The effect of stellar activity and limb-darkening on the precision of planet radii

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Based on: Csizmadia, Pasternacki, Dreyer, Cabrera, Erikson, Rauer: A&A 549, A9 (2013)
and Csizmadia et al. (2013) in prep.

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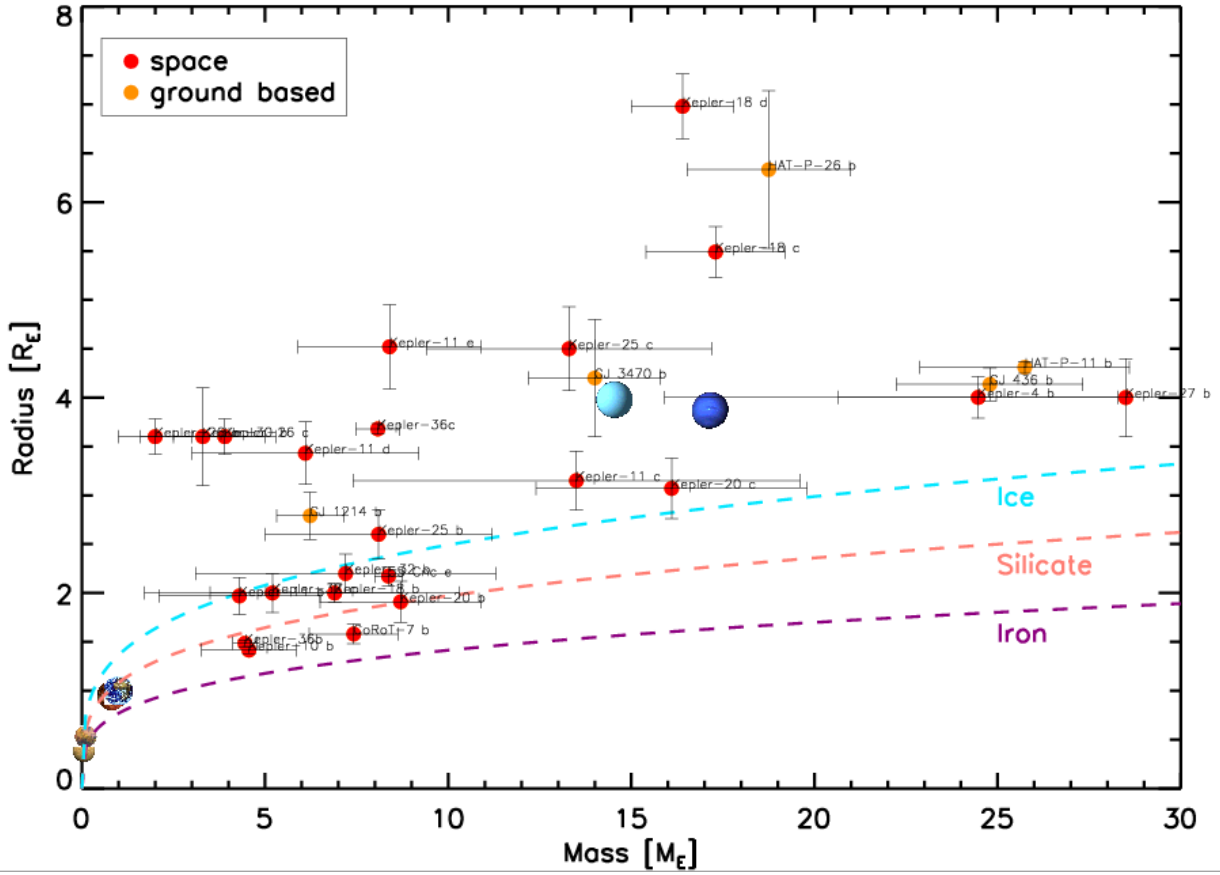
motivation: parameters for transiting planets

to which precision?

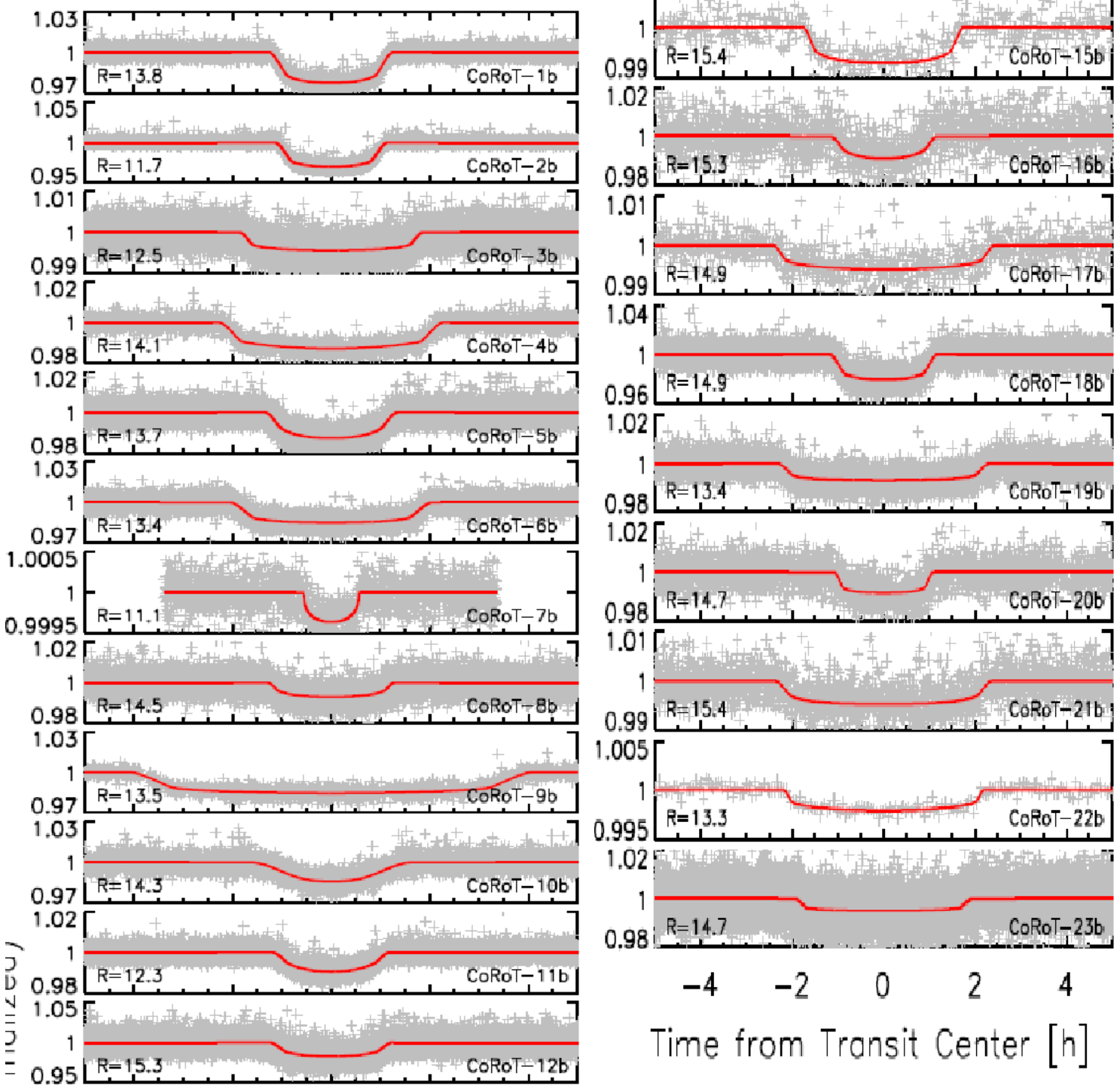


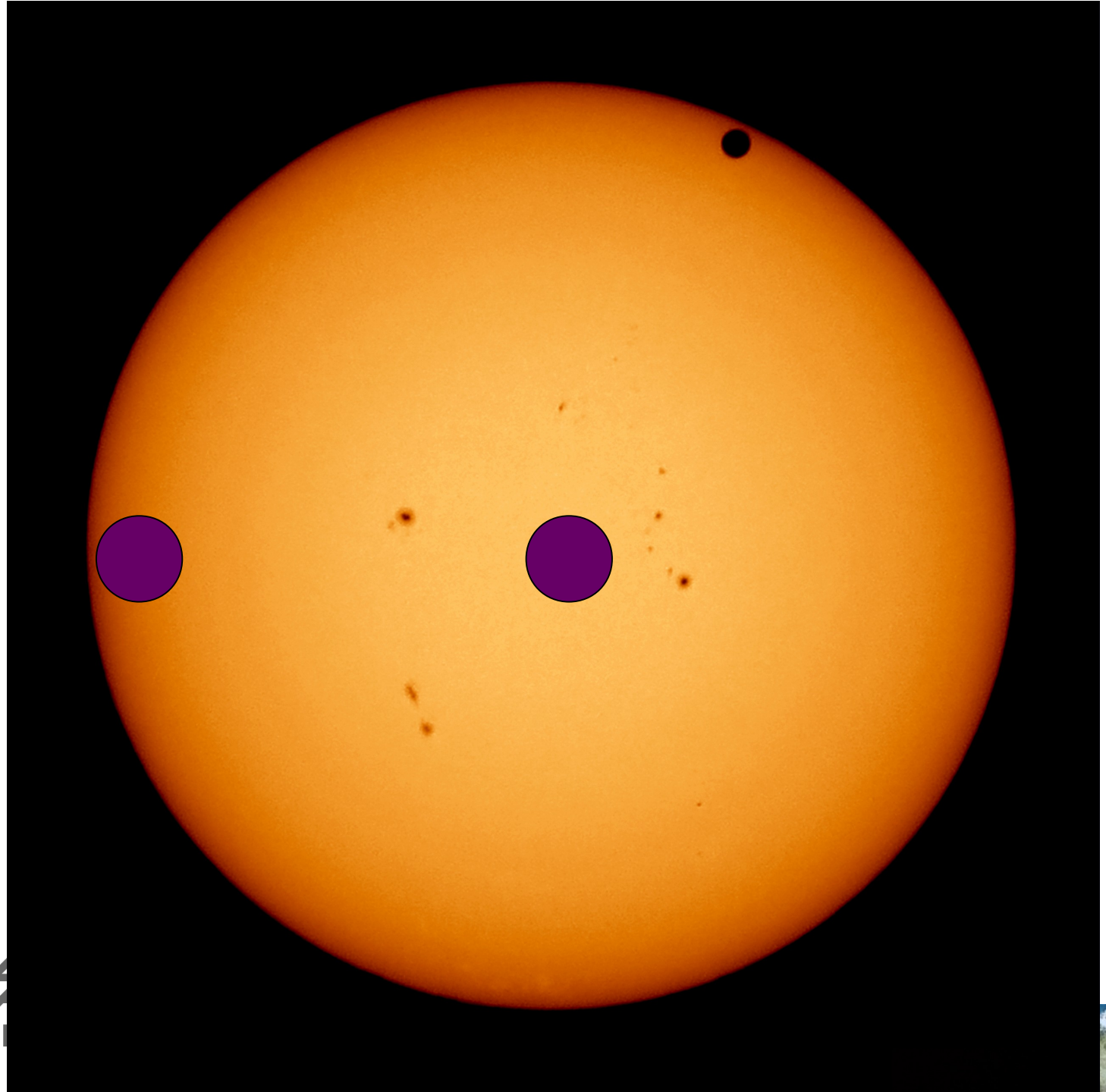
mass to **10%** and radius to **5%** to distinguish between solid rocky and water rich planets

better than **2%** in radius for further bulk characterization

(Valencia et al. 2009, ApJ, 665; Grasset et al. 2009, ApJ, 693; Wagner et al. 2011, Icarus, 214, 366)

CoRoT transit family





Effect of limb darkening on transit depth and shape

~50% approximation:

$$\Delta F = k^{2,} \qquad k = \frac{R_{planet}}{R_{star}}$$

Precise:

$$\Delta F = k^2 L_D(T_{eff}, g, \lambda, [M/H]...)$$

Knowledge of L_D would reduce the number of free parameters and the degeneracy which occurs from time to time.

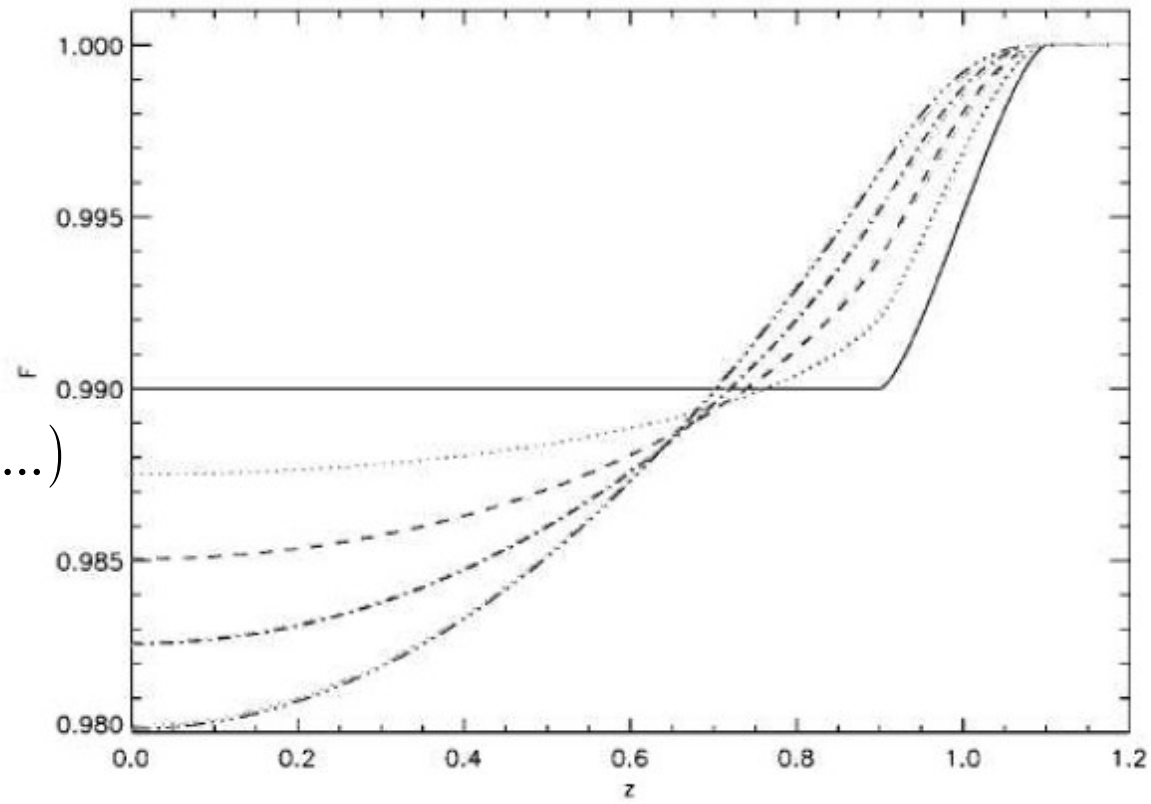


FIG. 2.—Transit light curves for $p = 0.1$ and $c_1 = c_2 = c_3 = c_4 = 0$ (*solid line*), and all coefficients equal zero but $c_1 = 1$ (*dotted line*), $c_2 = 1$ (*dashed line*), $c_3 = 1$ (*dash-dotted line*), or $c_4 = 1$ (*dash–triple-dotted line*). The thinner lines (nearly indistinguishable) show the approximation of § 5.

Mandel & Agol (2002) ApJ, 580

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Limb darkening: observations vs theory

sometimes, theory and observations agree well:
e.g. CoRoT-8b (Bordé et al 2010), CoRoT-11b (Gandolfi et al. 2010)…

sometimes there are large differences:
e.g. CoRoT-13b (Cabrera et al. 2010; Southworth 2011), CoRoT-12b (Gillon et al 2010), HD 209458 (Claret 2009), Kepler-5b (Kipping & Bakos 2011), WASP-13 (Barros et al. 2012)…

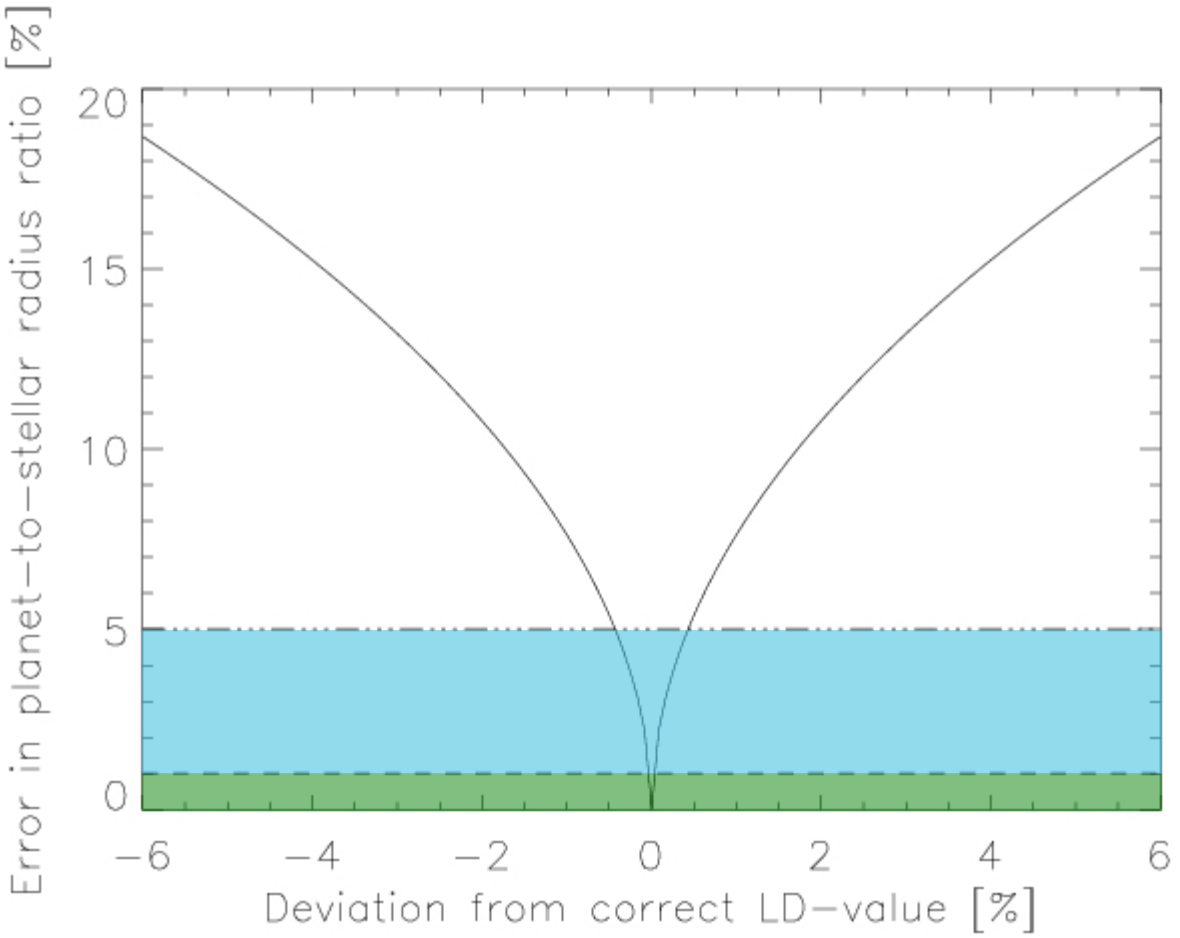
Motivating factors:
(1) To understand these agreements/disagreements.
(2) To understand the results of the homogeneous re-analysis of the CoRoT transits.
(3) To understand the accuracy and systematics of our planetary raddii (and mean densities).

Calculation shows (Csizmadia et al. 2013, A&A 549, A9): to measure the planet-to-stellar radius ratio with 5% uncertainty, you need to know the limb darkening with at least 0.5% precision.

In general, we do not have this precision.

Stellar parameters:
±100K in Teff
±0.1 in logg
±0.1 in [M/H]:

5% in limb darkening coefficients.



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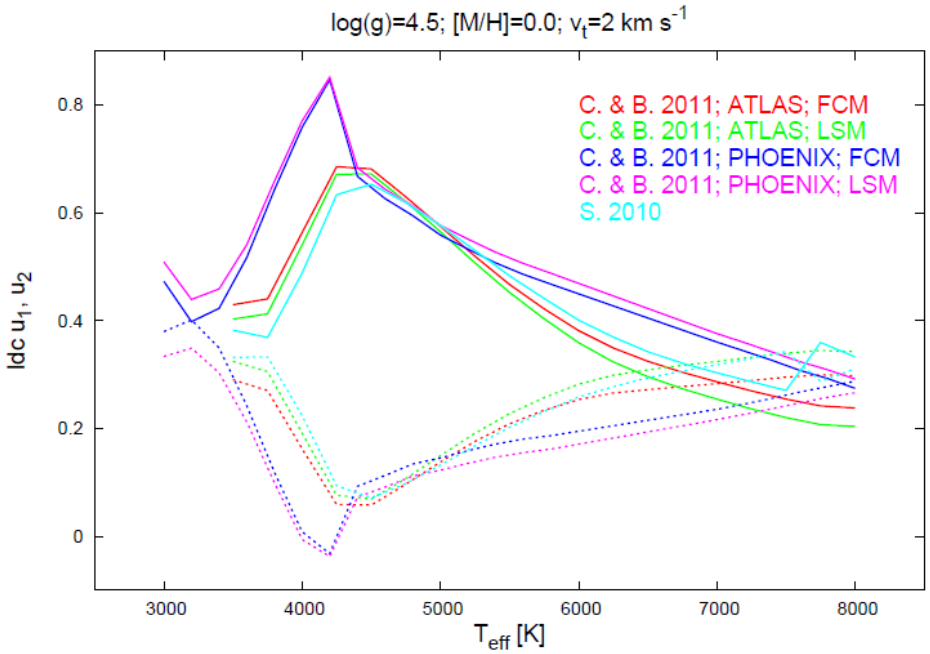
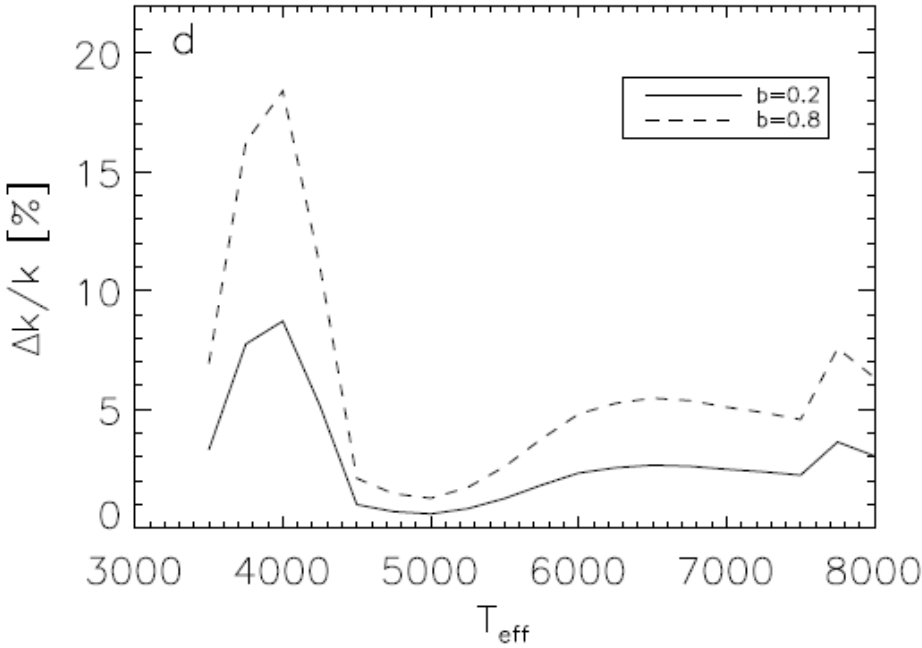
Theoretical uncertainties of 1D limb darkening





Csizmadia et al. (2013) A&A 549

{3D modeling efforts: Hayek et al. 2012, A&A,539}

modelling of planetary parameters:
impact of limb darkening

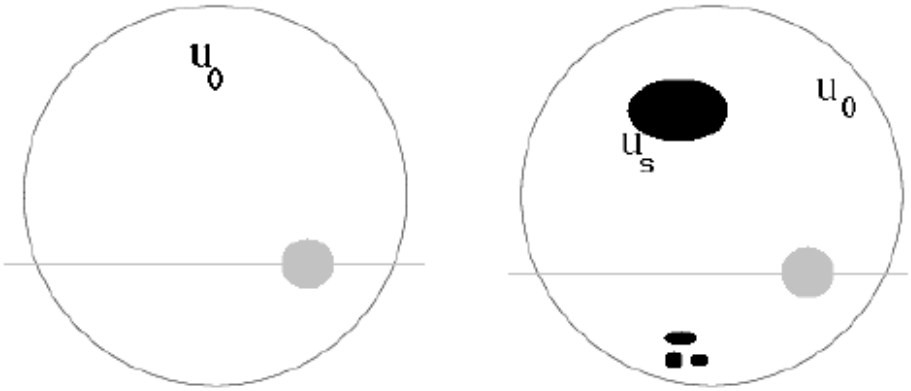


Fig. 4. Illustration of the effect of Type I spots. Left: the planet crosses an unmaculated star that is characterized with some limb darkening coefficient u_0. Right: the planet crosses the appareant stellar disc of a spotted star, where the spots and the planet have different impact parameters, as well as the stellar photosphere and the spots have different limb darkening coefficients (u_0, u_s). Grey area is the planet, black ellipses represent the spots.

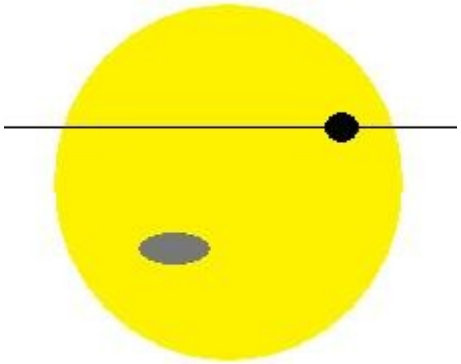
Csizmadia et al. (2013) A&A

apparent stellar disk cannot be characterized with single effective temperature (and not only because of gravity darkening, von Zeipel 1924; Barnes 2009...)
surface brightness cannot be characterized with single limb darkening coefficient (associated to a single effective temperature

Stellar spots and faculae

Type I

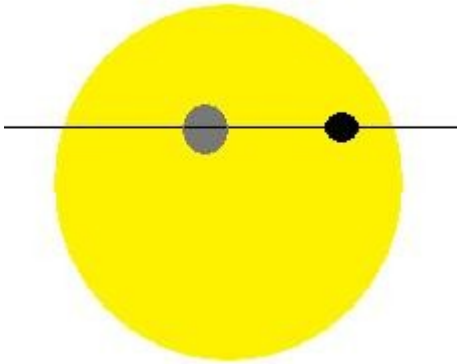
Short life-time,
not occulted



↑Can be removed by baseline-fitting

Type II

Short life-time,
occulted

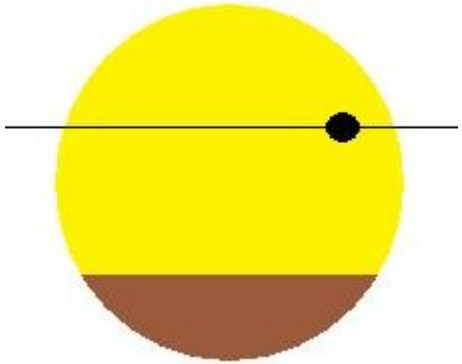


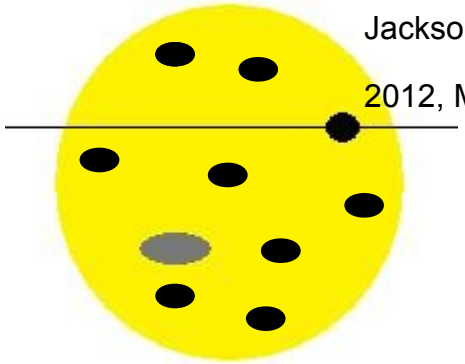
↑Can be removed by spot-modeling

{for spot crossing, see Silva-Valio&Lanza 2010; Sanchis-Ojeda&Winn 2011...}

Type III

Long life-time, pole-on,
slow rotation, no modulation





Jackson & Jeffries 2012, MNRAS 423

EXTRA ± CONTAMINATION!!

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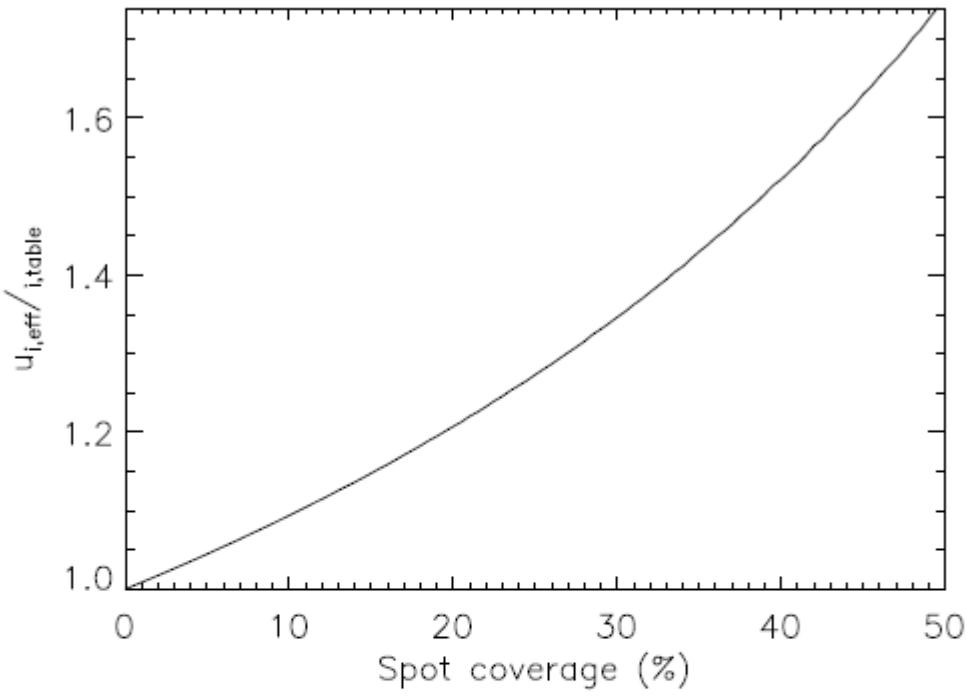
modelling of planetary parameters:
impact of limb darkening

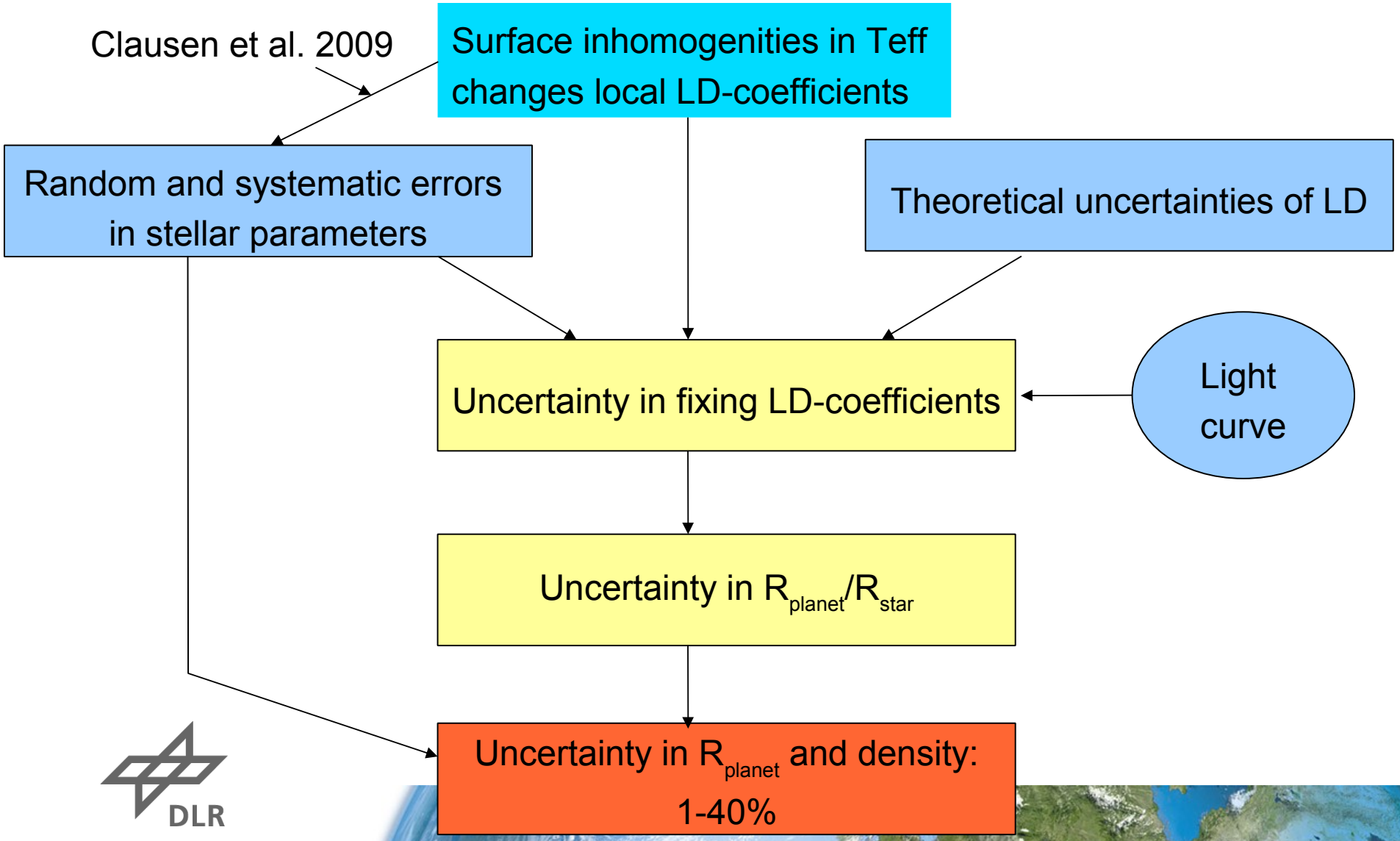
spots act as sources of contamination, but they also change the effective measured limb darkening coefficients



Csizmadia et al. (2013) A&A

Fig. 5. The x-axis is the total spotted area in percentage of the whole stellar surface area. The y-axis is the effective - i.e observed - limb darkening coefficients relative to the table value at the given stellar efffective temperature. For this figure we used $T_{star} = 5775$K and $T_{spots} = 3775$K, and the positions of the spots were chosen randomly on the visible hemisphere. The size of the spots were always the same, so higher spot coverage corresponds to larger number of spots. The limb darken-

Factors which affect the planetary radii determination



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Factors which affect the planetary radii determination

Clausen et al. 2009

Surface inhomogenities in Teff changes local LD-coefficients

Random and systematic errors in stellar parameters

Adjusting LD-coefficients

Light curve

Uncertainty in R_{planet}/R_{star}

Uncertainty in R_{planet} and density 1-20%, dominated by Rstar

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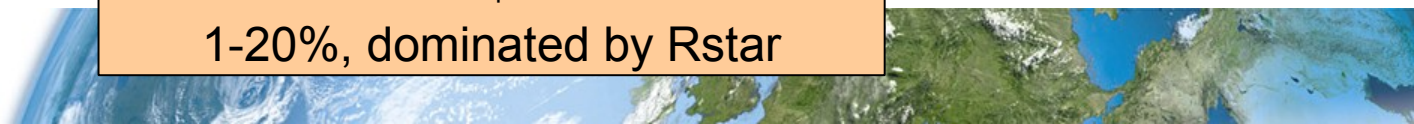

Conclusion

(1) We have a much deeper understanding of spot-limb darkening relation, and what the impact of LD-uncertainty on the planetary parameters is.

(2) We advise to fit the limb-darkening coefficients, even if the SNR is low. (Systematics due to spots!)

(3) Now we can interpret the results of the homogeneous re-analysis of the CoRoT transit light curves (Csizmadia et al. 2013, in prep.).

(4) 3D models of stellar atmospheres are urgently needed for space observatories (MOST, CoRoT, Kepler, PLATO, etc.). Effect of spots should be included somehow.

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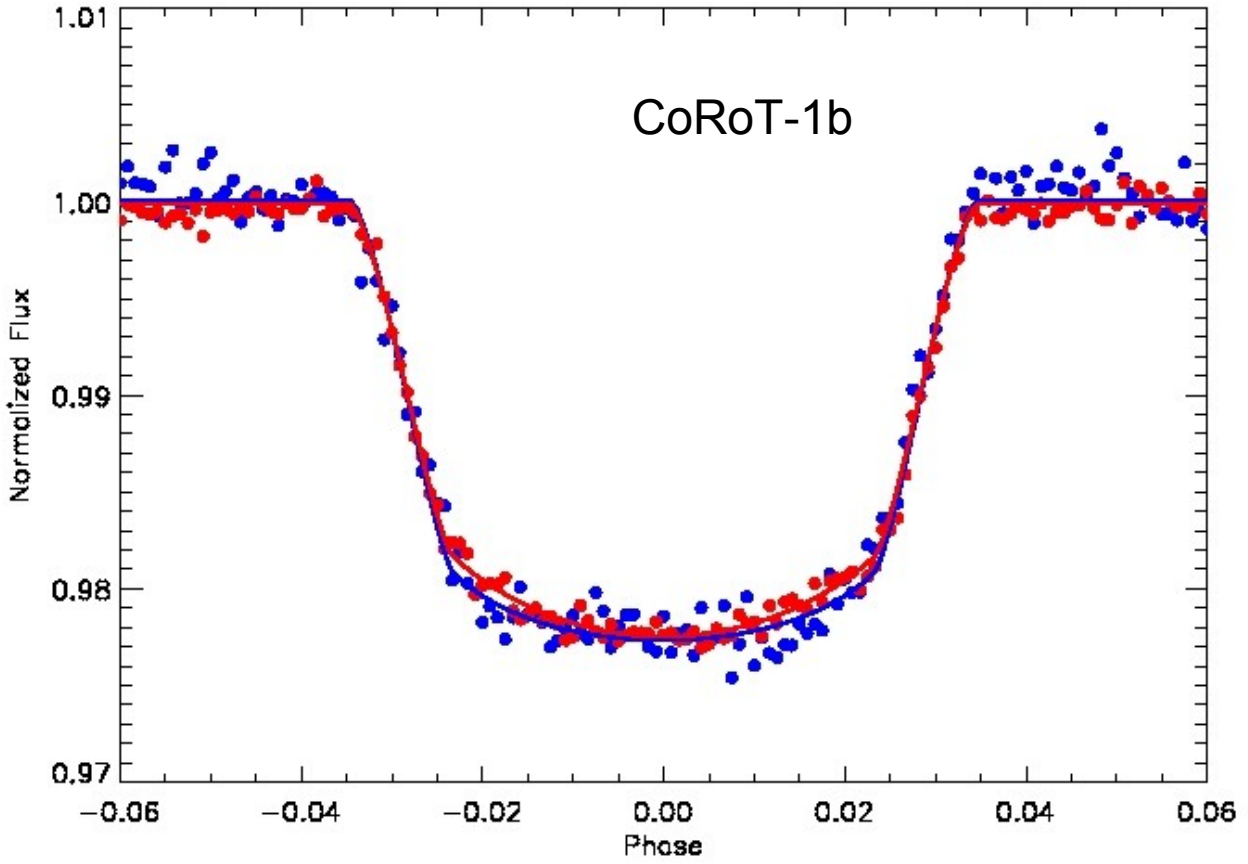
Backup slides



CoRoT host stars:

24 systems, 25 transiting planets

14 coloured+white LCs

Out of the 14 multicolour transits:

8 has normal behaviour (57%)

6 has inverse behaviour (43%)

The study of the correlation between this effect and activity indicators is still ongoing.

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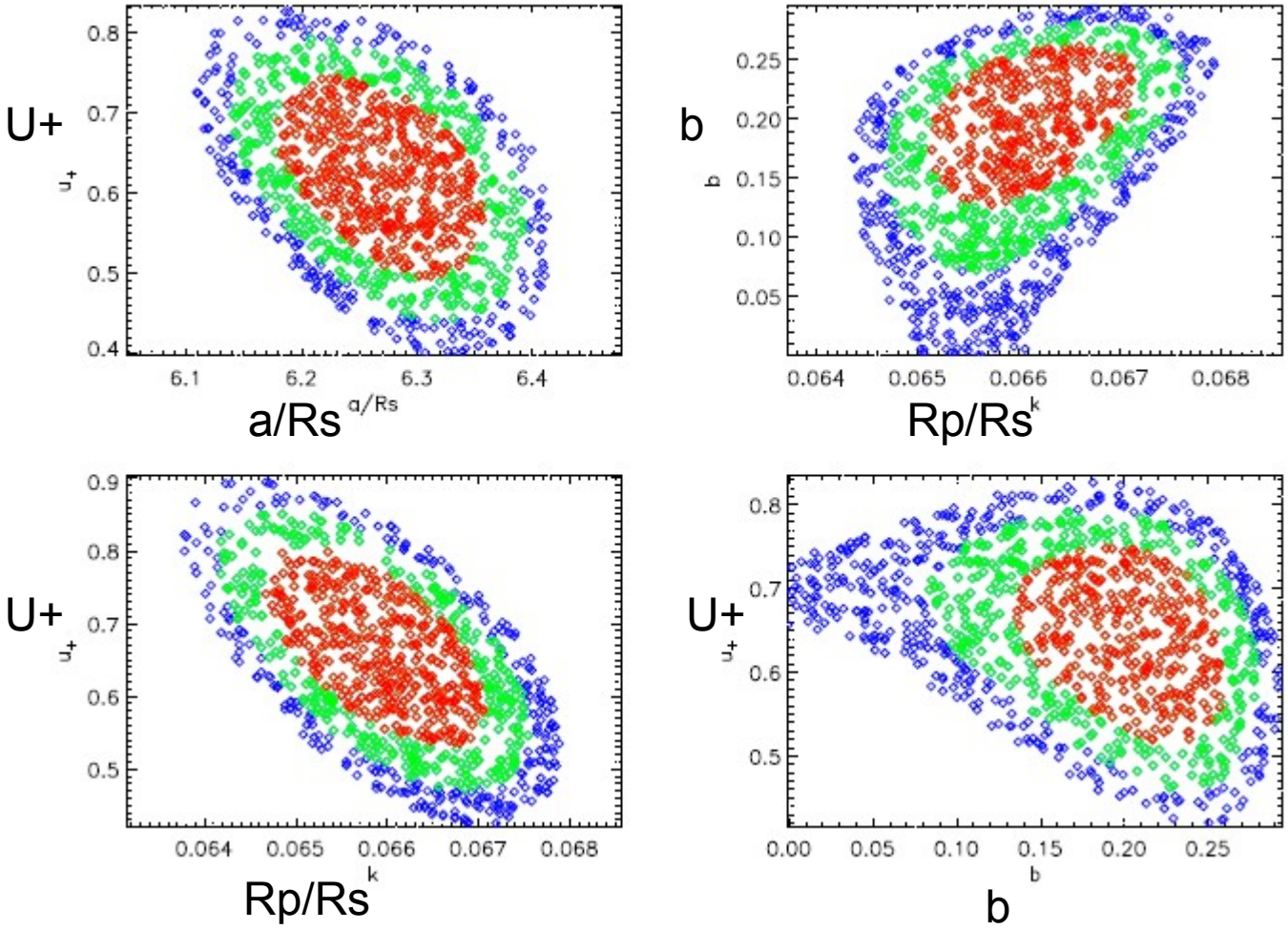
modelling of planetary parameters:
impact of limb darkening



Csizmadia et al. (2011) A&A, 531 [CoRoT 17b]

CAVEAT:

Limb darkening is a polynomial expresison of the coeffciients:

$$I(\mu)=I_0(1-u_1(1-\mu)-u_2(1-\mu)^2-...)$$

Other numbers can be as good approximations. Not The value of the coefficients are important, but the shape of the intensity distribution.

However, inverse effect remains.

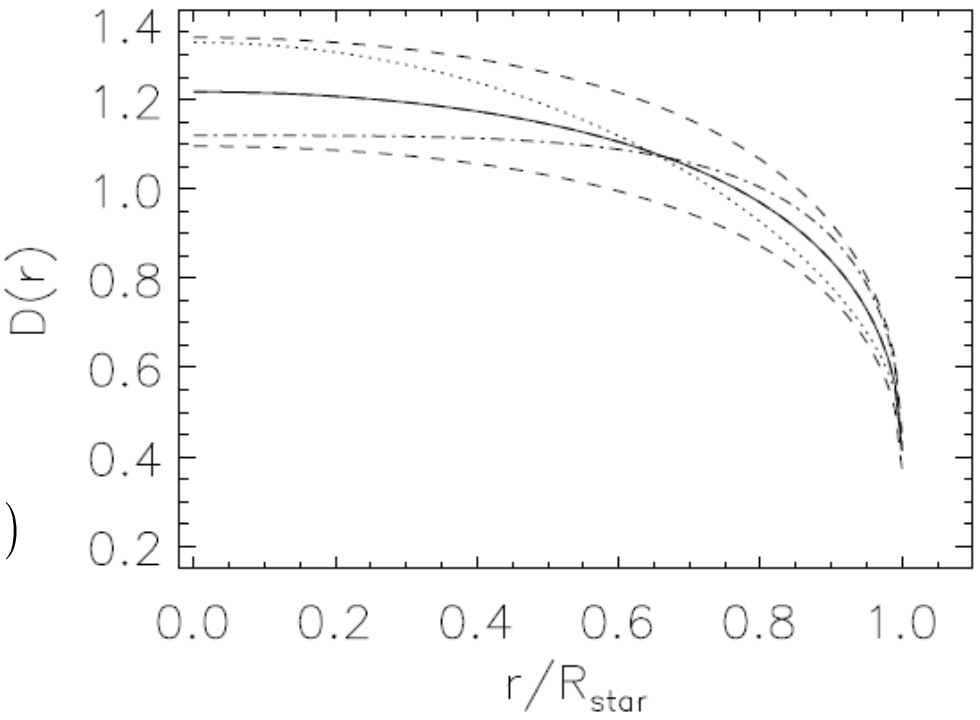


Fig. 7. The radial intensity profile $D(r/R)$ as a function of the sky-projected distance r from the stellar centre (R is the stellar radius). As in all calculation in this paper, $\mu = \sqrt{1-(r/R)^2}$. The solid line shows the effect of limb darkening $D(r) = L_D(u_1, u_2, \mu)/(1 - u_1/3 - u_2/6)$ that - multiplied by k^2 - is directly proportional to the light loss during a transit. The dashed lines show the tolerable ranges: between these lines the radial intensity distribution profile will produce a radius ratio k that is in the tolerance range of ±5%. The dotted line is an example of an acceptable radial intensity distribution profile with $u_1 = 0.82, u_2 = -0.16$, while the dot-dashed line is with $u_1 = 0.02$, $u_2 = 0.6$.

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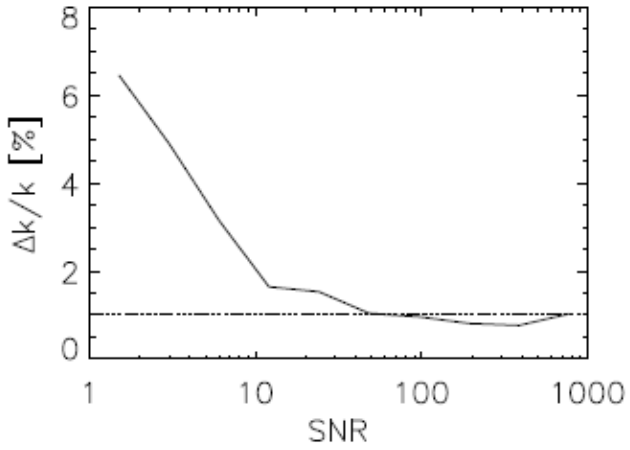
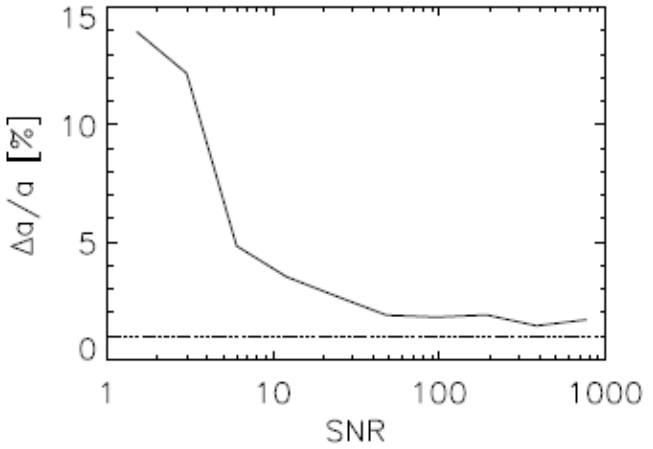
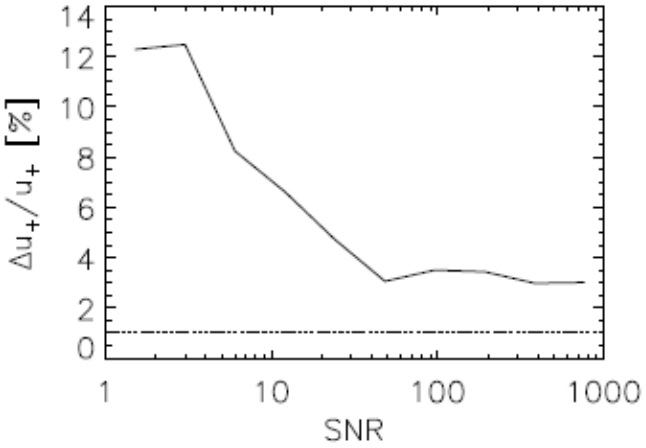
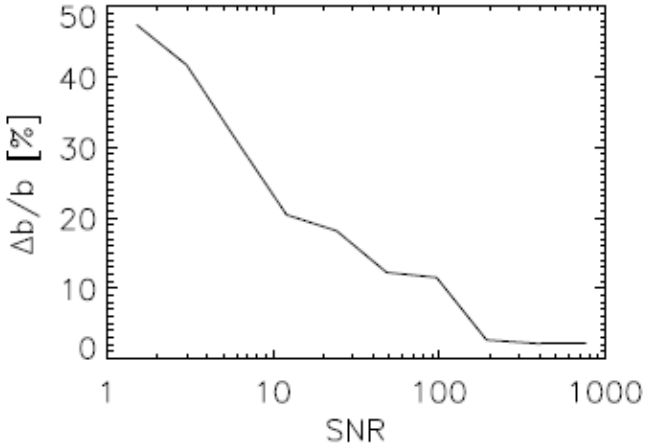
modelling of planetary parameters:
impact of limb darkening









Csizmadia et al. (2013) A&A

Random and systematic errors in stellar parameters

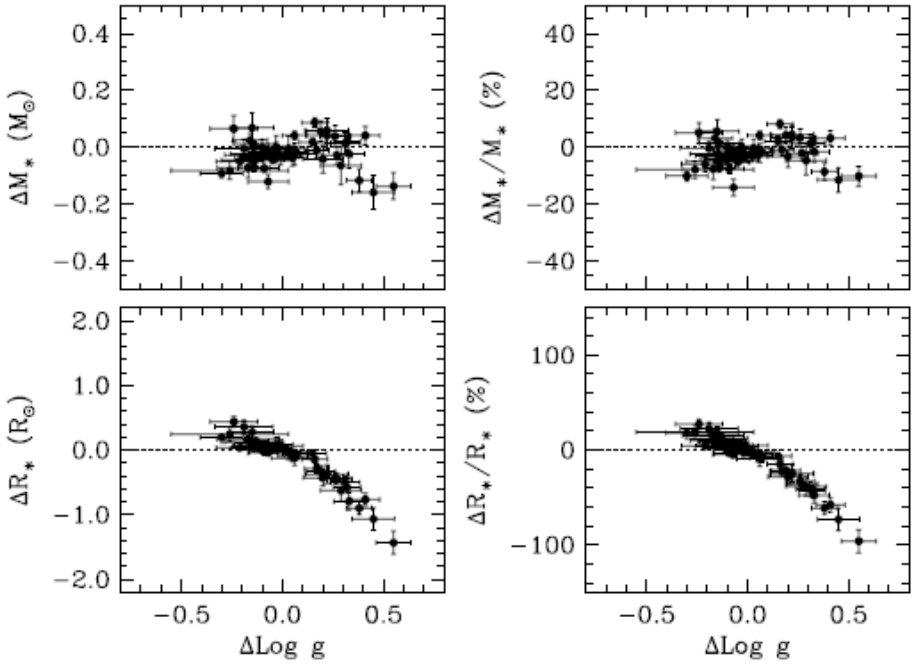


FIG. 10.— Mass and radius differences resulting from the use of constrained and unconstrained spectroscopic properties from SME along with stellar evolution models. Differences in the sense ⟨constrained minus unconstrained⟩ are shown in absolute units on the left, and as a percentage of $M_\star$ or $R_\star$ on the right.

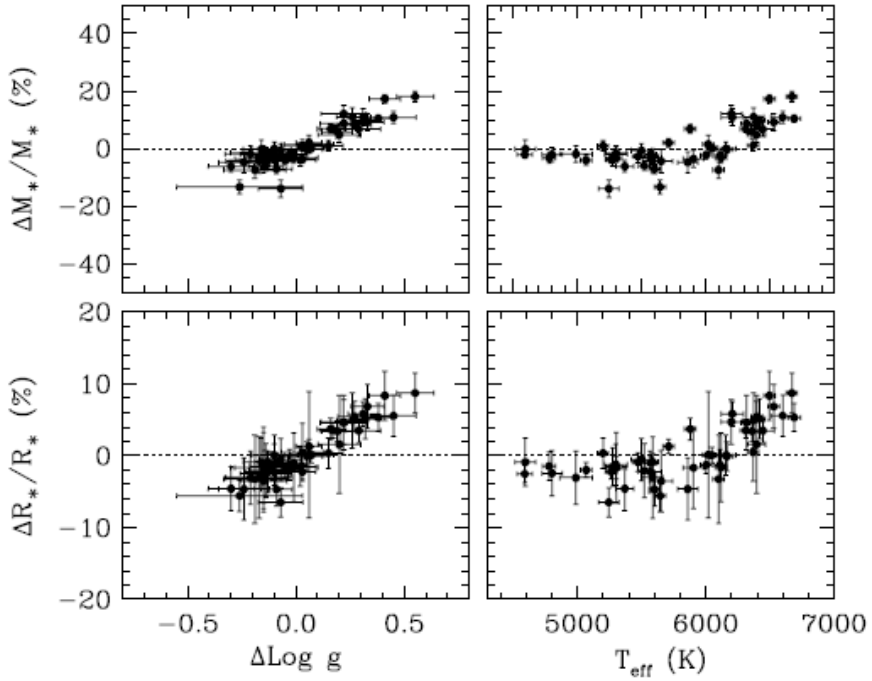


FIG. 11.— Systematic errors in the stellar mass and radius (expressed as a percentage) when using *unconstrained* values of $T_{\rm eff}$ and [Fe/H] from SME together with the external photometric constraint on $\log g$ from the mean stellar density. The differences shown are between the mixed usage just mentioned and the constrained results from a second iteration of SME described in the text. in the sense ⟨mixed minus constrained⟩.

Torres et al. (2012) ApJ, 757

Even in the best case, uncertainties in planetary parameters can be up to **10%**

{only way through is asteroseismology, from space (CoRoT, Kepler) but limited amount of targets (limited by brightness) → ...PLATO (Rauer, Friday)}

DLR