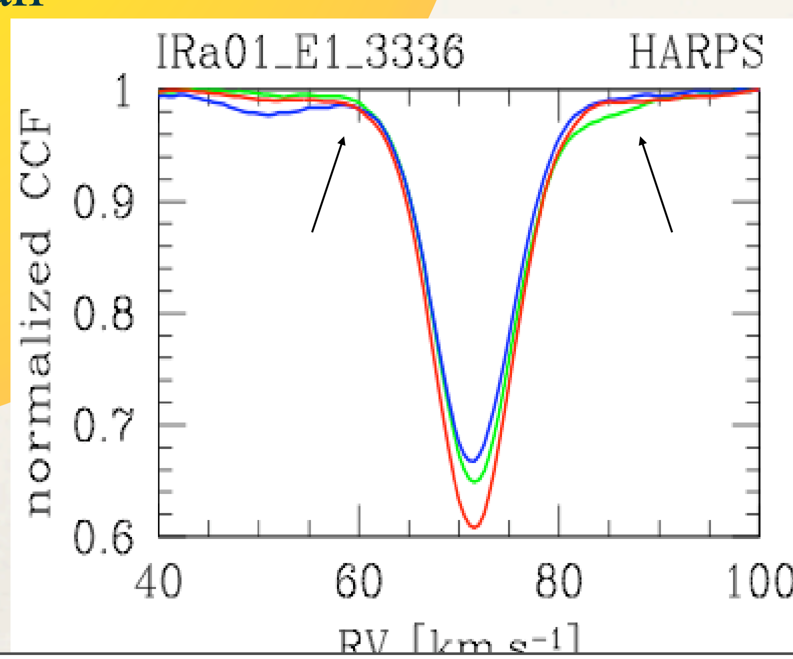

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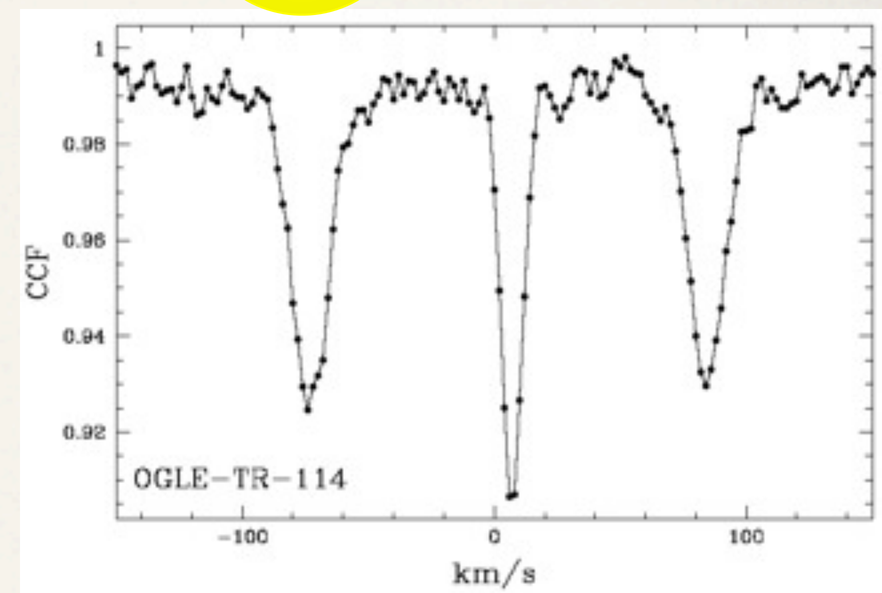

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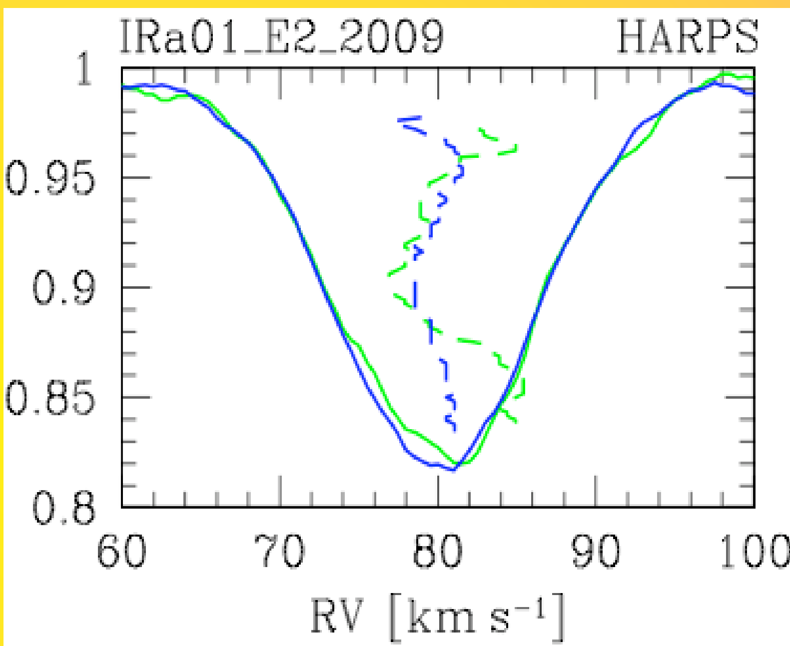

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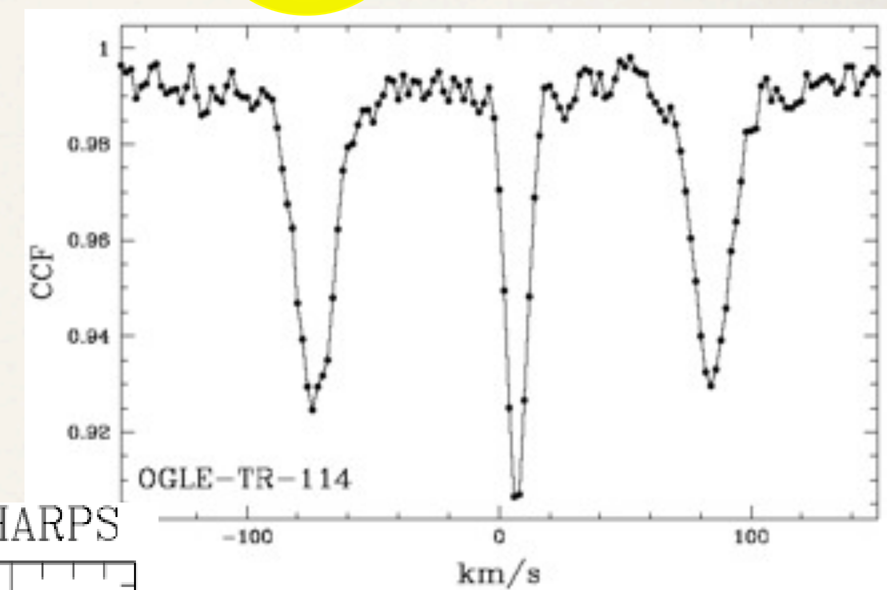

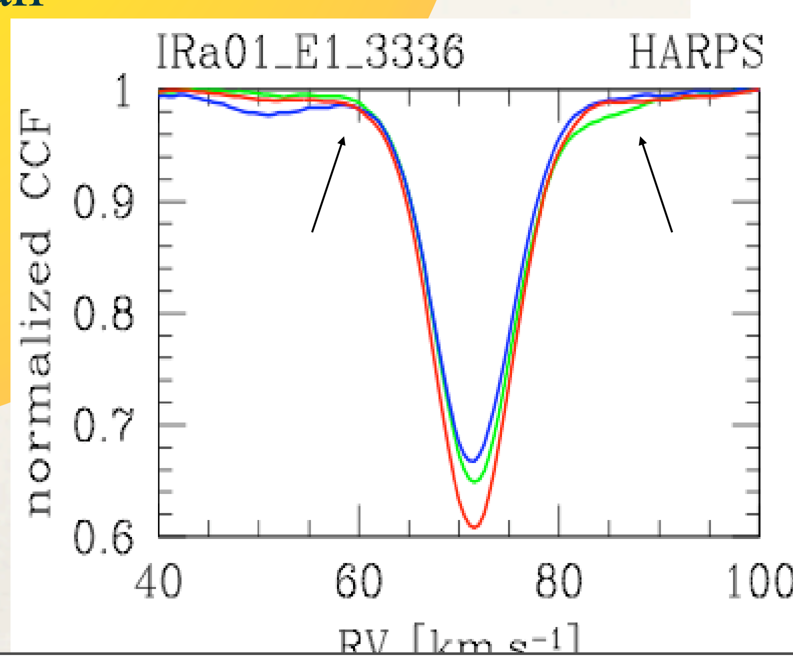

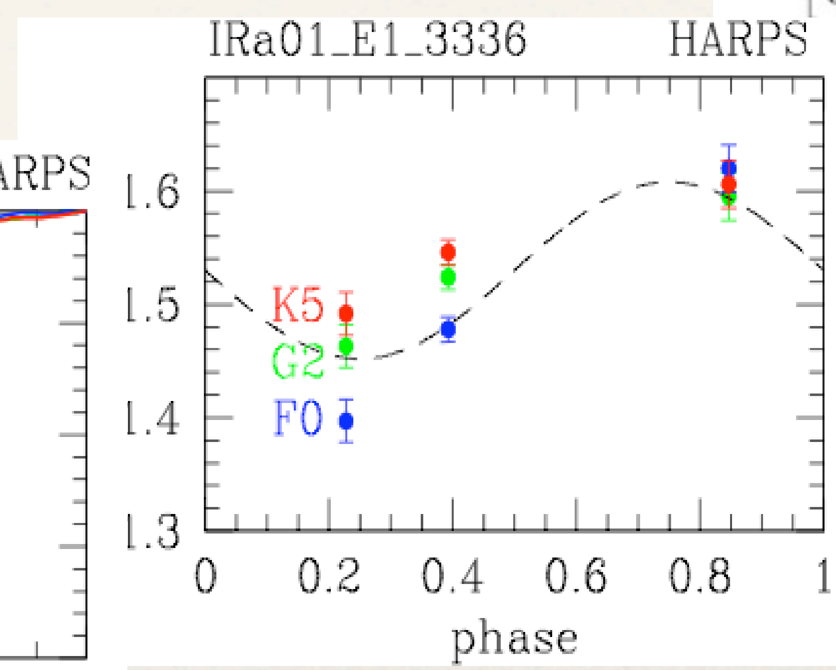

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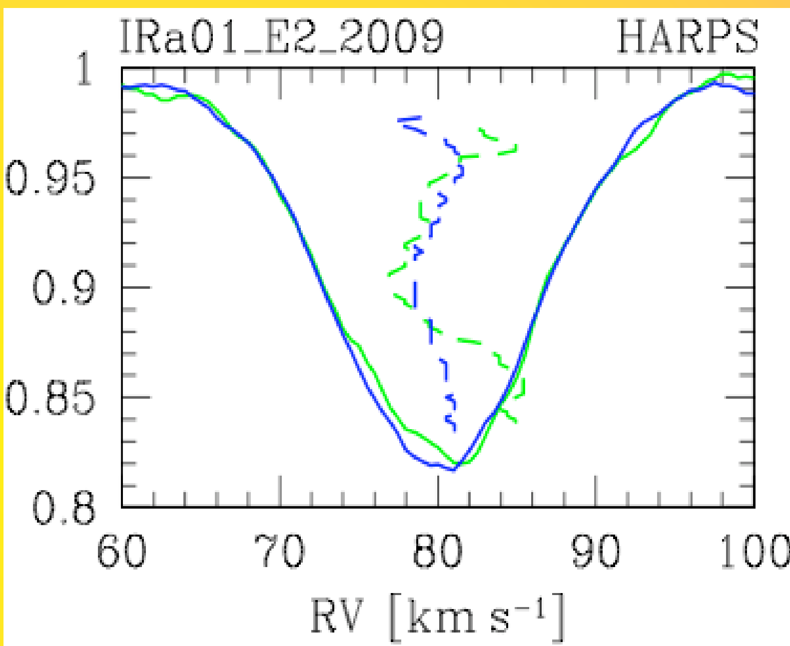

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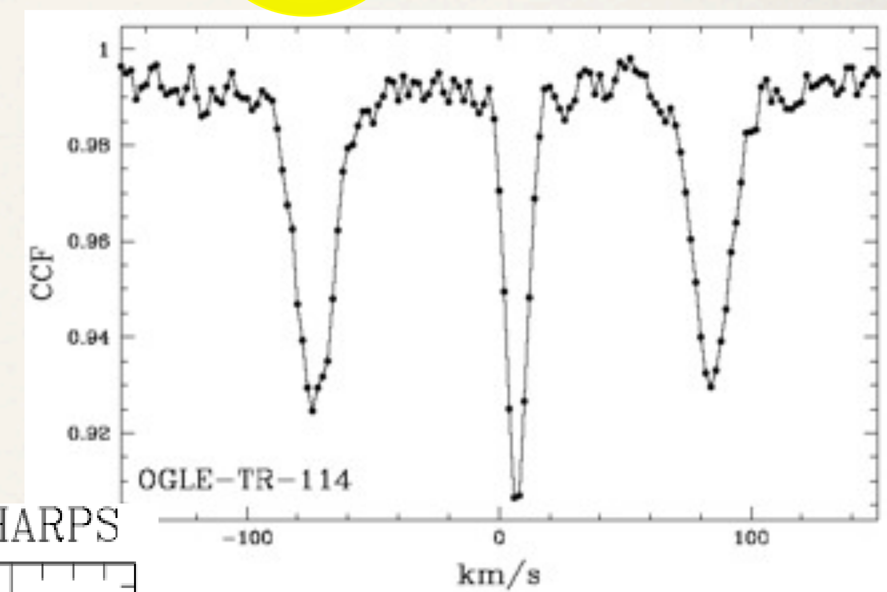
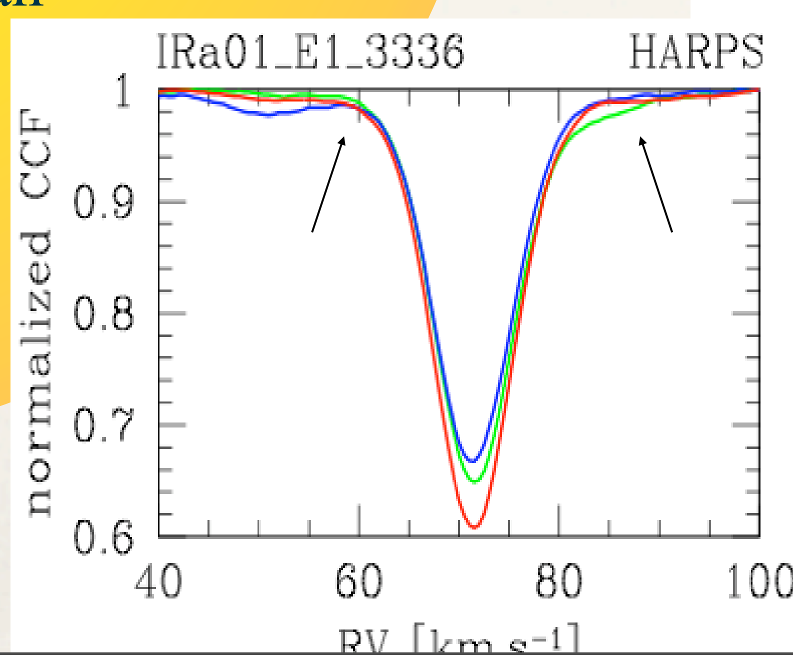
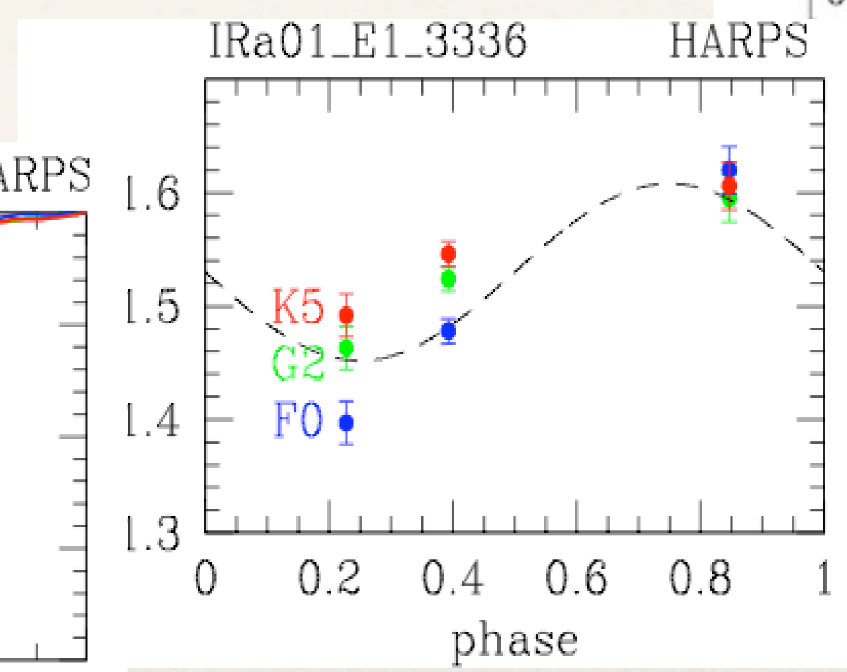
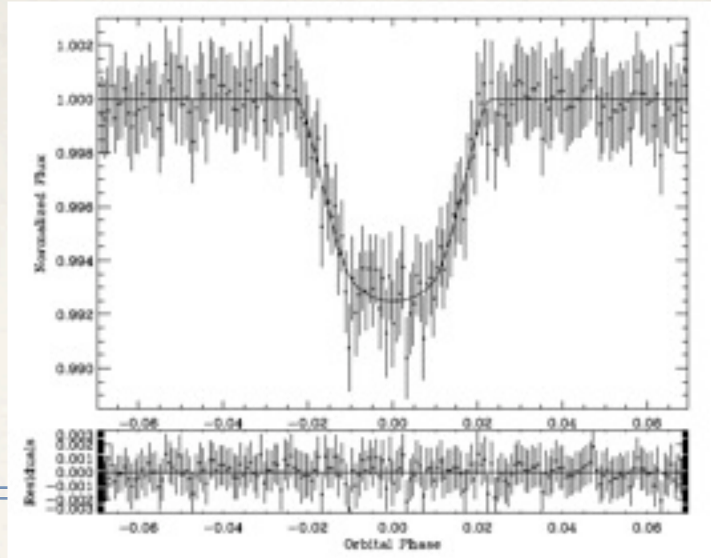






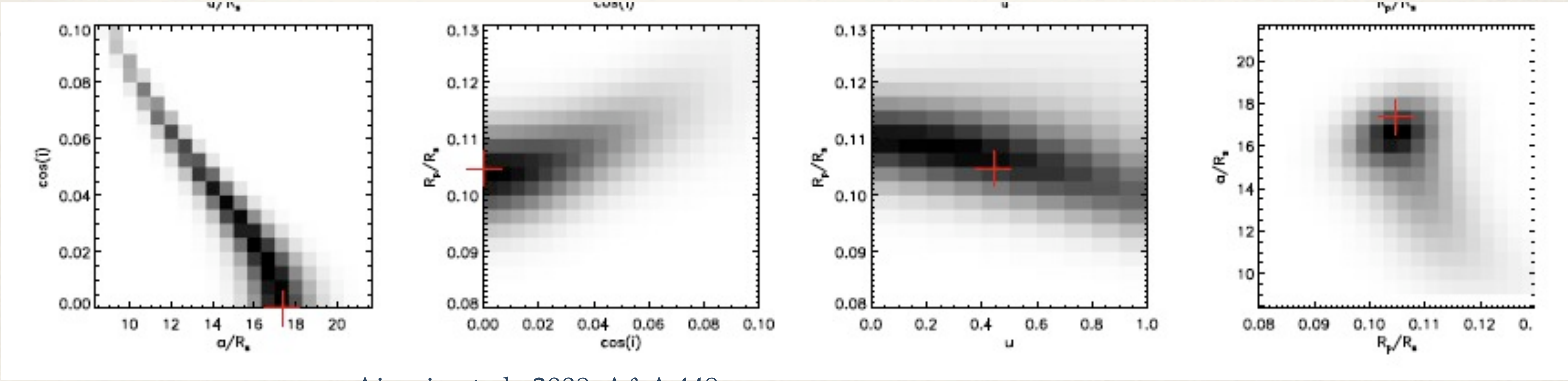
Amplitude change
with the CCF template

Transits : in practice



Different codes exist to calculate realistic LC
e.g. Giménez (2006,A&A 207) on the phase-folded transit determine : the transit center *Tc*, the orbital phase at first contact θ1, the ratio of radii *k*, the orbital inclination *i* and the limb darkening coefficients

or global analysis of the photometry and the radial velocity measurements with Bayesian Markov Chain Monte-Carlo (MCMC) algorithm : the ratio of the radii, the transit width (from first to last contact) *W*, the transit impact parameter, the orbital period *P, the* time of minimum light *T*0, the two parameters √(*e*) cosω and √(*e*) sinω where *e* is the orbital eccentricity and ω is the argument of periastron, and the parameter , $K2 = K\sqrt{(1-e^2)}P^{1/3}$ where *K* is the RV orbital semi-amplitude.



Aigrain et al., 2008, A&A 448

Transit versus radial velocity

Method	transit	radial velocity
parameters	P, R_p, i	Msini, P, e
limitations	star's size; stars' parameters	slow rotators, stellar activity
bias	dwarfs	spectral type

Association of the two methods :

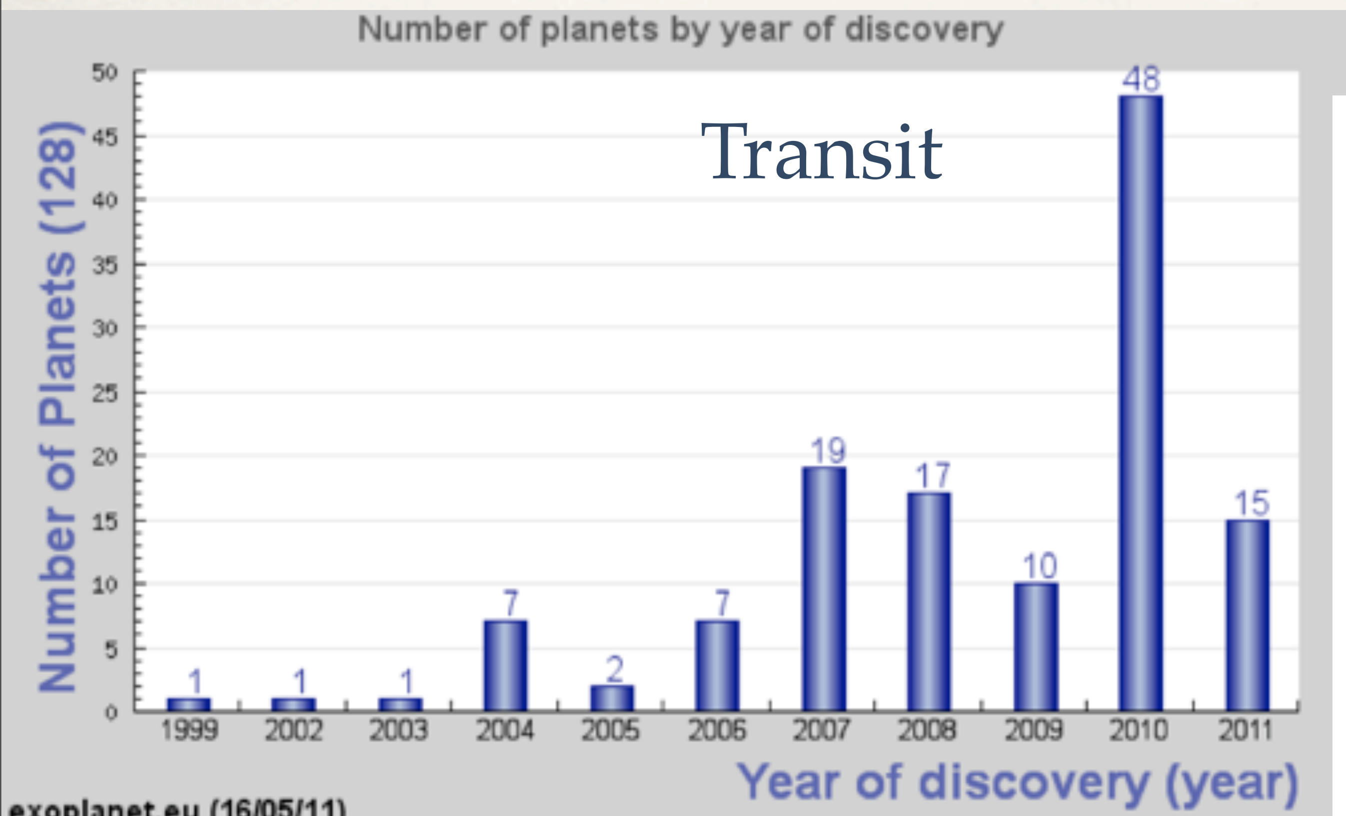
- the planet's fundamental parameters ;
- the complete orbit parameters;
- allow to enlarge the space parameters toward active stars or fast rotators

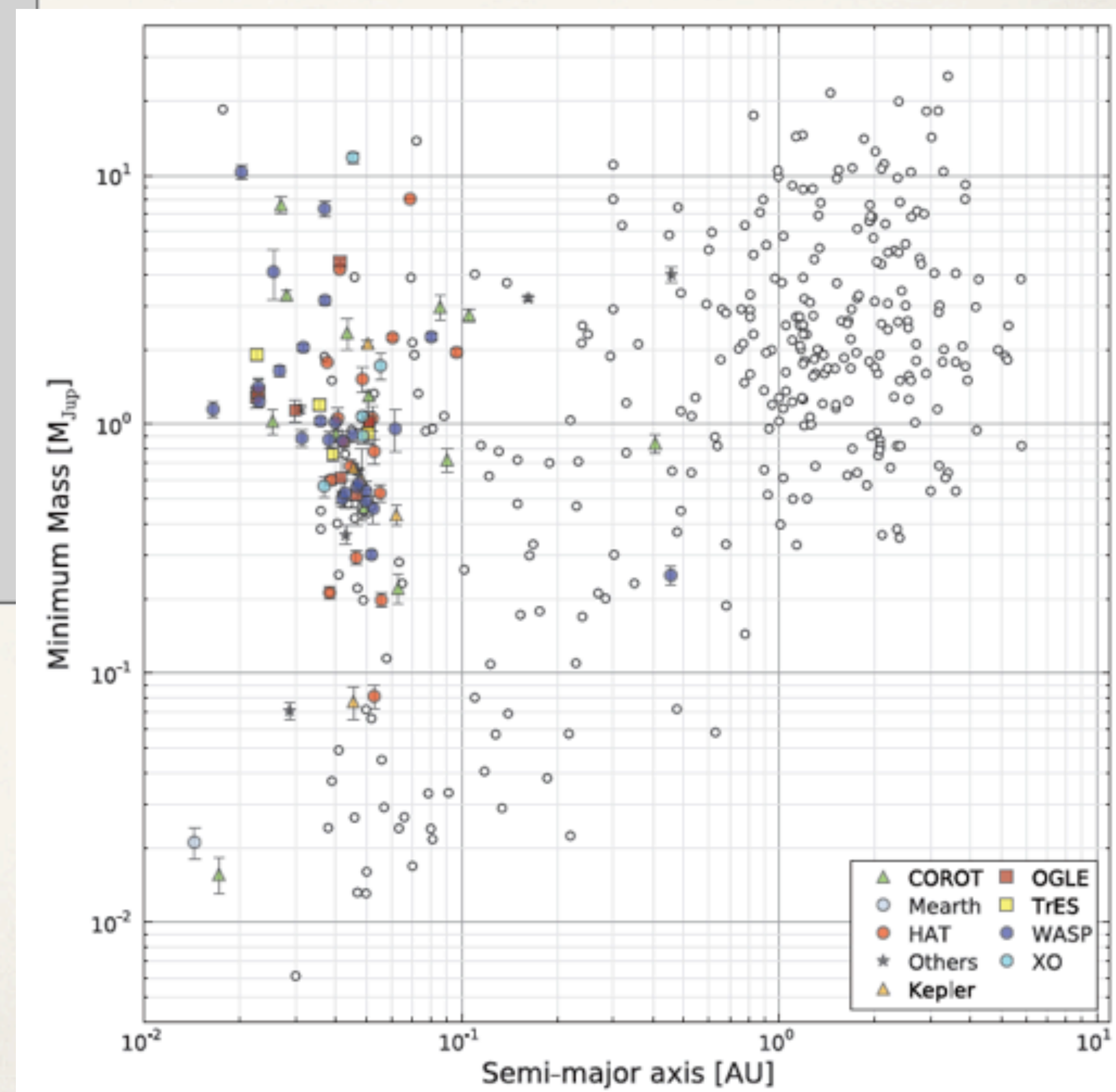
Transits : probing planetary systems

Assuming the photometric precision is high enough you can :

- measure the planetary radius : bring constrains on the planet evolution and migration history and on planet's composition and atmosphere.
- the orbital plane configuration : period, eccentricity, inclination
- the planet's atmospheric properties :
  - albedo,
  - thermal emission,
  - composition
- Stellar surface: limb darkening, spots
- Star - planet interactions
- Additional unseen companion (TTV) planet or moons
- Rings and satellites
- Oblateness & obliquity

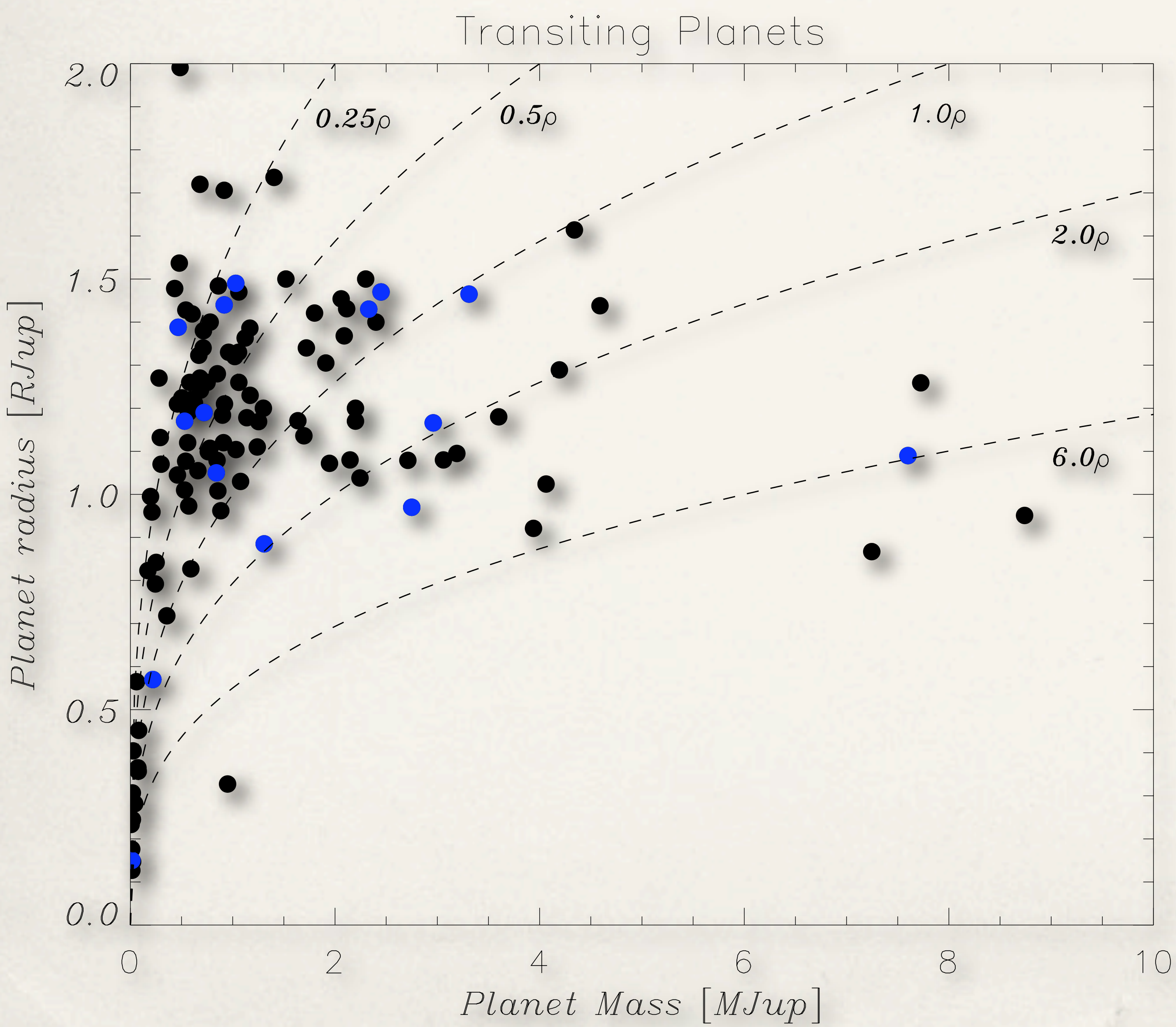
Transits - current situation

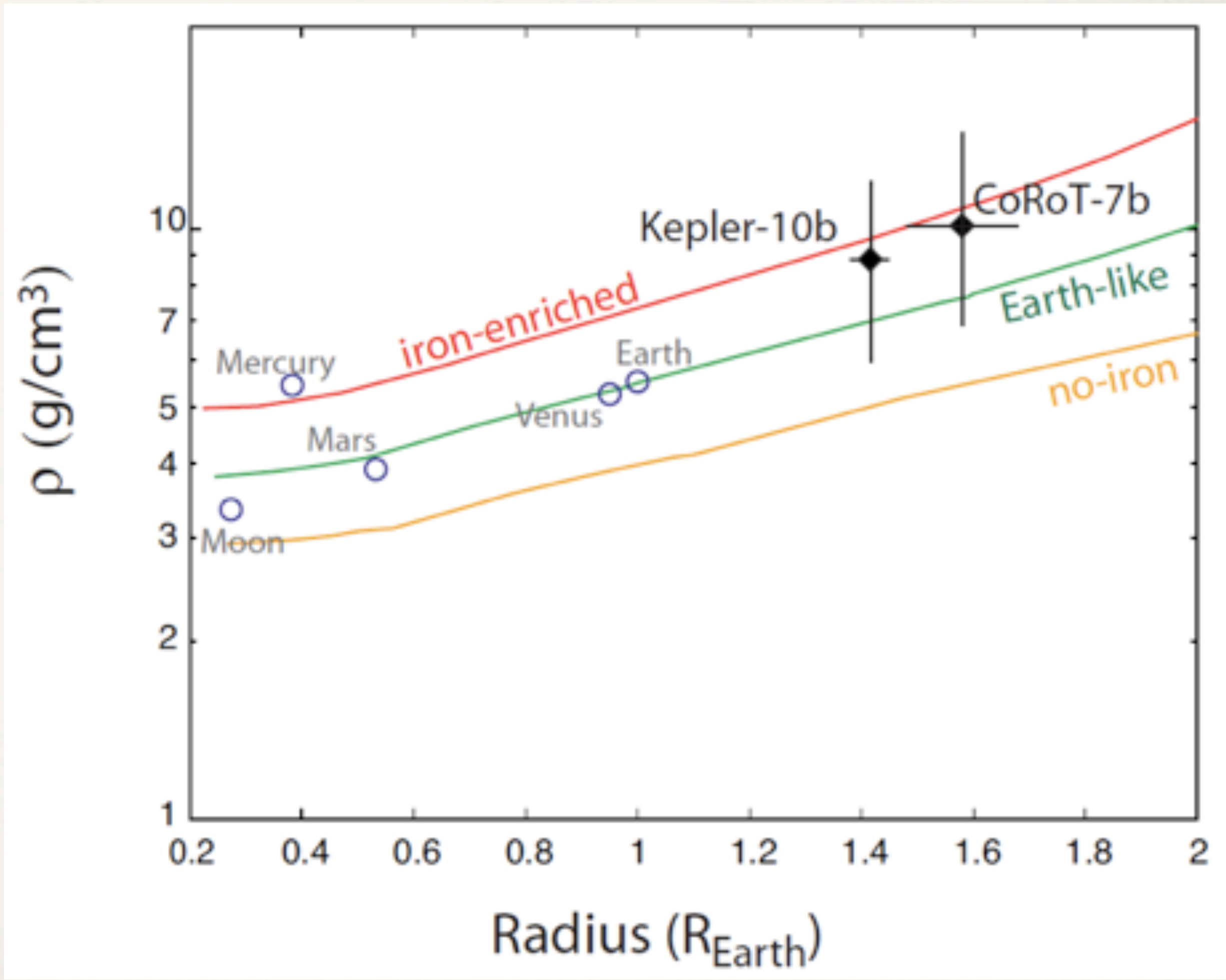




Transits - planet's nature

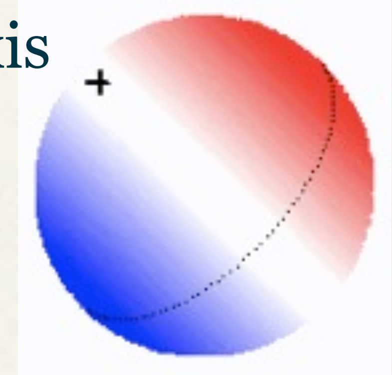
123 transiting planets ➛ a striking diversity & the very first secured rocky planets





Spectroscopic transit or the Rossiter-McLaughin effect

- star's rotation axis



$V_{rad} > 0$ when the distance source - observer increases - red

$V_{rad} < 0$ when the distance source - observer decreases- blue

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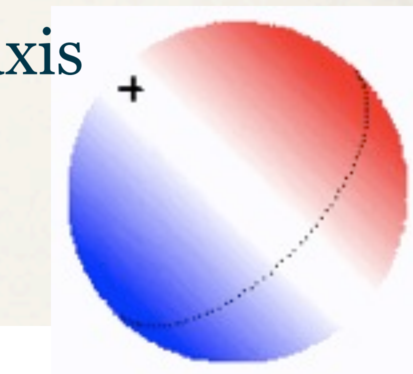

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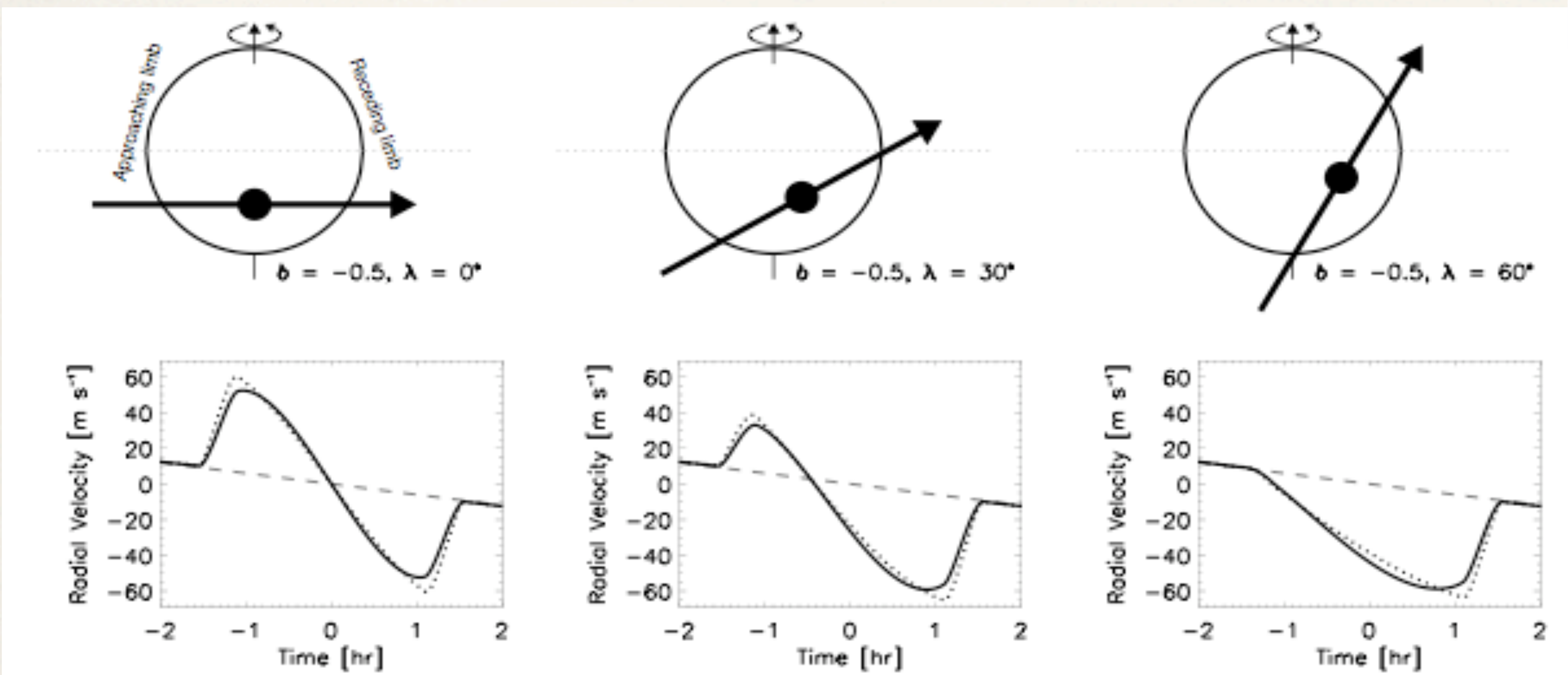

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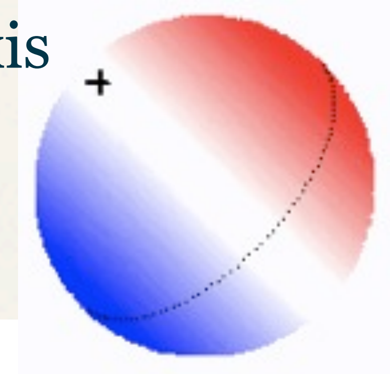

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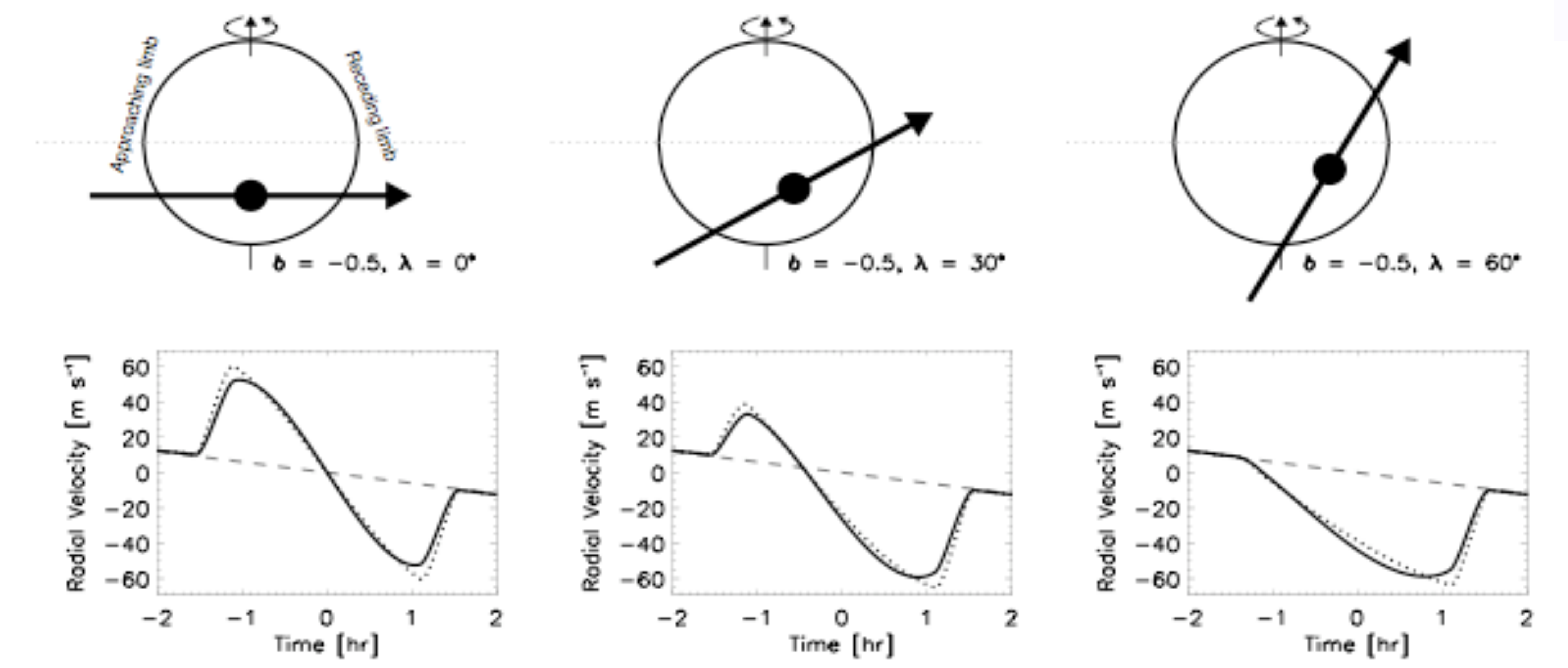
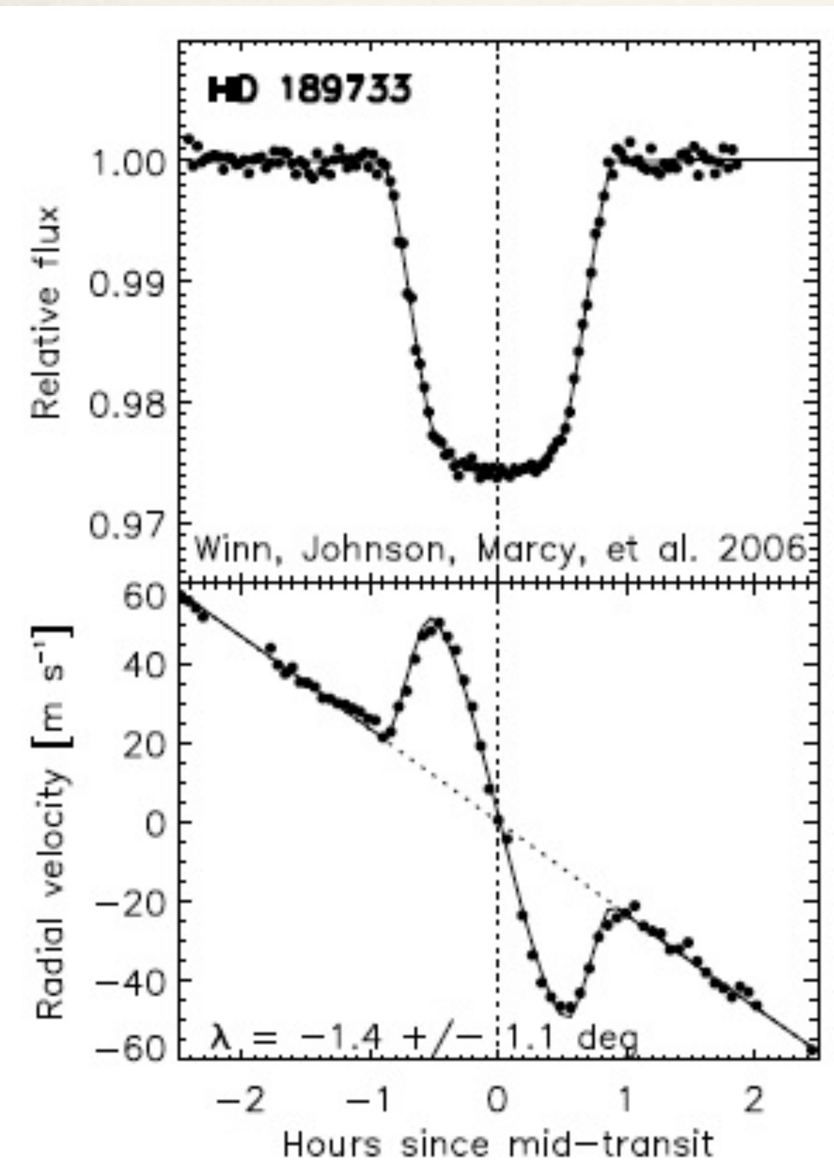
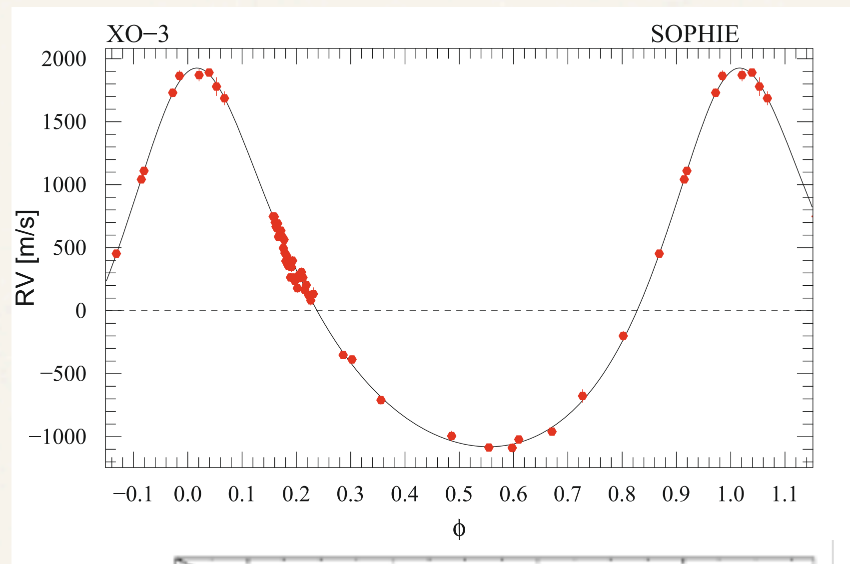
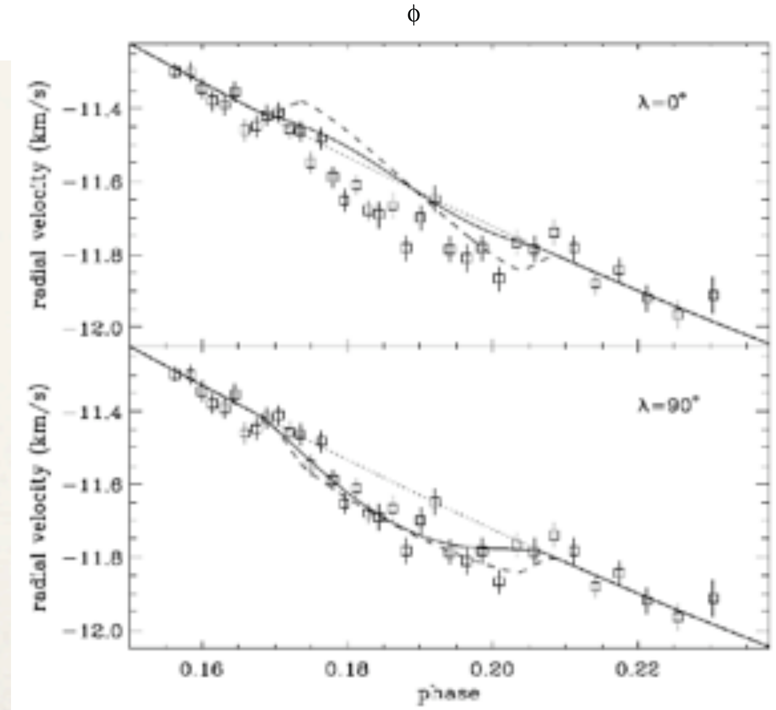


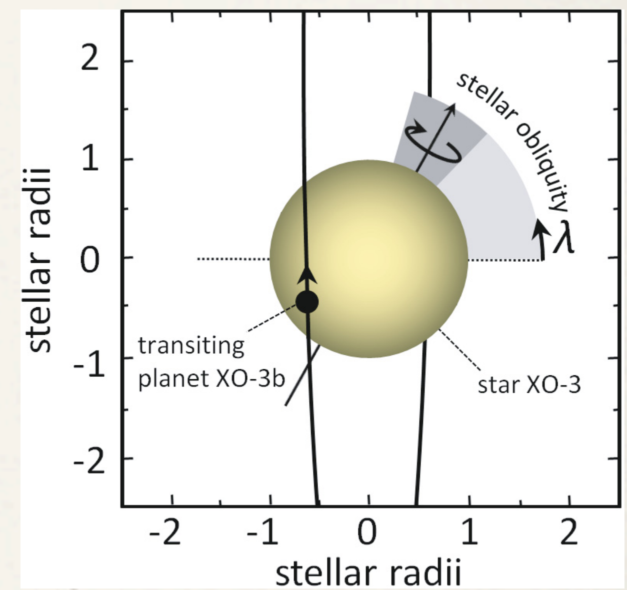
- Measure of the sky-projected angle between the stellar rotation axis and a planet's orbital axis see Queloz et al., 2000, A&A 359 L13 e.g.

Spin-orbit : probing the hot Jupiters dynamical origin



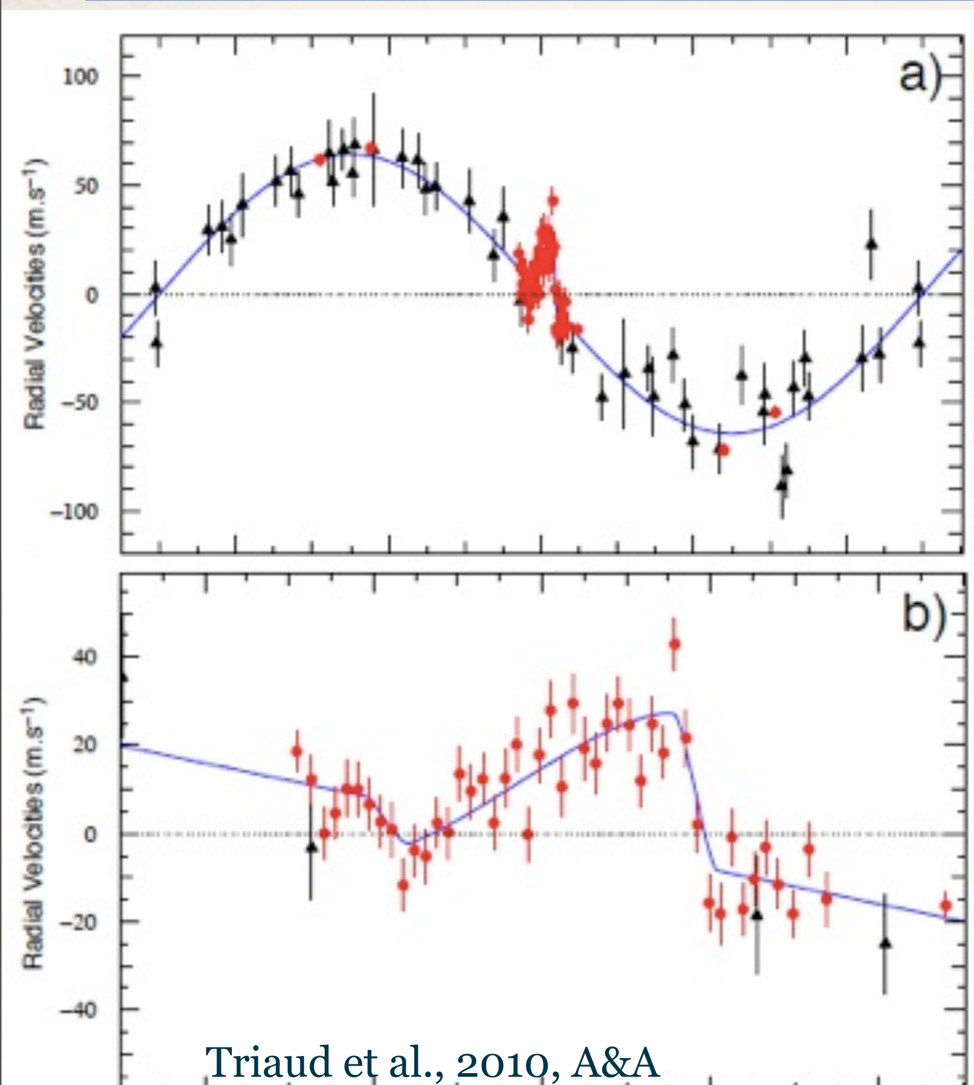


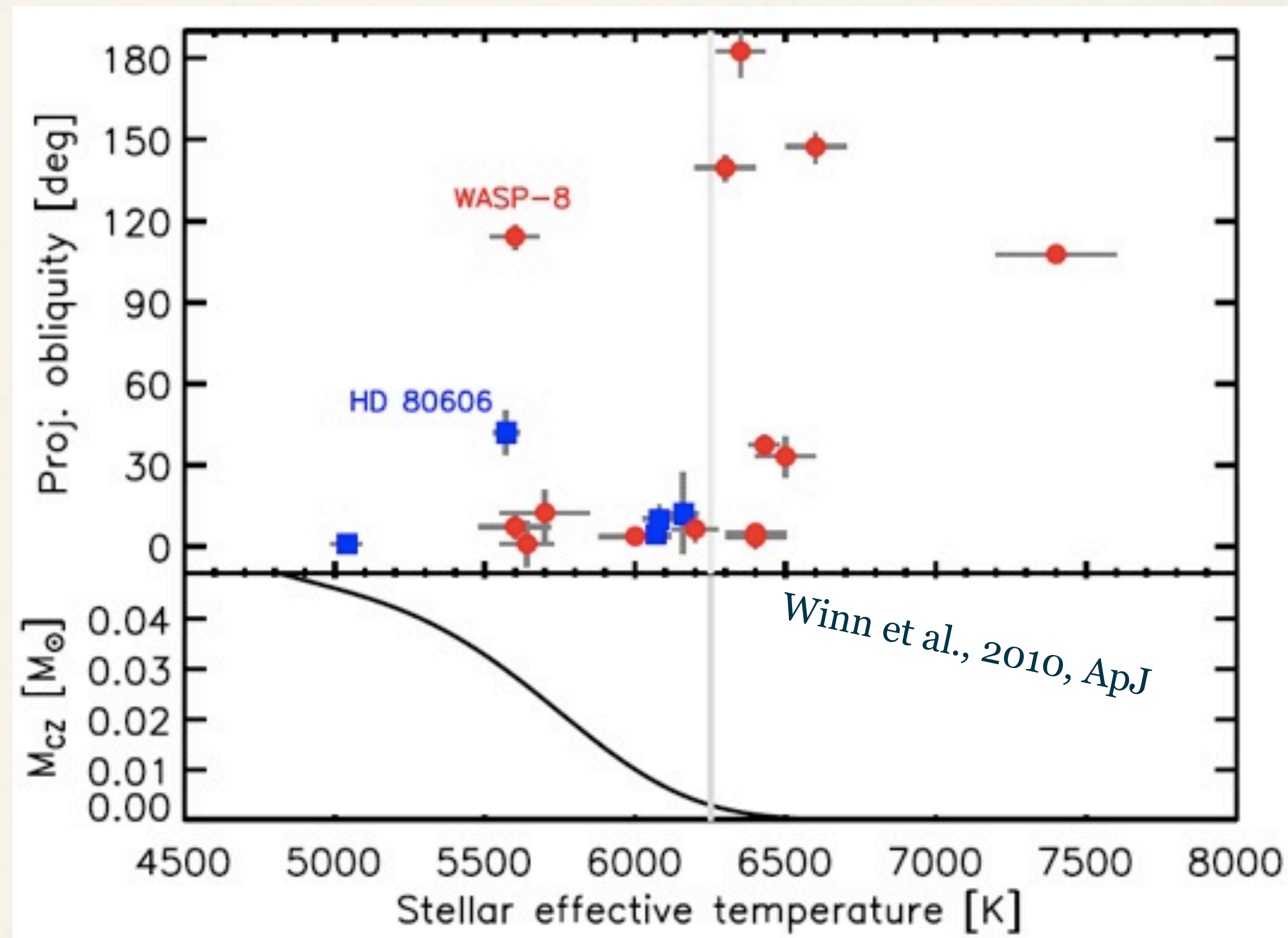




Hébrard et al., 2008, A&A 488, 763

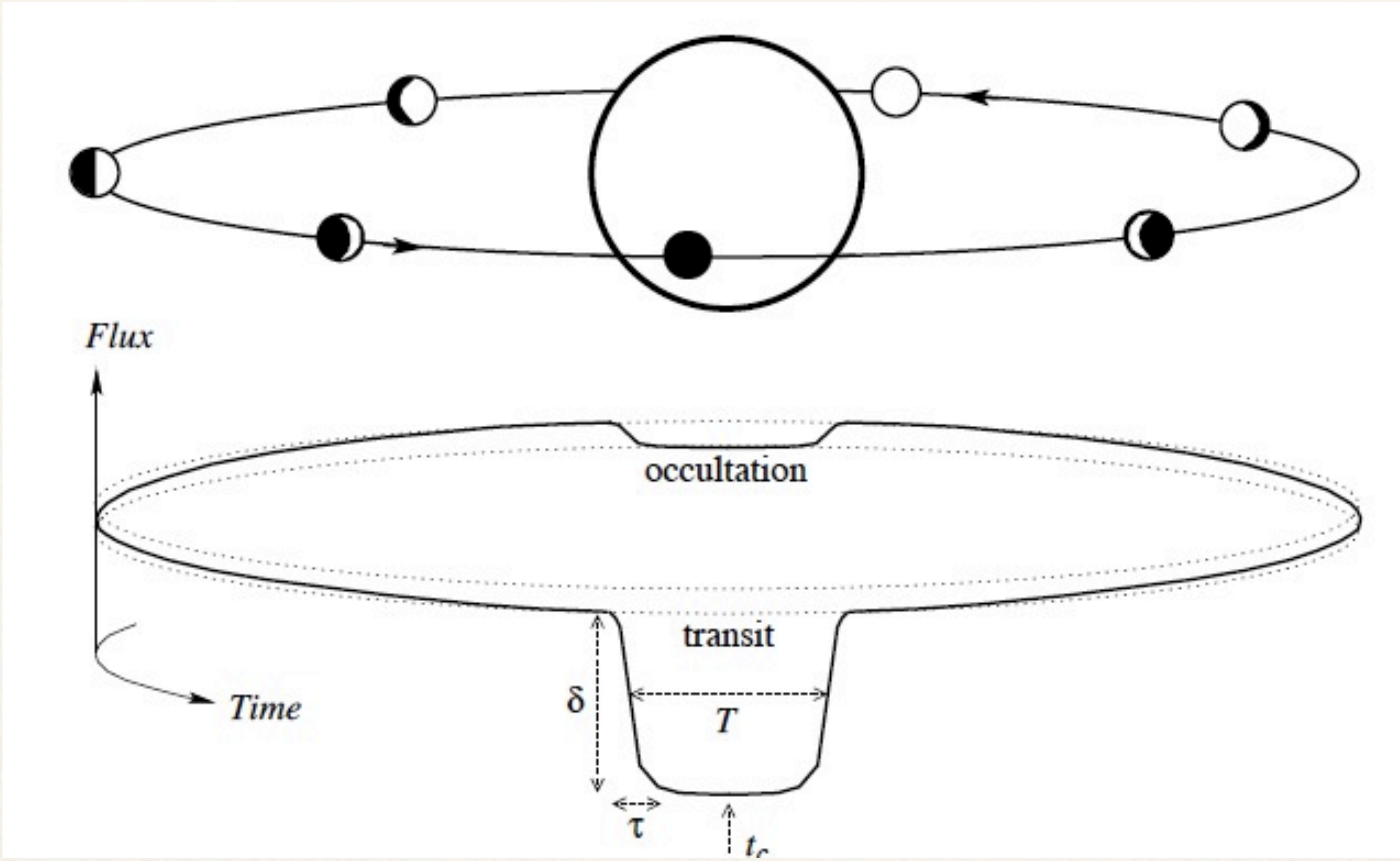
Spin-orbit : probing the hot Jupiters dynamical origin





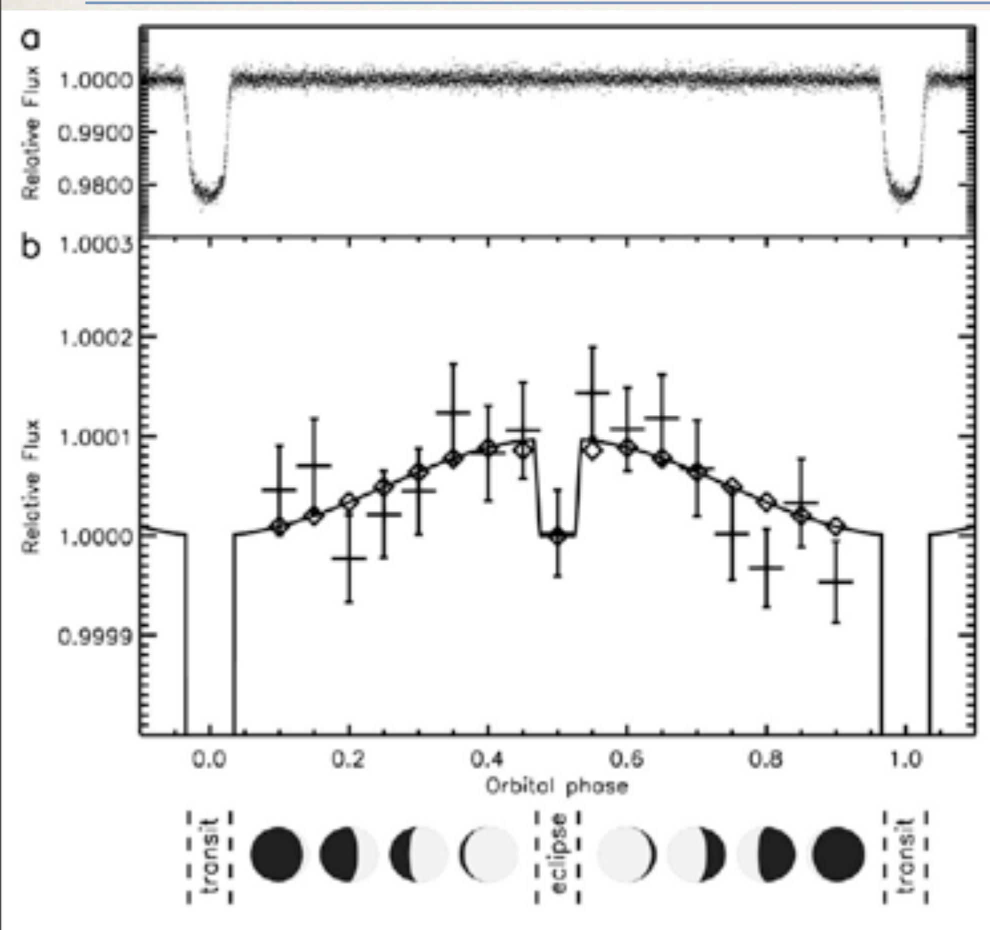
- 8 out 26 misaligned ➛ the creation of retrograde planets involves another body: planetary or stellar
- Trend with the $M_\star$/Teff ➛ planet formation and migration depend on the stars' mass or the final evolution is linked to the internal structure of the stars, specifically the depth of the outer convective zone

Transits : probing the atmosphere

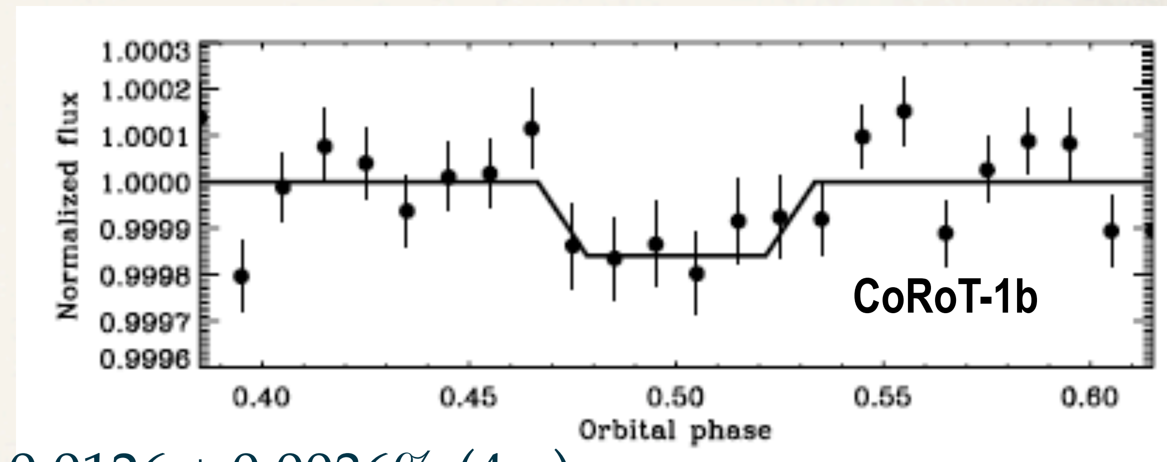


- planet's phase variation ➛ albedo
- occultation ➛ atmospheric properties

Transits : planet’s atmosphere



CoRoT-1b : optical phase variation



Red LC : depth = 0.0126 ± 0.0036% (4σ)

T = 2390 K +/- 90

geometric albedo < 0.20

Snellen et al., 2009, Nature

White LC : Depth = 0.016 ± 0.006% (3.5 σ)

T_p = 2330 +120 /-140K

Alonso et al., 2009a A&A

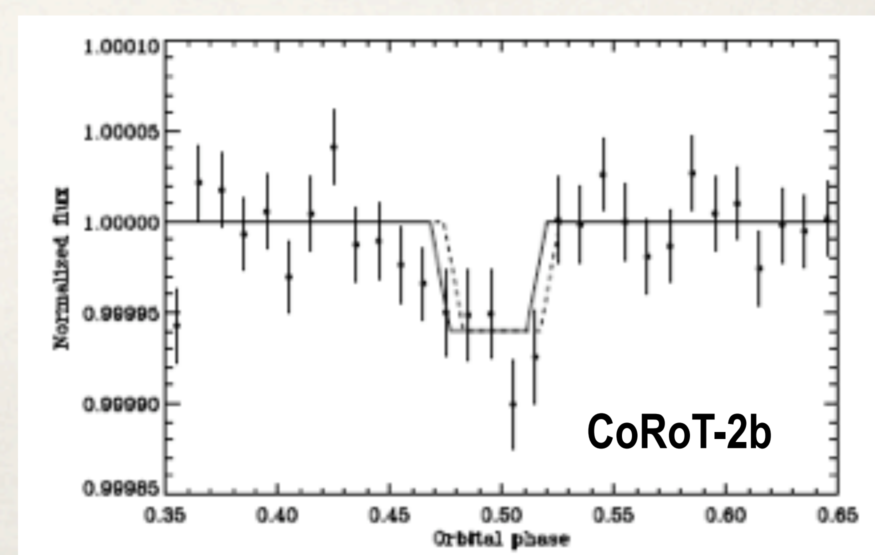
CoRoT-2b

White LC : Depth = 0.006 ± 0.002%

T_p = 1910 +90 /-100K

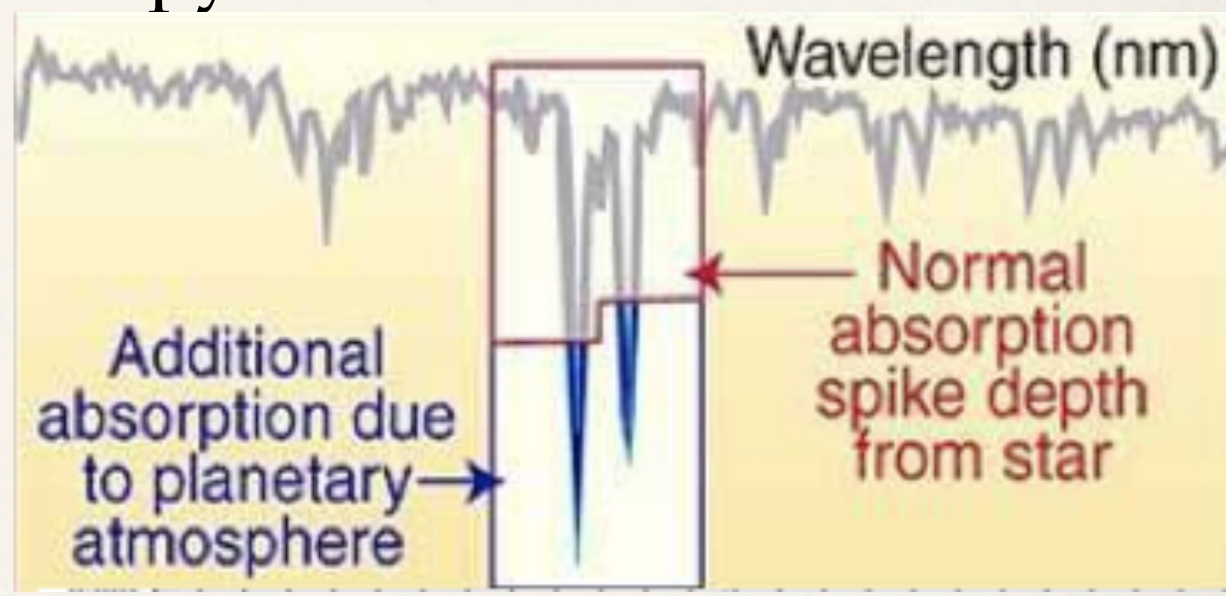
geometric albedo < 0.12

Alonso et al., 2009b A&A

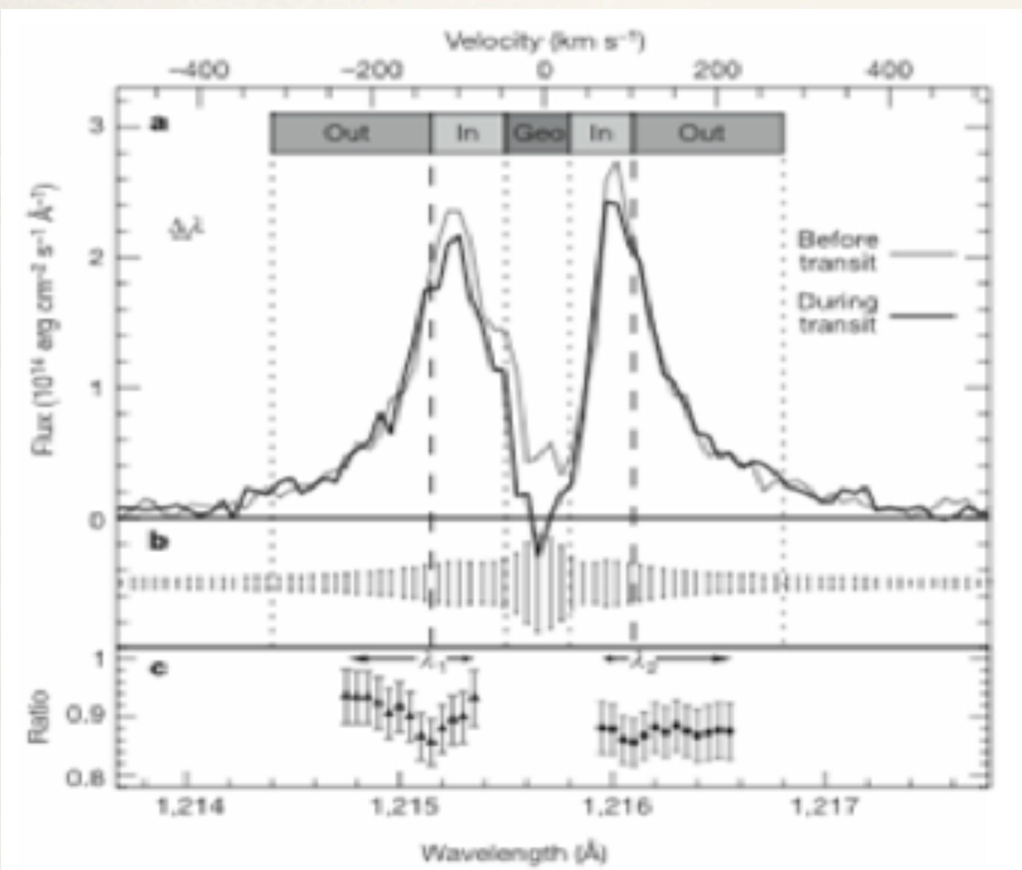


Transit : atmosphere composition

- In - off transit - transmission spectroscopy

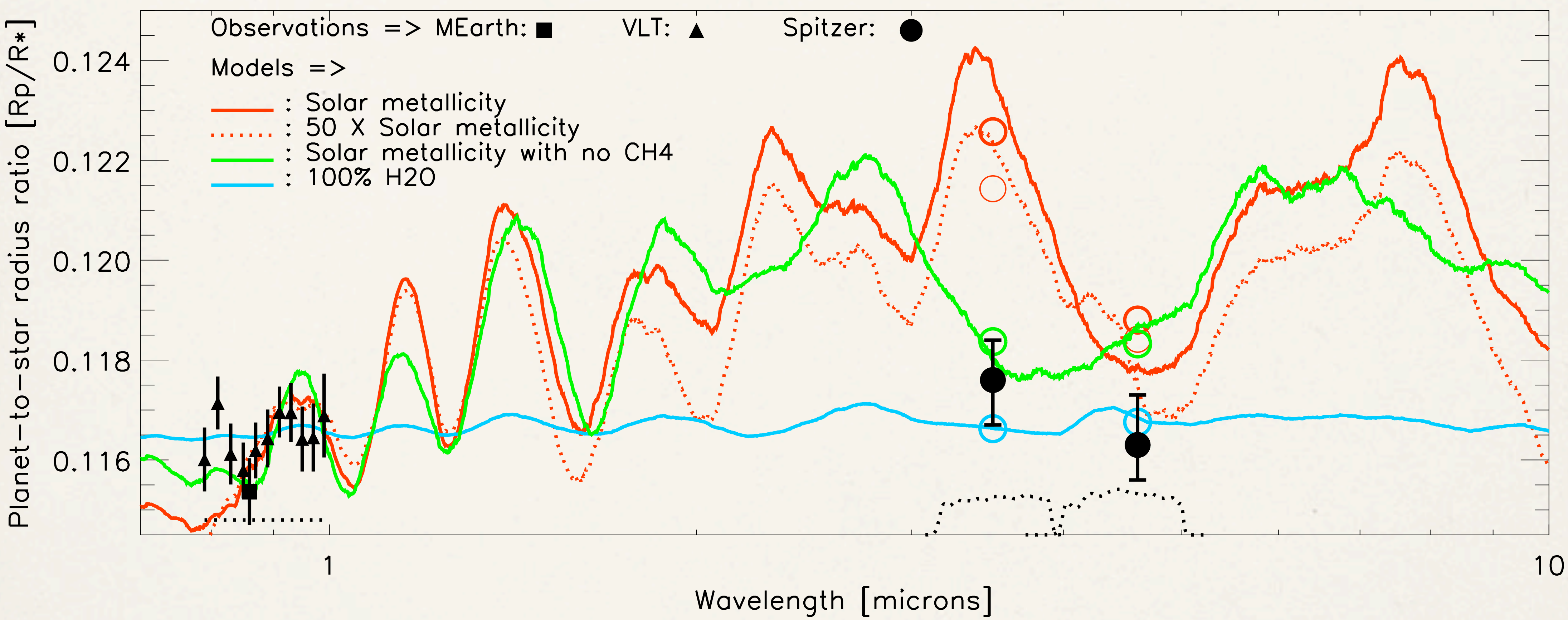


Na D lines : additional absorption during transit
Charbonneau et al., 2002



Hydrogen detection in Lyman α - HST observations
Planetary "blowoff"
Vidal-Madjar et al., 2004

Transit : atmosphere composition 2



GJ1214b $M_p = 6.55 +/- 0.98\ M_{Jup}$ $R_p = 2.68 +/- 0.13\ R_{Earth}$ star : M4V

at 3.6 and 4.5 microns with Spitzer

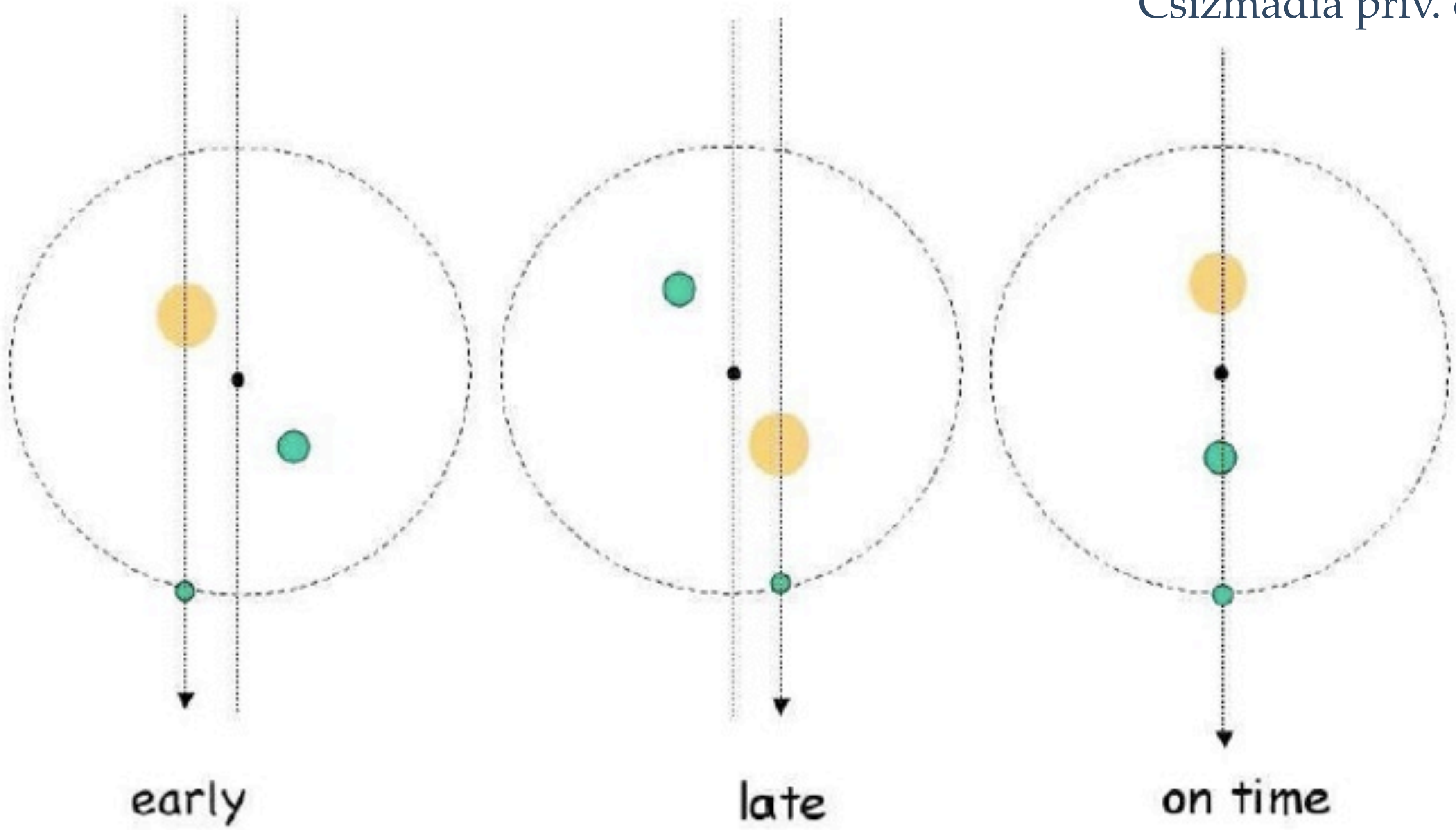
flat transmission spectrum over the large wavelength domain

➛cloud-free, metal rich atmosphere

Désert J.-M. et al., 2011, ApJ 731

Transits : timing variation induced by an additional planet

Csizmadia priv. com.



$$\Delta t \approx -\frac{x_*}{v_{pl} - v_*} \approx -\frac{T_{pl} a_{in} \mu_{in} \sin[2\pi(mT_{pl} - t_0)/T_{in}]}{2\pi a_{pl}}$$

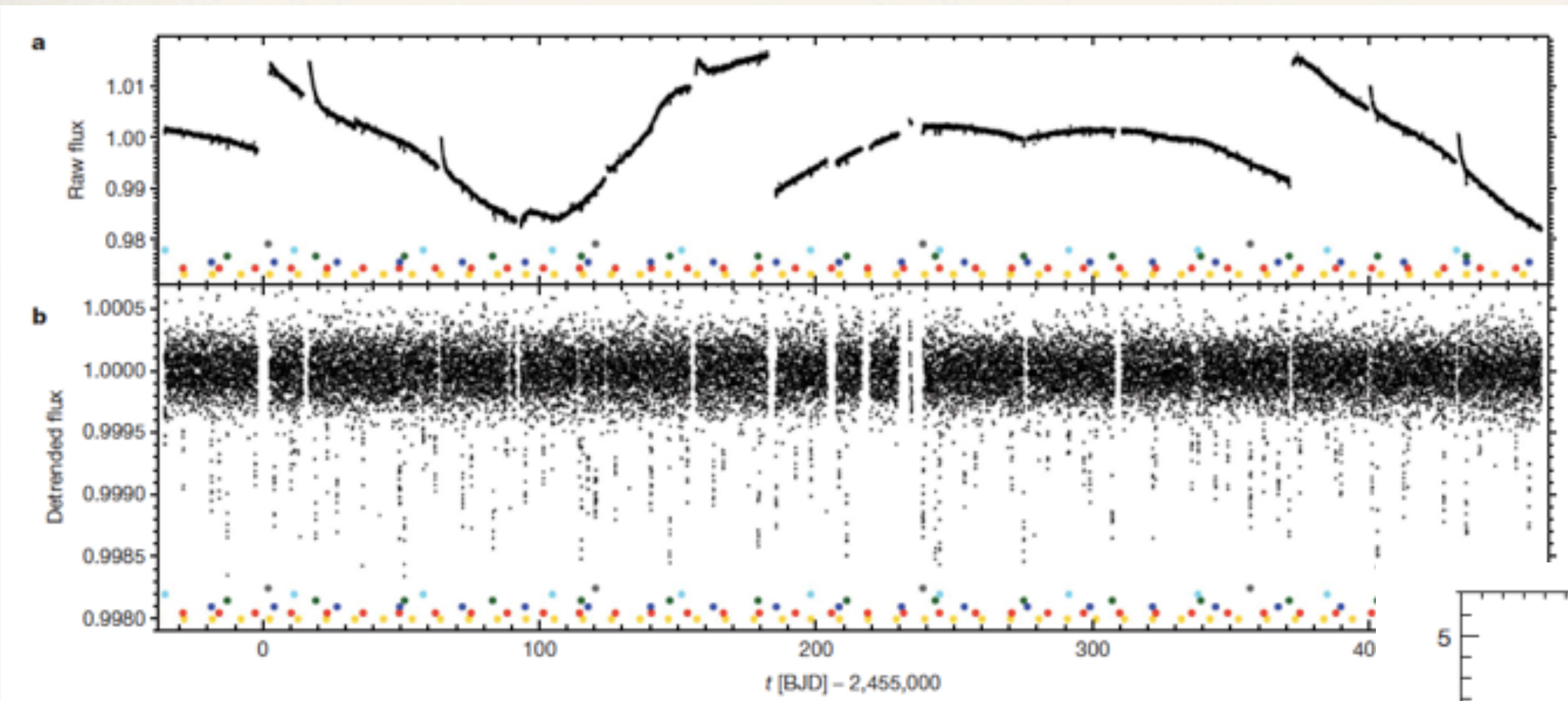
Transiting planet: Jupiter

Perturbing planet: Earth

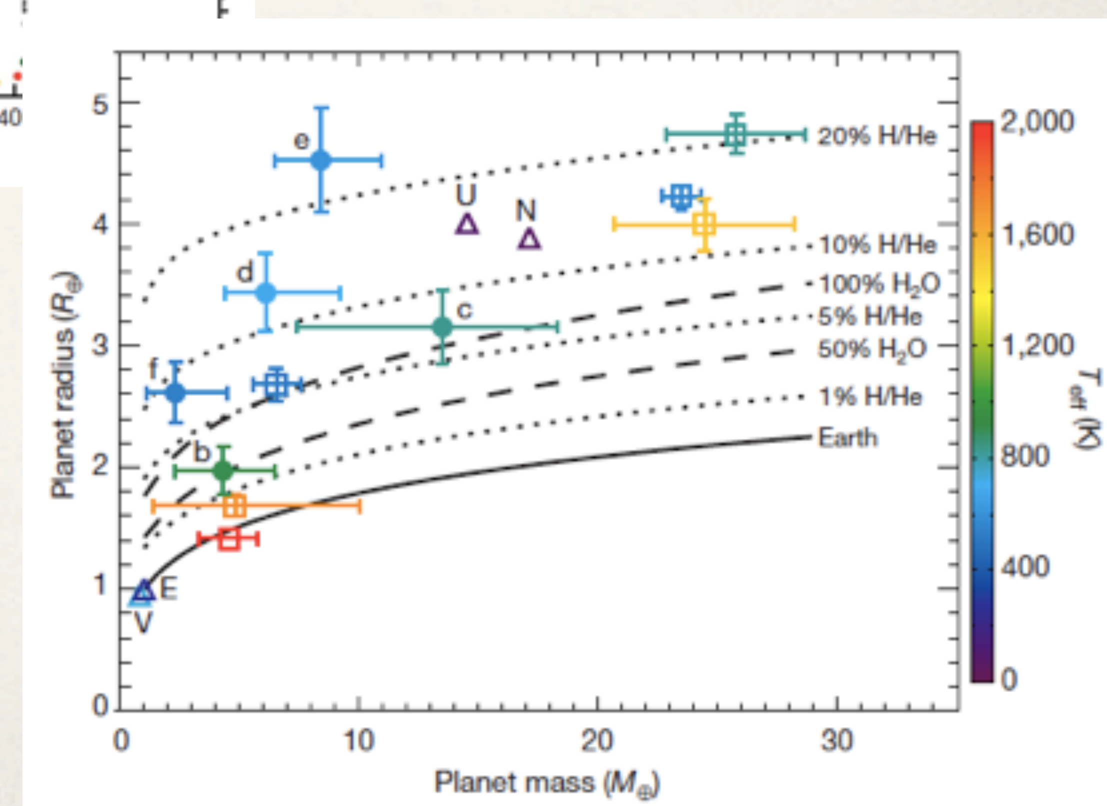
$\Delta t \approx 34$s

Agol, E. et al., 2005, MNRAS, 359, 567

TTV first success : Kepler-11 system



Lissauer et al., 2011, Nature



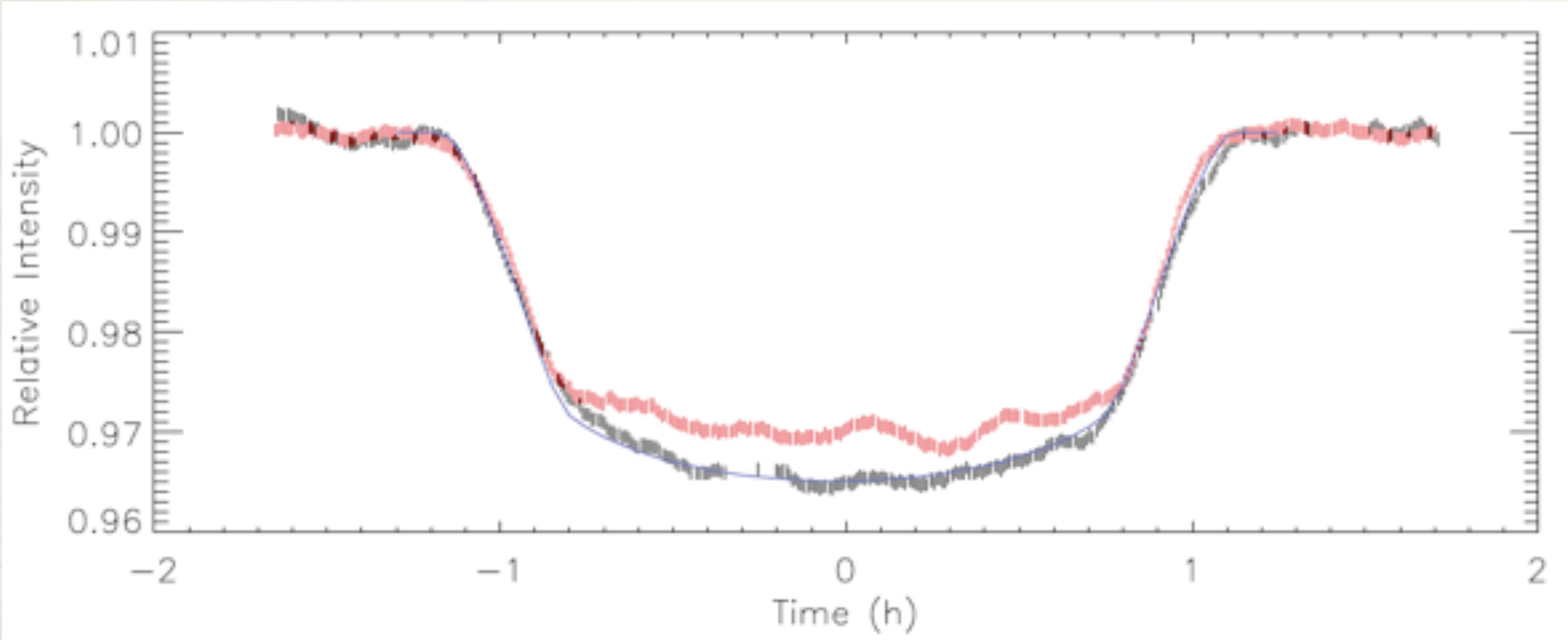
6 planets with orbital period between 10 & 118 days

Radii : 2 to 4.5 $R_\oplus$

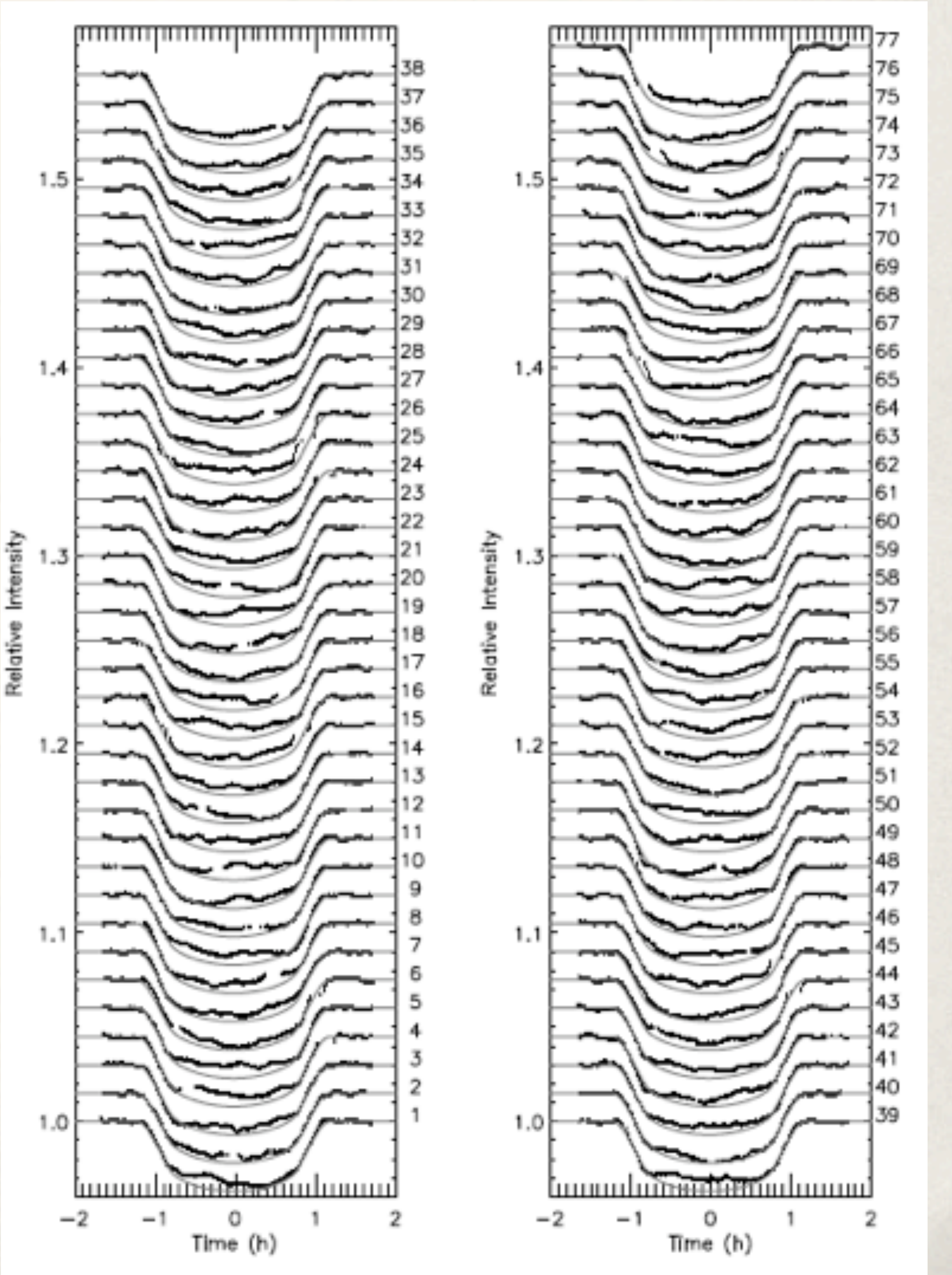
Masses from dynamics (but Kepler-11g)!

Probing the star's surface and understanding the star's activity

- stellar spots leave their imprints on the transits
  - $R_p/R_\star = 0.172$ (3% larger)
  - Average of 7 spots covered per transit
  - spot size : 03 - 0.6 Rp
  - Temperature : 4600 to 5400 K
    ($R_\star$ =5625K)
  - rise & decay ~ 30 days



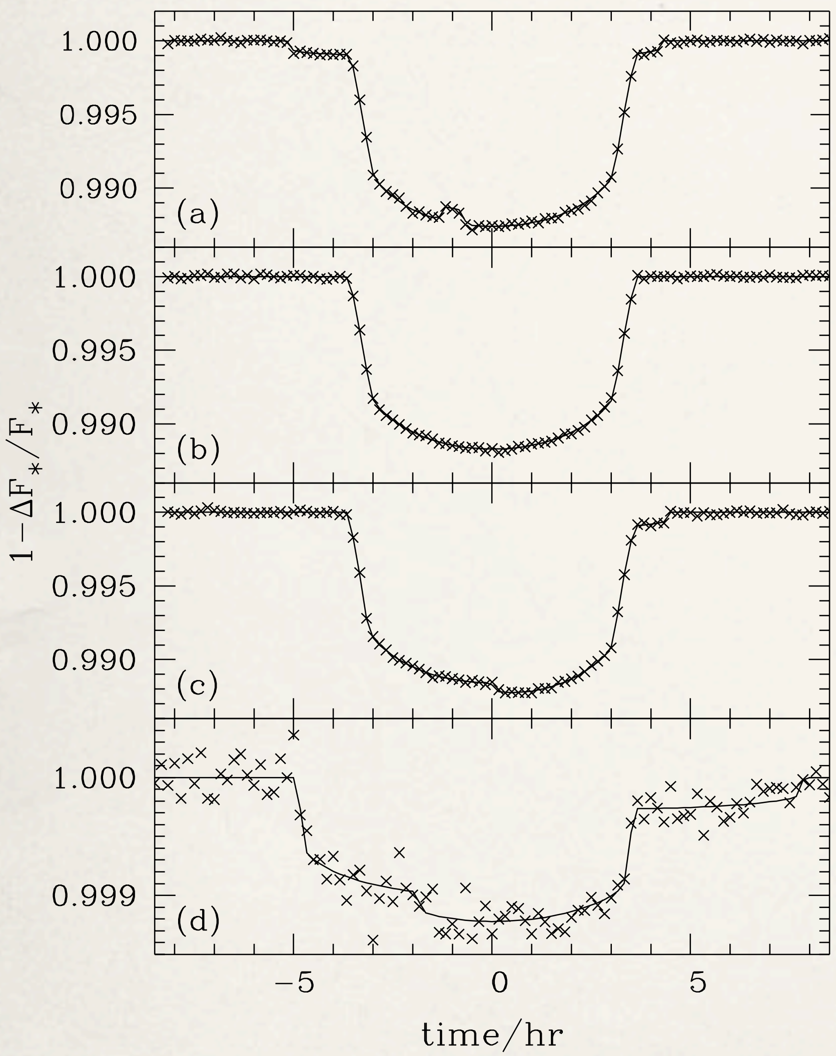
Czesla et al., 2009, A&A 505
Wolter et al., 2009, A&A 504

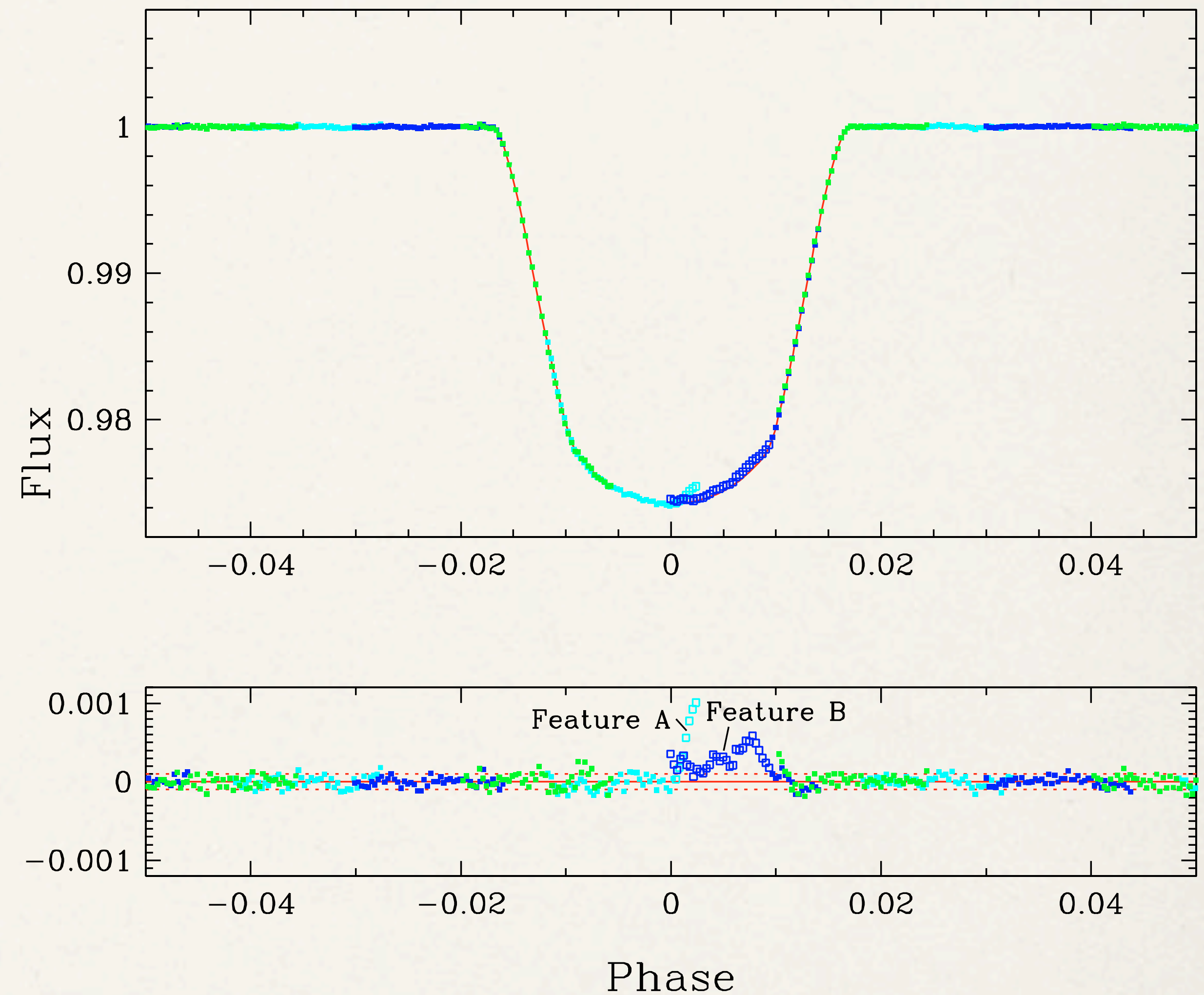


Silva-Valio et al., 2010, A&A 510

Moons, rings & others

direct measure of the transit of a moon





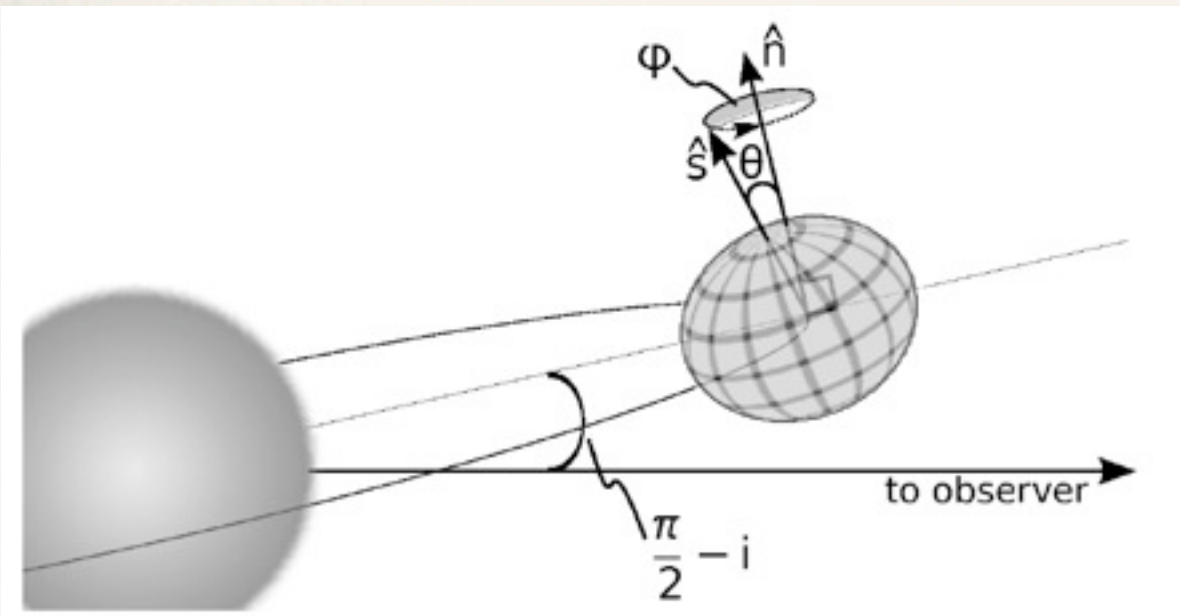
Test on HD 189733 : moon or rings but a large spot complex (> 80 000km)
Pont et al., 2007, A&A 476

Theoretical study :
Sartoretti & Schneider 1999, A&A

Moons, rings & others

Measure of the planet's oblateness & spin precession

Carter et al., 2011, ApJ 730



Saturne oblateness : 200 ppm and 2 ppm for a synchronized hot Jupiter

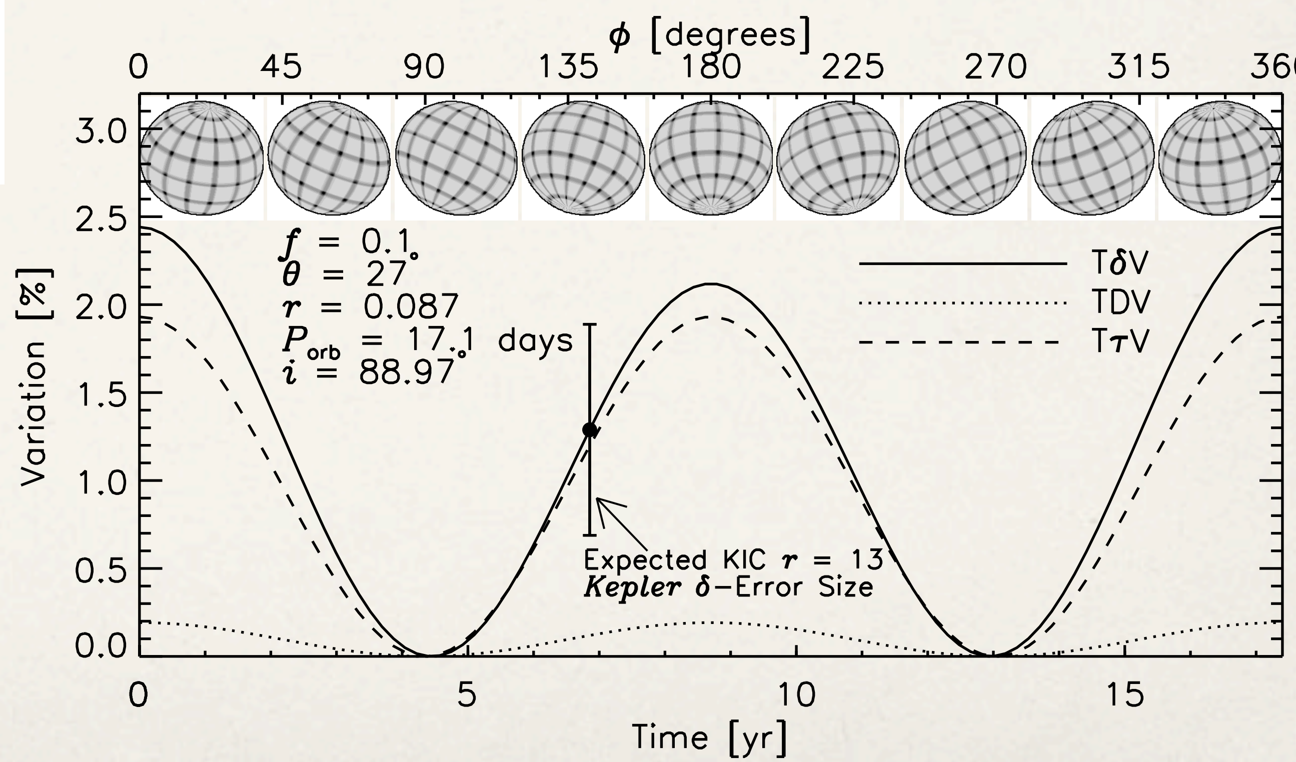
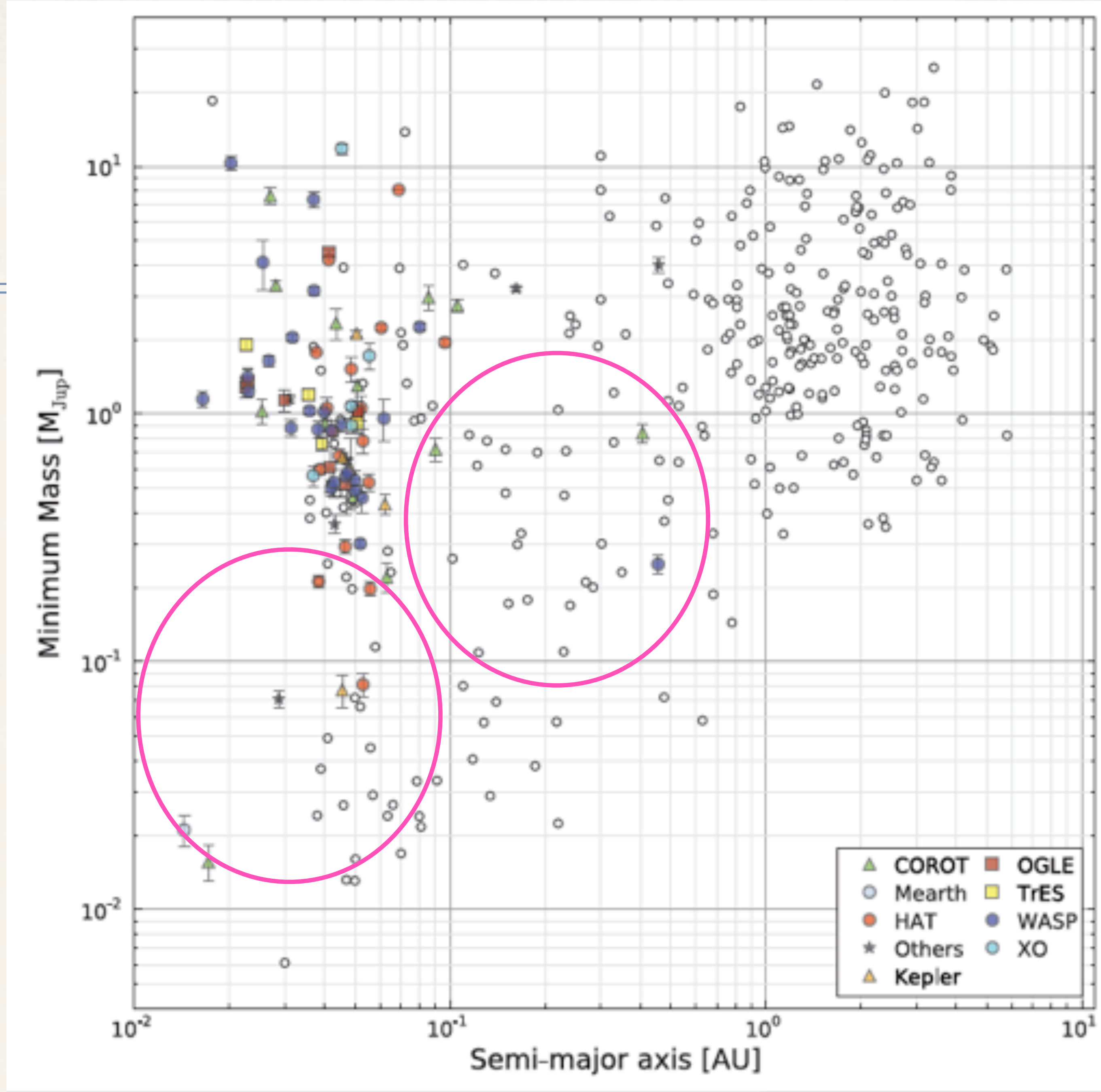


FIG. 4.— Variations in the transit light curve due to an oblate, oblique, precessing exoplanet. Plotted are the transit depth (δ), total duration ($T_{\rm full}$) and ingress duration (τ) fractional variations (TδV , TDV, and TτV, respectively) that are expected for a uniformly precessing Saturn-like planet around a Sun-like star. The time scale is based on the assumption $P_{\rm orb}$ = 17.1 days.

Precession of an oblate oblique planet causes changes in the **depth** and duration of transits

Conclusions



* Transits : a powerful tool for characterizing planetary systems :

fundamental parameters, orbit configuration .. ➛ constraints for their formation mechanism(s) and evolution

* Allow to enlarge the space parameters and to start physics studies

* Objectives : toward the small size planets and the long orbital periods

* Observations of bright targets are now required!