Characterization of Exoplanets and Exoplanetary Systems: Transition from CoRoT & Kepler to TESS & PLATO

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The Space Photometry Revolution
CoRoT Symposium 3 – Kepler KASC 7 Joint Meeting
Toulouse, France
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The Royal Road of Transiting Exoplanets

Detection of a candidate

Validation

Confirmation

Characterization

The Royal Road of Transiting Exoplanets

Detection of a candidate

Validation

Confirmation

Characterization:

planetary mass	**albedo, equilibrium temperature**
planetary radius	dayside temperature
orbital elements	nightside temperature
moons	rotational period and obliquity
rings	atmospheric composition
ellipsoidal shape?	interior structure and composition
magnetic field	surface properties
star-planet interaction	(atmospheric) mass-loss rate

The Royal Road for Transiting Exoplanets

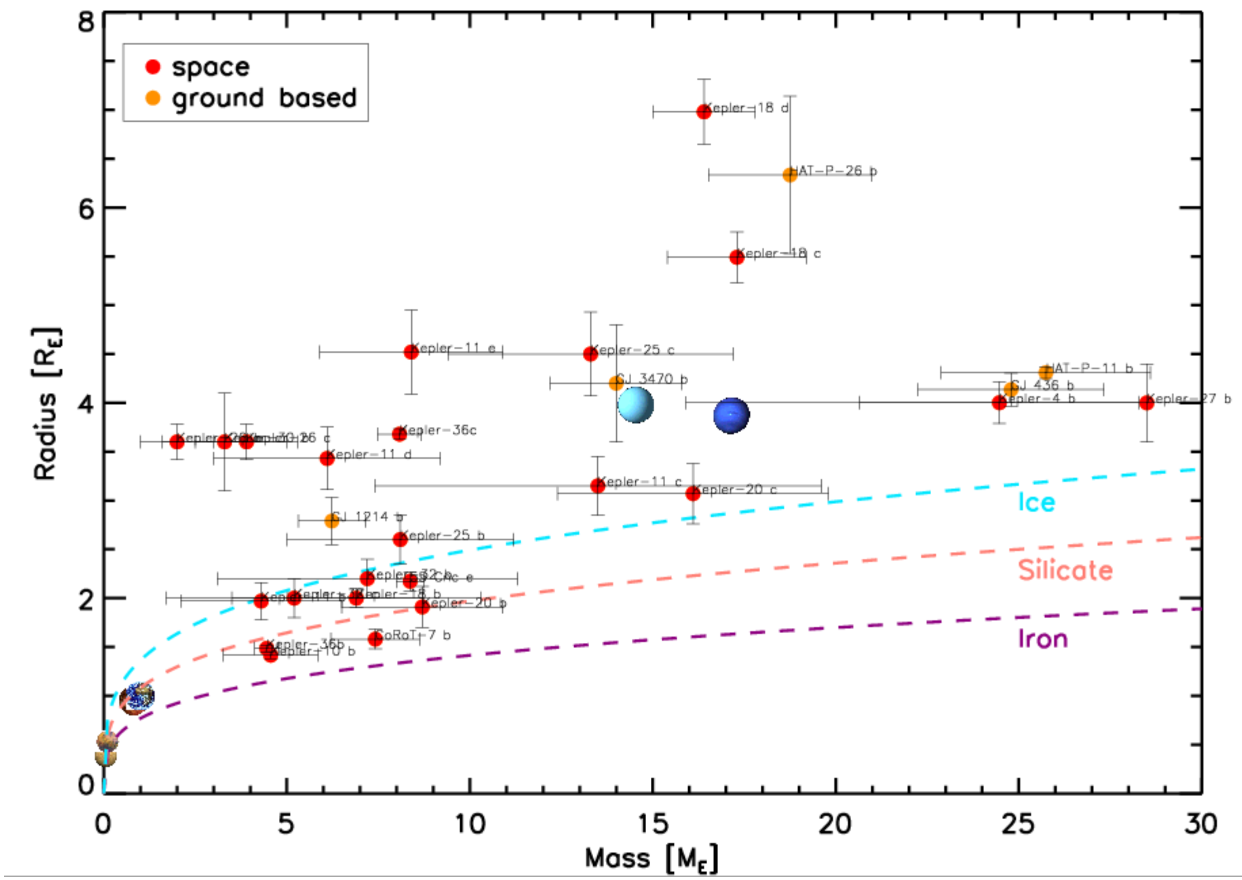
Detection of a candidate

Validation

Confirmation

Characterization: - for masses: talk by A. Santerne
- non-spherical stars (gravity darkening): talk by J. Cabrera

motivation: parameters for transiting planets
to which precision?

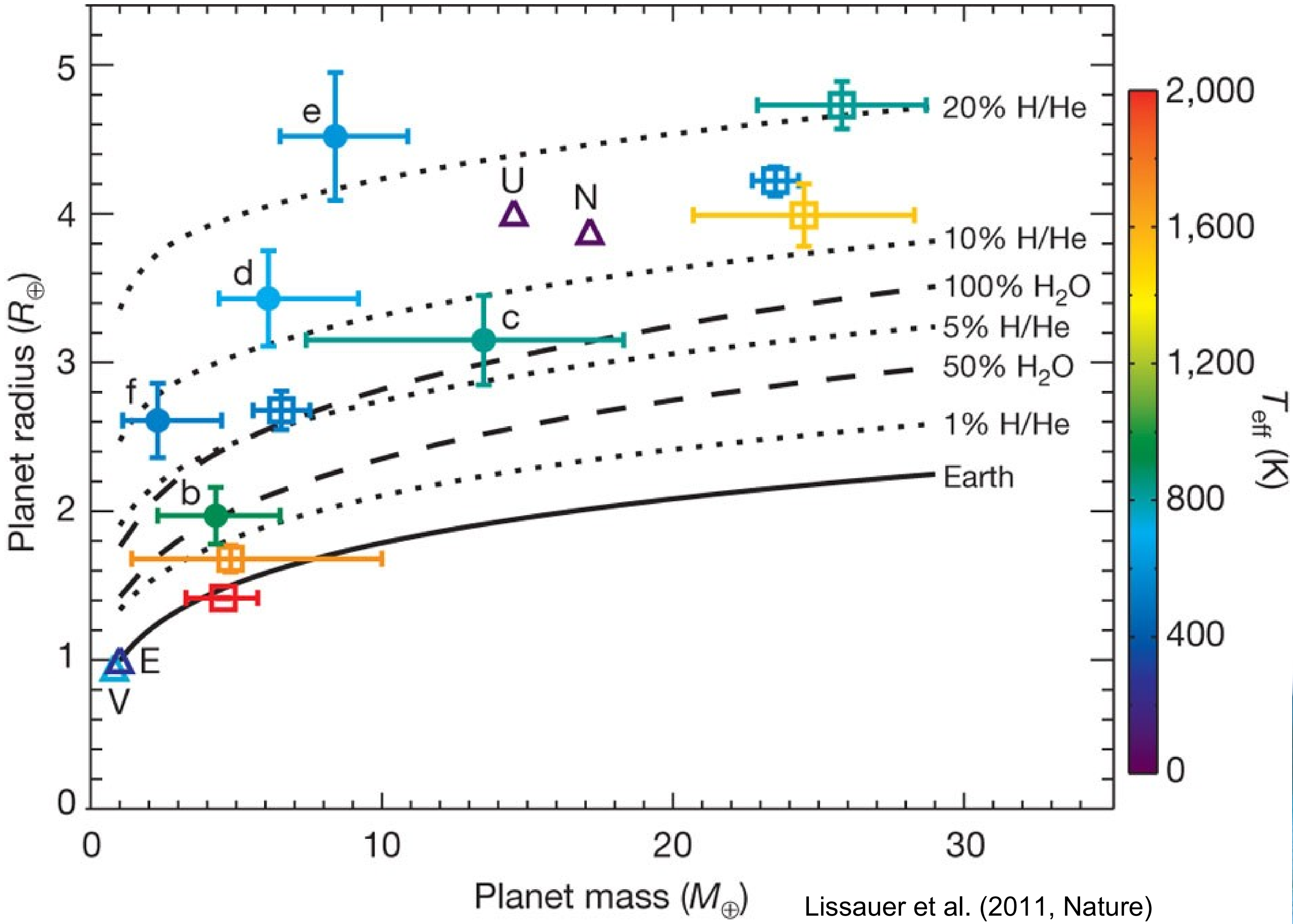


mass to **10%** and radius to **5%** to distinguish between solid rocky and water rich planets

better than **2% in radius** for further bulk characterization (upper mass limits not enough)

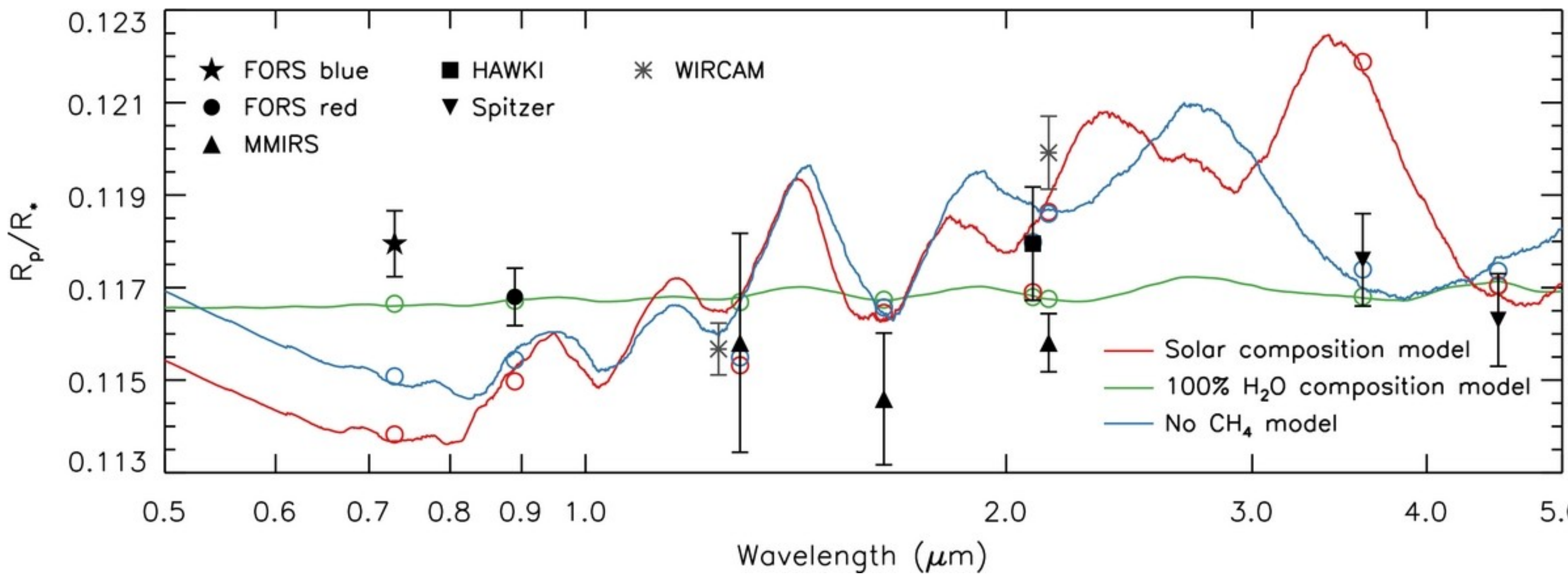
(Valencia et al. 2009, ApJ, 665; Grasset et al. 2009, ApJ, 693; Wagner et al. 2011, Icarus, 214, 366)

Degeneracies in the mass-radius diagram



Lissauer et al. (2011, Nature)

DLR



Bean et al. (2011, ApJ)

Radius of Transiting Exoplanets

$$\frac{\Delta F}{F} = \left(\frac{R_{planet}}{R_{star}} \right)^2$$

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DLR

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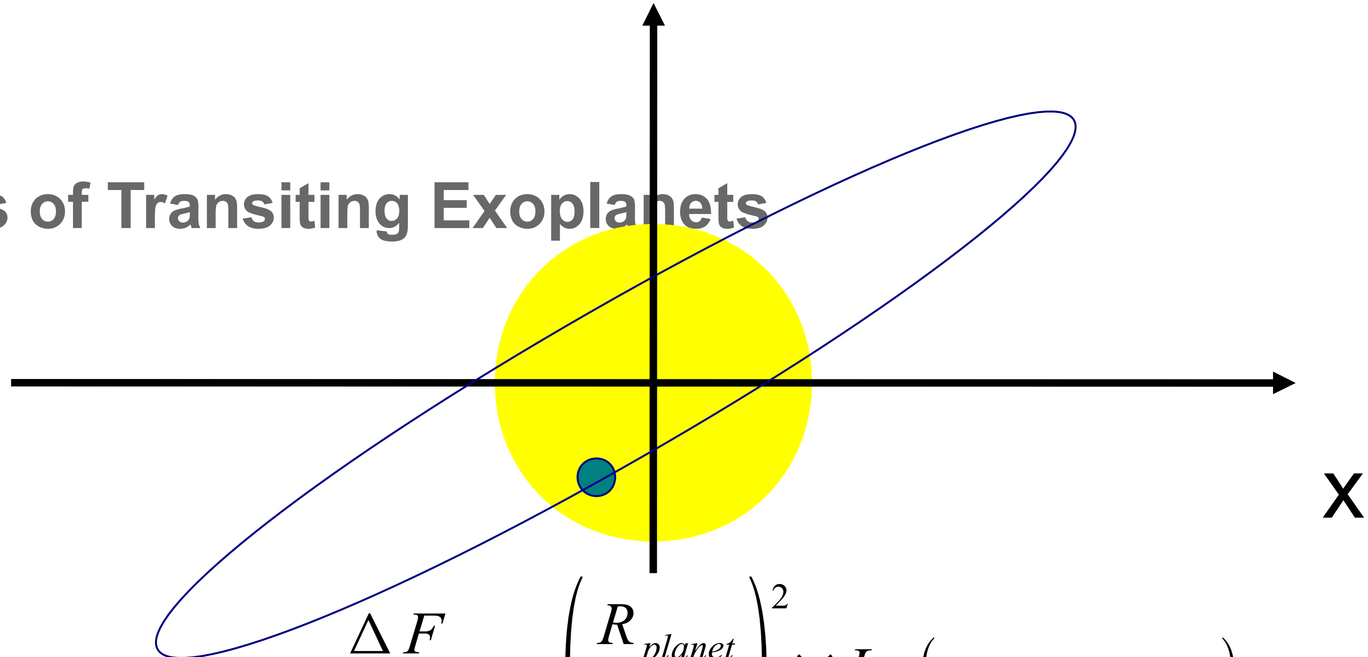
DLR

Radius of Transiting Exoplanets

$$\frac{\Delta F}{F + F_{cont}} = \left(\frac{R_{planet}}{R_{star}} \right)^2 \times L_D(u_a, u_b, x, y)$$

Radius of Transiting Exoplanets



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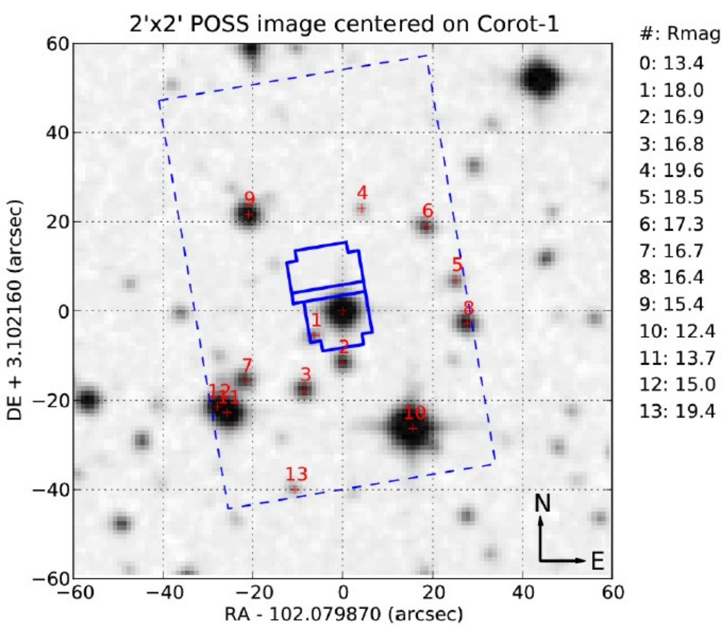
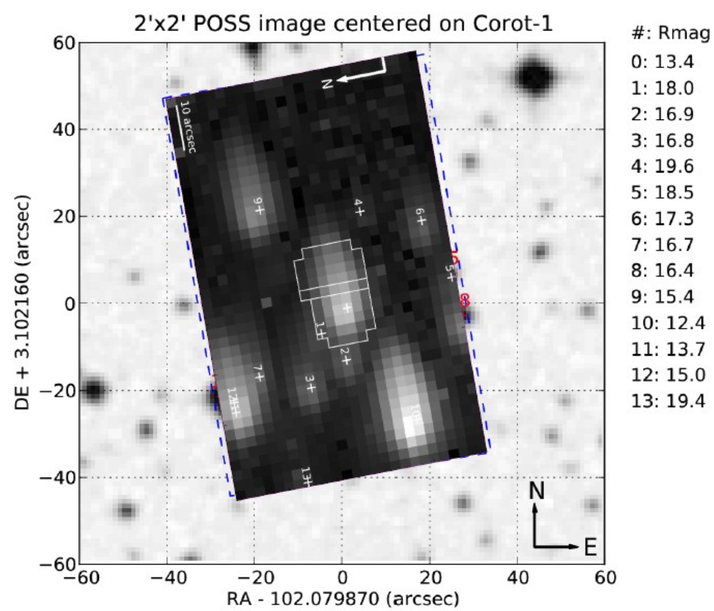
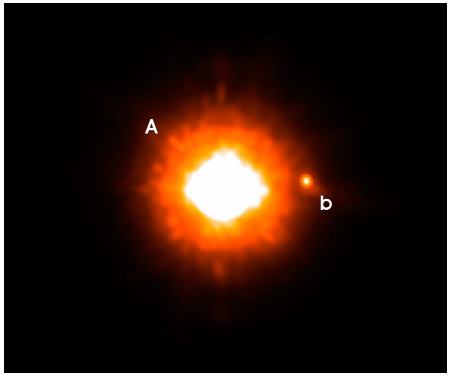




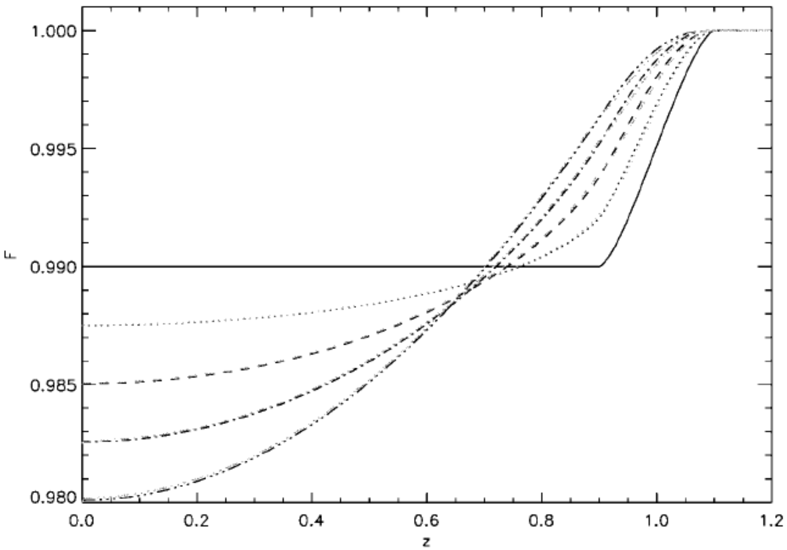
Radius of Transiting Exoplanets



$$\frac{\Delta F}{F + F_{cont}} = \left(\frac{R_{planet}}{R_{star}} \right)^2 \times L_D(u_a, u_b, x, y)$$

Many faint companions within 1“ (E. Günther's talk yesterday; Bergfors et al. 2013, MNRAS 428, 182); many of them seems to be faint enough that we can neglect them. Other remarkable, more distant optical or real companions are routinely taken into account.

Change in transit depth due to limb darkening



s 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*), $c_4 = 1$ (*dash–triple-dotted line*). The thinner lines (nearly indistinguishable) show the approximation of § 5.

Mandel & Agol (2002)

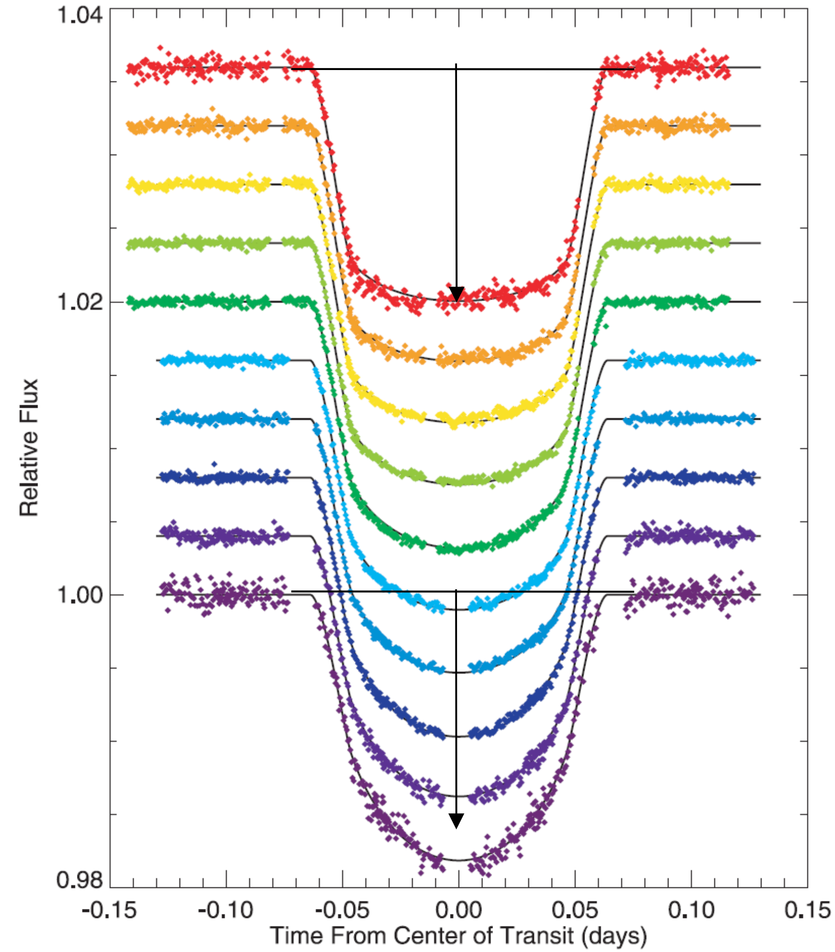


FIG. 3.—Normalized data for the 10 bandpasses shown in Fig. 2, with theoretical transit curves using the best-fit parameters from a simultaneous fit of all bandpasses ıbles 4 and 6) and model four-parameter nonlinear limb-darkening coefficients overplotted. Note that each bandpass contains data from two separate visits, consisting of ır spacecraft orbits each (visits are plotted individually in Fig. 1 for reference). Each successive transit curve is offset by 0.004. Although the transit curves are a good fit most of the data, there are some systematic deviations on timescales comparable to that of a *HST* orbit (see Fig. 4) that are discussed in § 5.2.

Knutson et al. (2007)

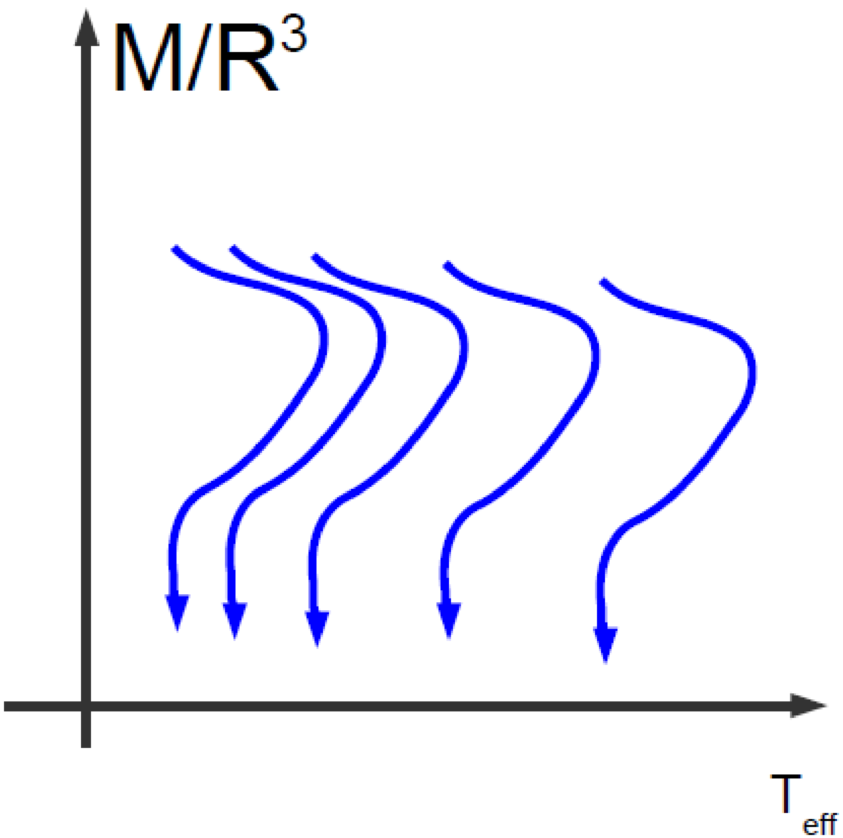
DLR

Radius of Transiting Exoplanets

$$\frac{\Delta F}{F + F_{cont}} = \left(\frac{R_{planet}}{R_{star}} \right)^2 \times L_D$$

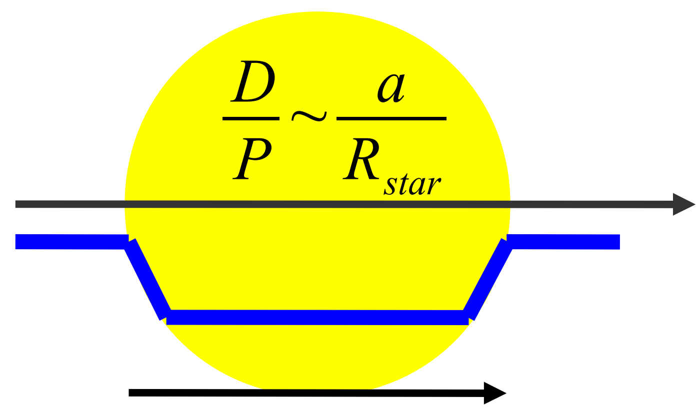
Sources of stellar radius

isochrone fitting; empirical scaling relation; interferometry

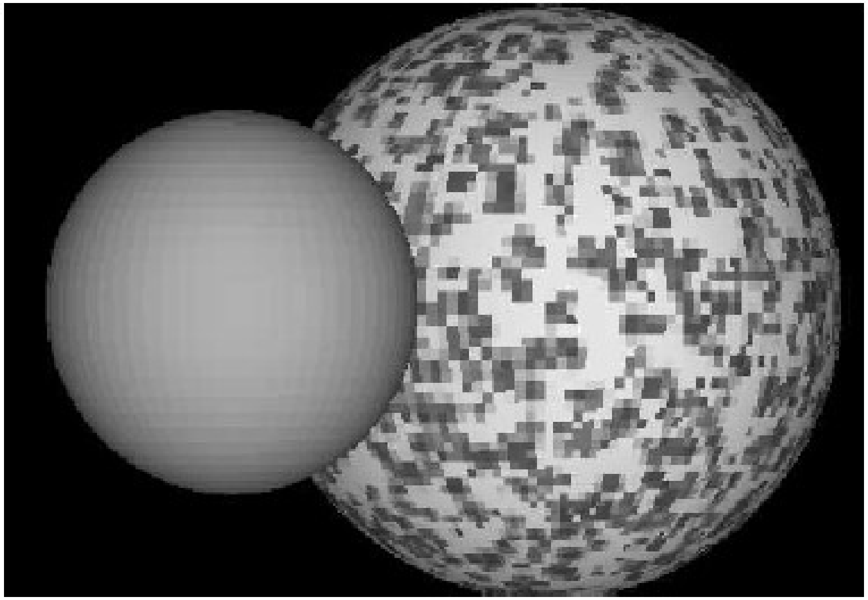


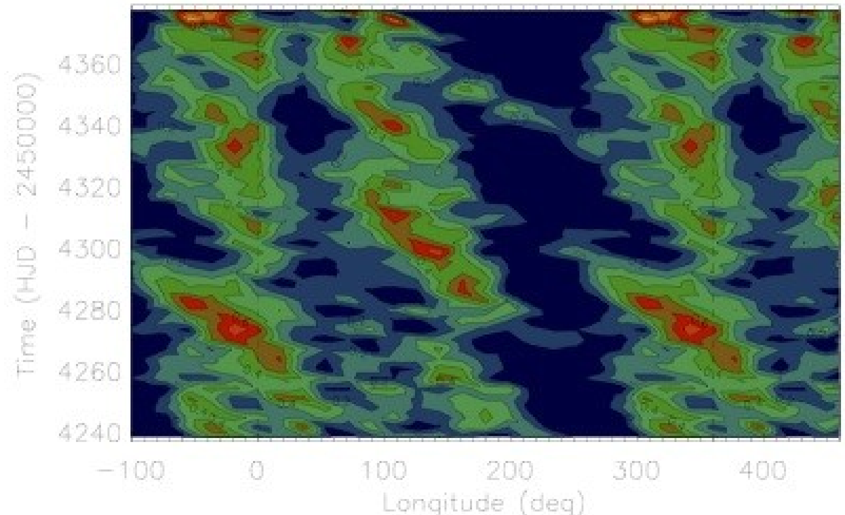
$$a^3 = P^2 \left(M_{star} + M_{planet} \right)$$

$$\left(\frac{a}{R_{star}} \right)^3 \approx P^2 \frac{M_{star}}{R_{star}^3}$$



$$\frac{D}{P} \sim \frac{a}{R_{star}}$$





SV Cam model of Jeffers (MNRAS 359, 729, 2005)

Spot-filling map of CoRoT-2 by Lanza et al. (A&A 493, 193, 2009)

Heavily spotted stars among single and binaries, too.
Spottedness is a function of mass, radius, age, phase of activity cycle, binarity, etc. …

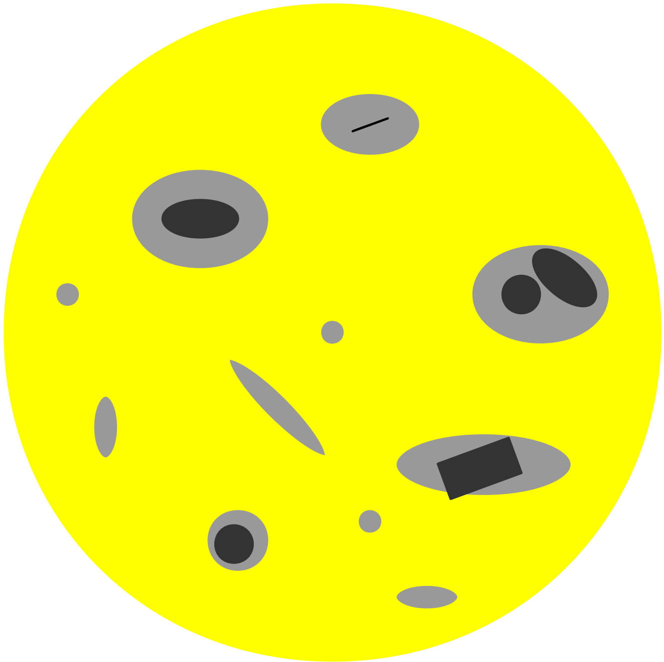
Jackson & Jeffries (2012, MNRAS 423, 2966): *there can be many small spots on the star causing spectroscopic, but no photometric activity indication.*

DLR

Stellar spots affect temperature distribution and measurements – systematics?

Spruit & Weiss (1986, A&A 166, 167), Jackson & Jeffries (2014, MNRAS): spots change the measured stellar radii, T_{eff}, and internal structure.

Clausen et al. (2009, A&A): Stars with mass < 1 Msun have systematically different radius from the theoretically calculated ones, because spots falsify the temperature and hence the luminosity/radius measurements.



Torres (2013, AN 334, 4): systematic M, K-dwarf problems, maybe due to spots, magnetic inflation and/or convection. 10-50% systematics in low-mass stellar radius.

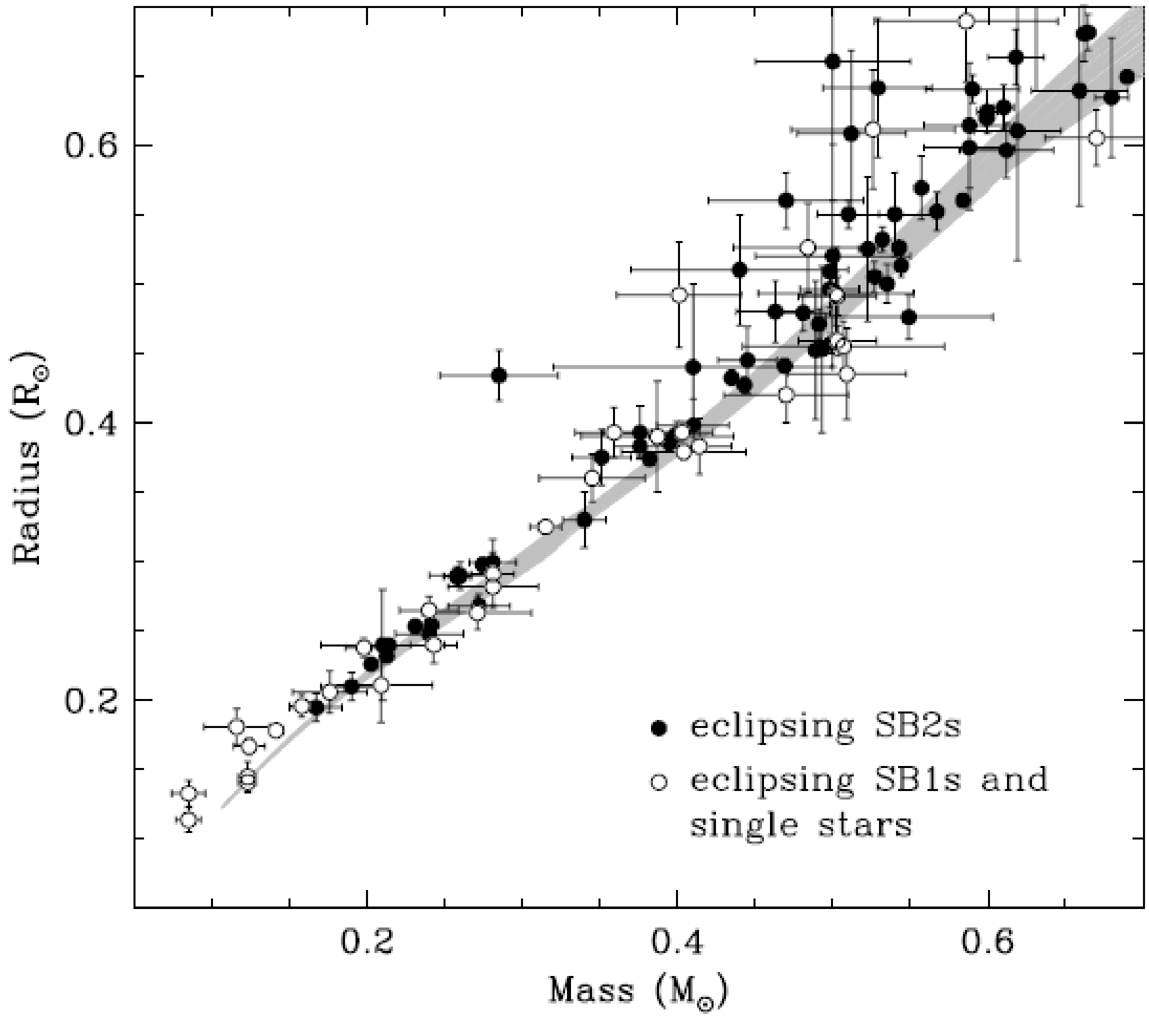
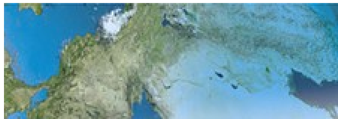


Fig. 2 Mass-radius diagram for low-mass stars, including all measurements for double-lined eclipsing binaries (SB2s, filled symbols) as well as determinations for single-lined eclipsing systems (SB1s) and single stars (open symbols). Solar-metallicity Dartmouth isochrones are shown for comparison, for ages ranging from 1 to 13 Gyr (grey band).

Figure from

Torres (2013)

DLR



Reliable stellar radii

Today:

Only SB2 systems can provide reliable stellar radius.
/We can <u>estimate</u> stellar radii from SB1 sometimes. Planet host stars can have 10-50% uncertainties in stellar radius./

(Near-)future:

Gaia will provide distances to the stars with ~20 μas, hence the luminosities. Combining this with the temperatures (ΔT = 100-200 K?) via $L = R^2 T^4$ we get the radius. (Cannot be better than ~8% because of the temperature determination which depends on logg, too!)

(Far-)future:

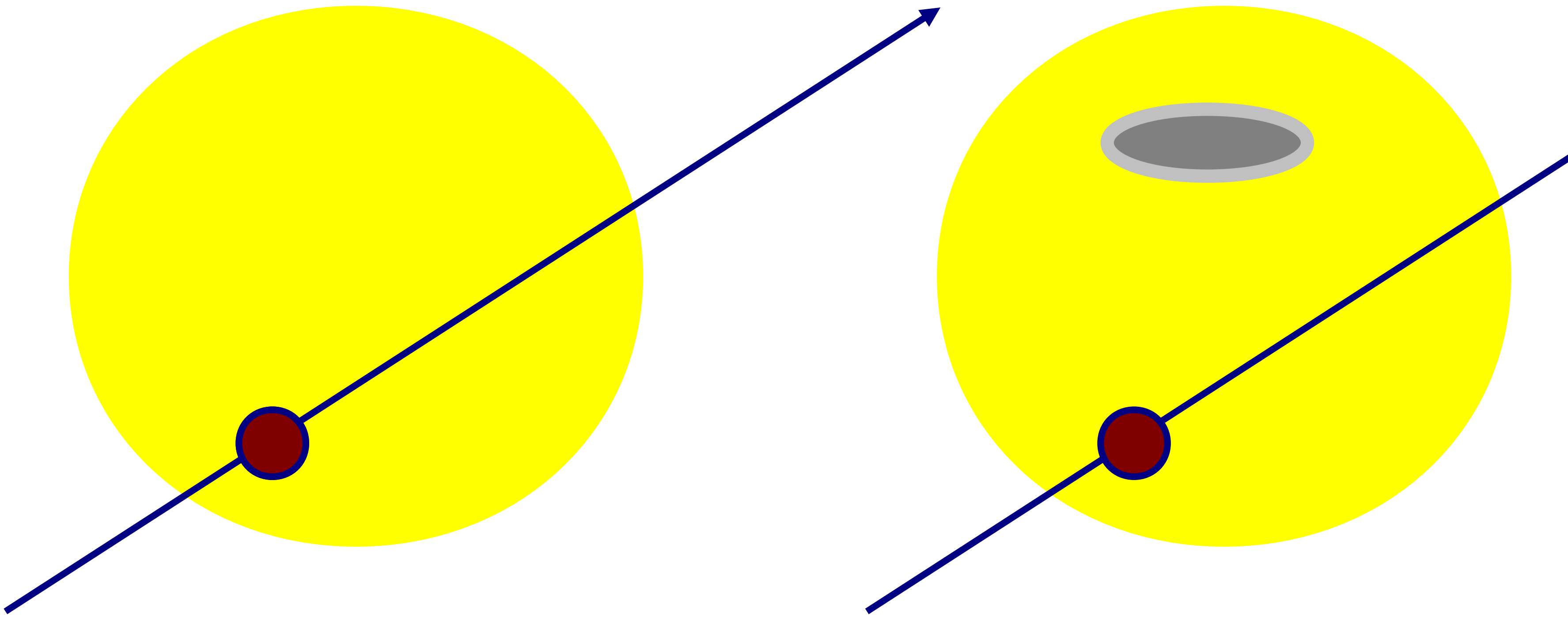
PLATO will give the asteroseismological constrain for M/R^3 (also will depend on temperature-determination of the star!), then this can be combined with the independent *Gaia* measurements: <u>2%</u> can be expected. (See J. Montalbán's talk yesterday about present accuracy reached by CoRoT/Kepler.)

DLR

Transit depth and contamination

$$\frac{\Delta F}{F + F_{cont}} = \left(\frac{R_{planet}}{R_{star}} \right)^2 \times L_D$$

DLR



$$\frac{\Delta F}{F - \Delta F_{spot}} = \left(\frac{R_{planet}}{R_{star}} \right)^2 L_D$$

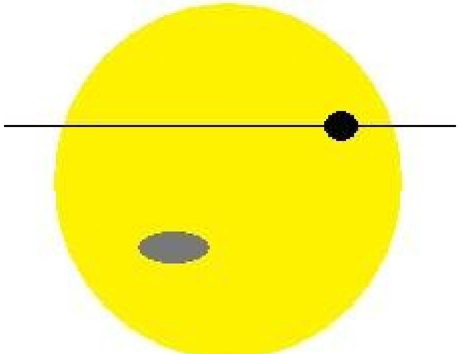
In case of stellar spot/facula, transit depth is different.

Stellar spots and faculae

Type I

Short life-time,

<u>not</u> occulted



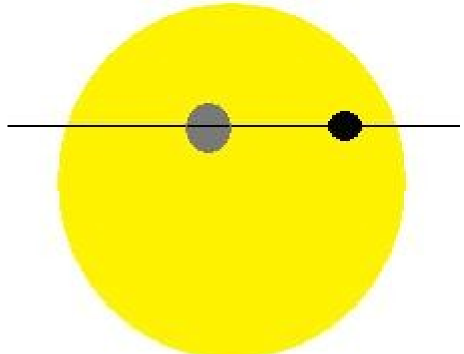
↑Can be removed by baseline-fitting

{selecting the deepest transit points: Czesla et al. 2009, but faculae should be checked}

Type II

Short life-time,

occulted



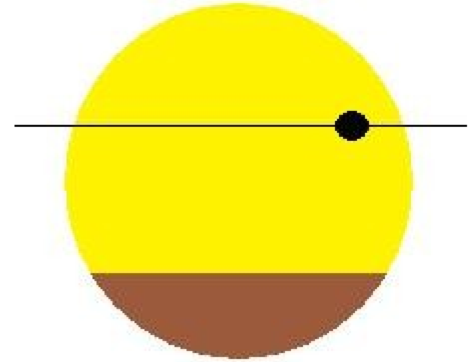
↑Can be removed by spot-modeling

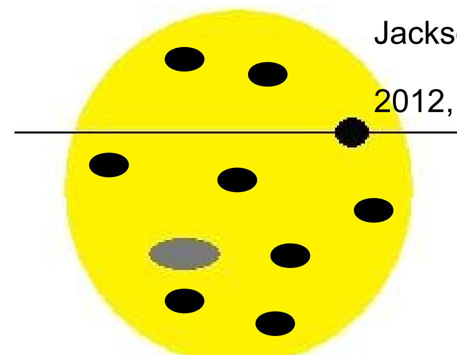
{for spot crossing, see Silva-Valio&Lanza 2010; Sanchis-Ojeda&Winn 2011...}

Type III

Long life-time, pole-on,

slow rotation, no modulation



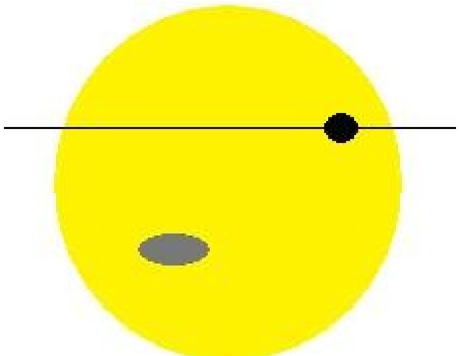


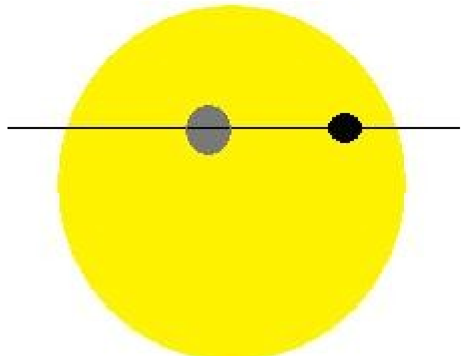
Jackson & Jeffries 2012, MNRAS 423

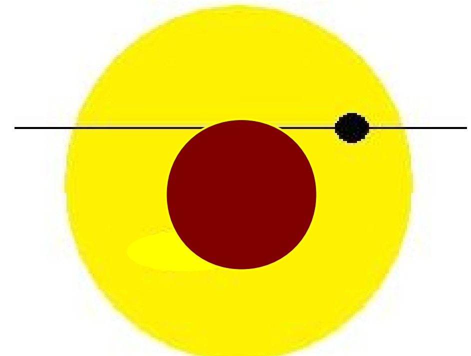
EXTRA ± CONTAMINATION!!

Stellar spots and faculae

Type I	Type II	Type III
Short life-time, <u>not</u> occulted	Short life-time, occulted	Long life-time, pole-on, slow rotation, no modulation

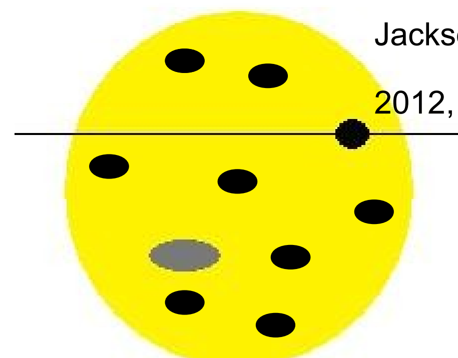






↑Can be removed by baseline-fitting

↑Can be removed by spot-modeling
{for spot crossing, see Silva-Valio&Lanza 2010; Sanchis-Ojeda&Winn 2011...}



Jackson & Jeffries 2012, MNRAS 423

EXTRA ± CONTAMINATION!!

Primary effect on stellar spots on transit depth and contamination

(i) Transit depth can be smaller/bigger (depending on bright faculae / dark spots) than in the case of an unspotted star.

(ii) Baseline-changes (fit or correct)

(iii) Extra – positive or negative! -, time-dependent contamination will appear beyond the contaminating stars, galaxies etc. Folded light curves: how to average them??? Or fold and bin them at all? Stellar activity is time-dependent!

(iv) Multicolour photometry? (CHEOPS, TESS, PLATO: monochromatic)

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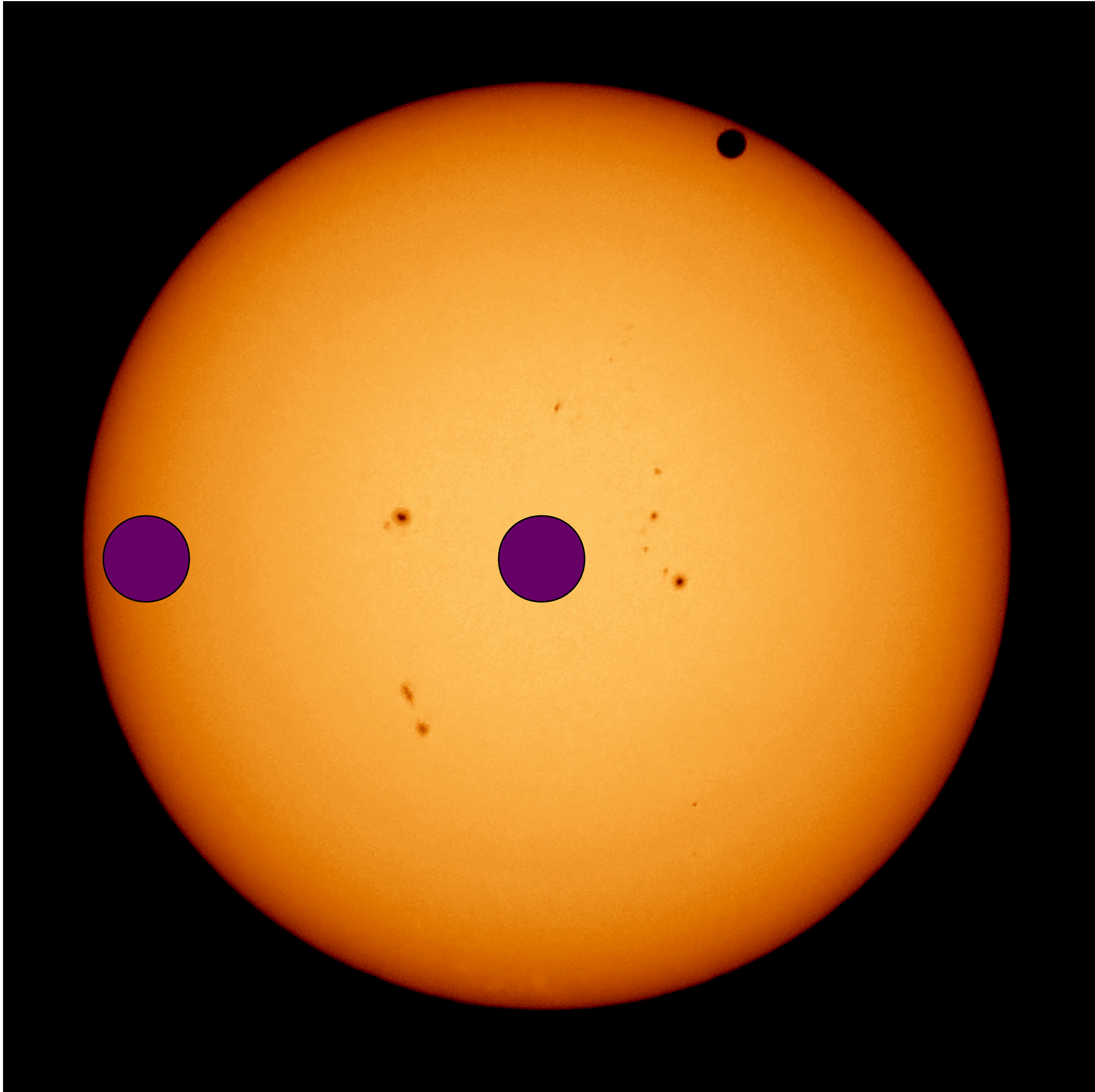
Effect of Limb Darkening on Radius of Transiting Exoplanets

$$\frac{\Delta F}{F + F_{cont}} = \left(\frac{R_{planet}}{R_{star}} \right)^2 \times L_D$$

DLR

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



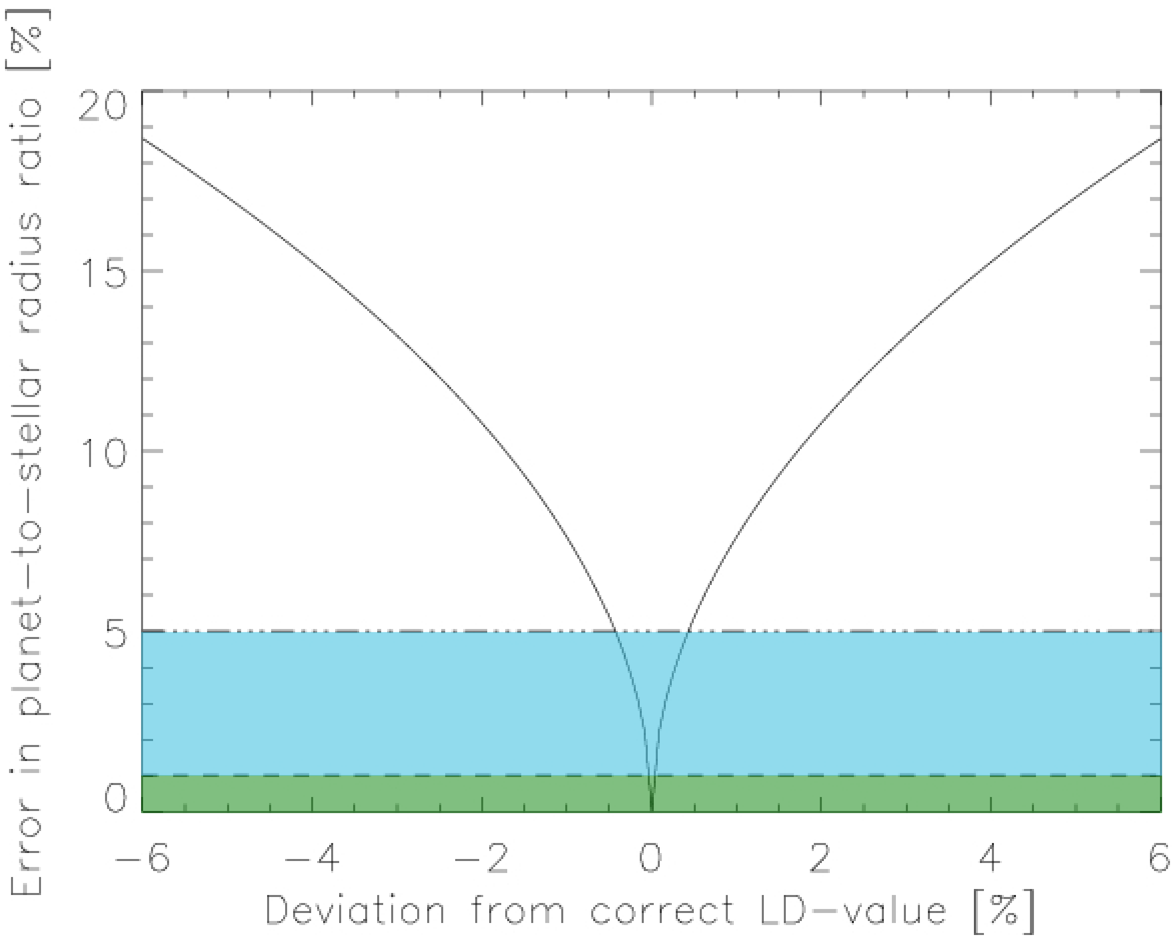
Calculation shows (Csizmadia et al. 2013, A&A 549, A9): to measure the planet-to-stellar radius ratio with 5% uncertainty, you need to know the limb darkening with at least ~0.5% precision.

In general, we do not have this precision.

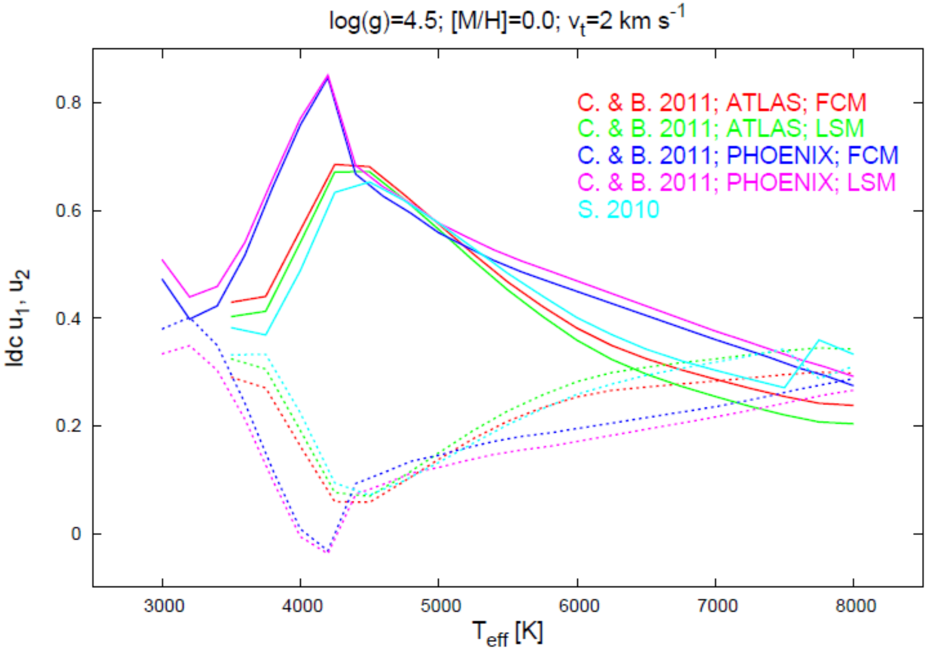
Stellar parameters:
±100K in Teff
±0.1 in logg
±0.1 in [M/H]:

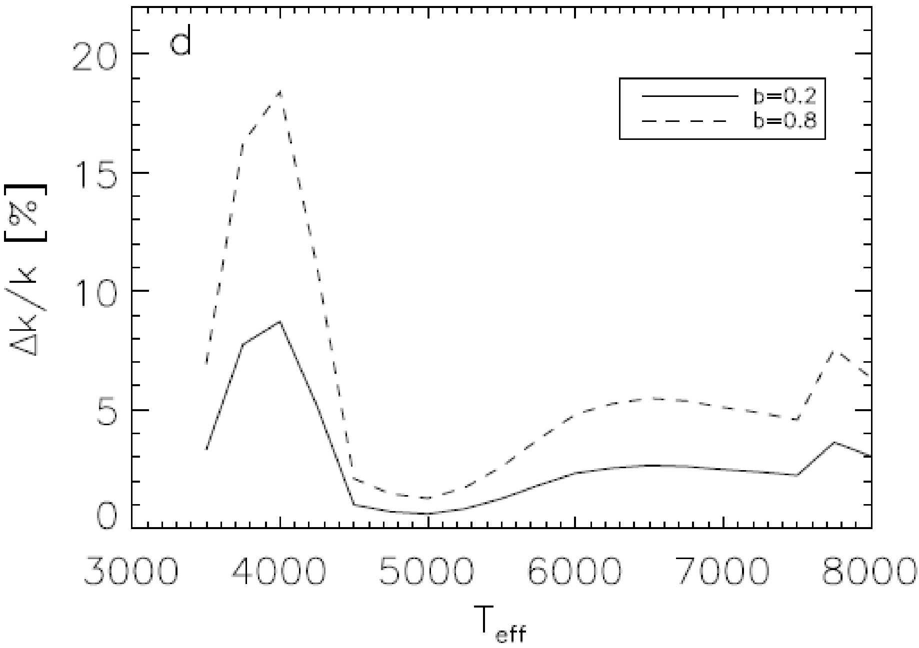
5% in limb darkening coefficients.

+ random/systematic errors in stellar parameters, see Torres et al. (2012) ApJ, 757



Theoretical uncertainties of 1D limb darkening



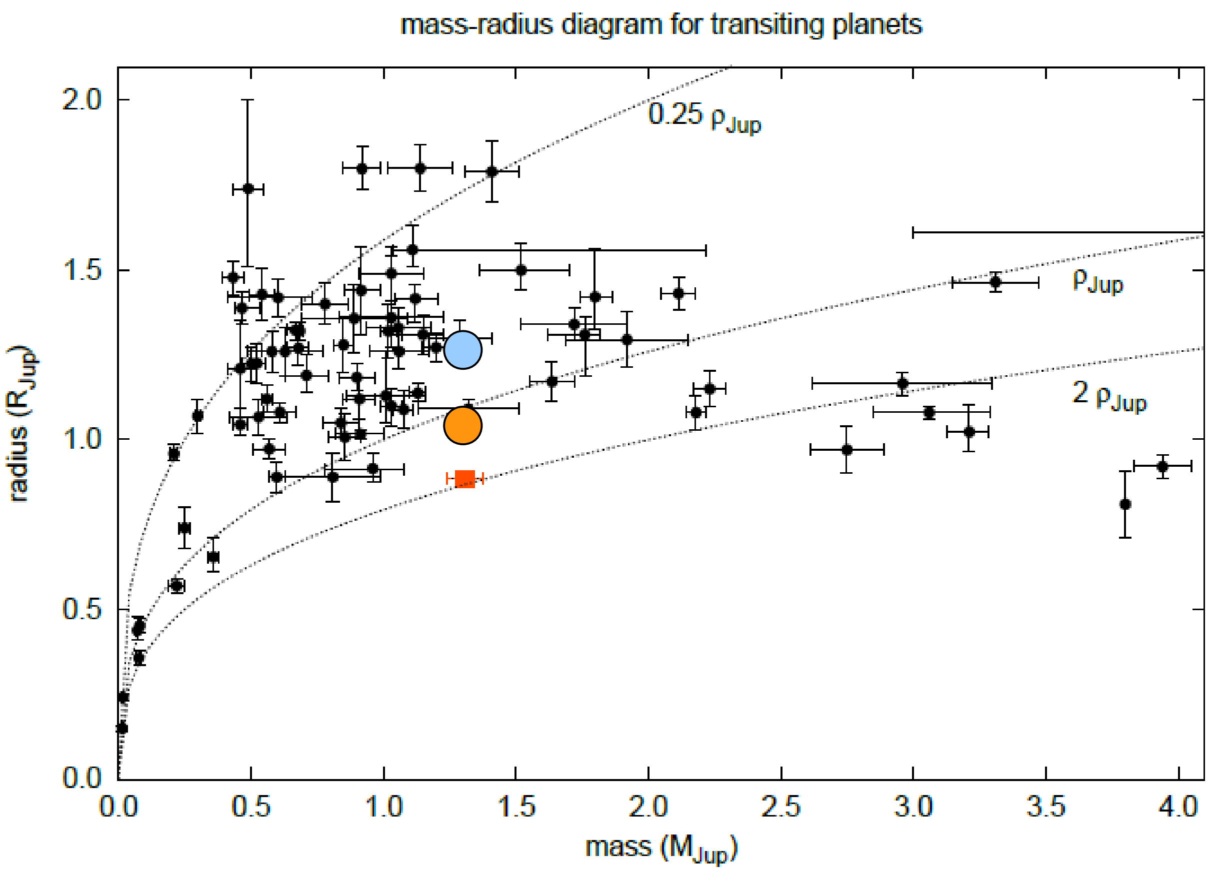


Csizmadia et al. (2013) A&A 549

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

Figure from

Cabrera et al. (2010)



~51% of heavy

elements (Cabrera et al)

Accepted by another study

Best χ^2 of the another study

Fig. 8. Position of CoRoT-13b (square) among the other transiting planets in a mass-radius diagram.

Plane parallel / spherical limb darkening models
(Neilson & Lester 2013, arxiv.org: 1305.1311)

3D attemps:

Trampedach (2013, ApJ 769, 18)

Convection?

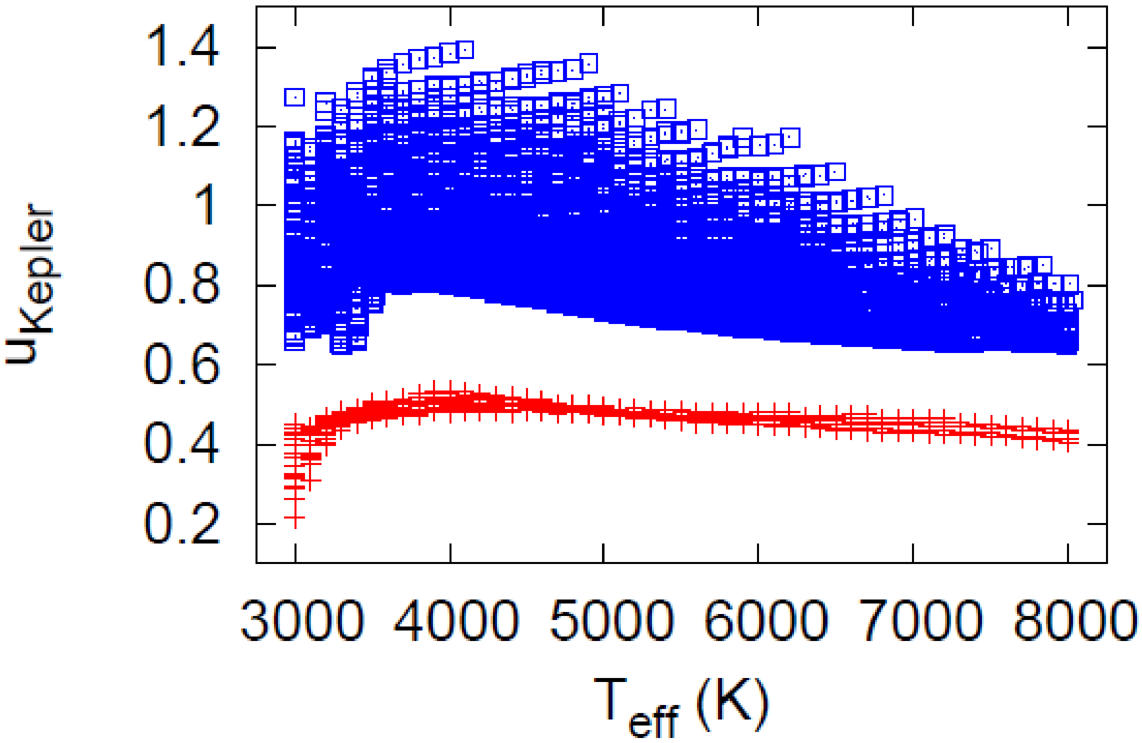
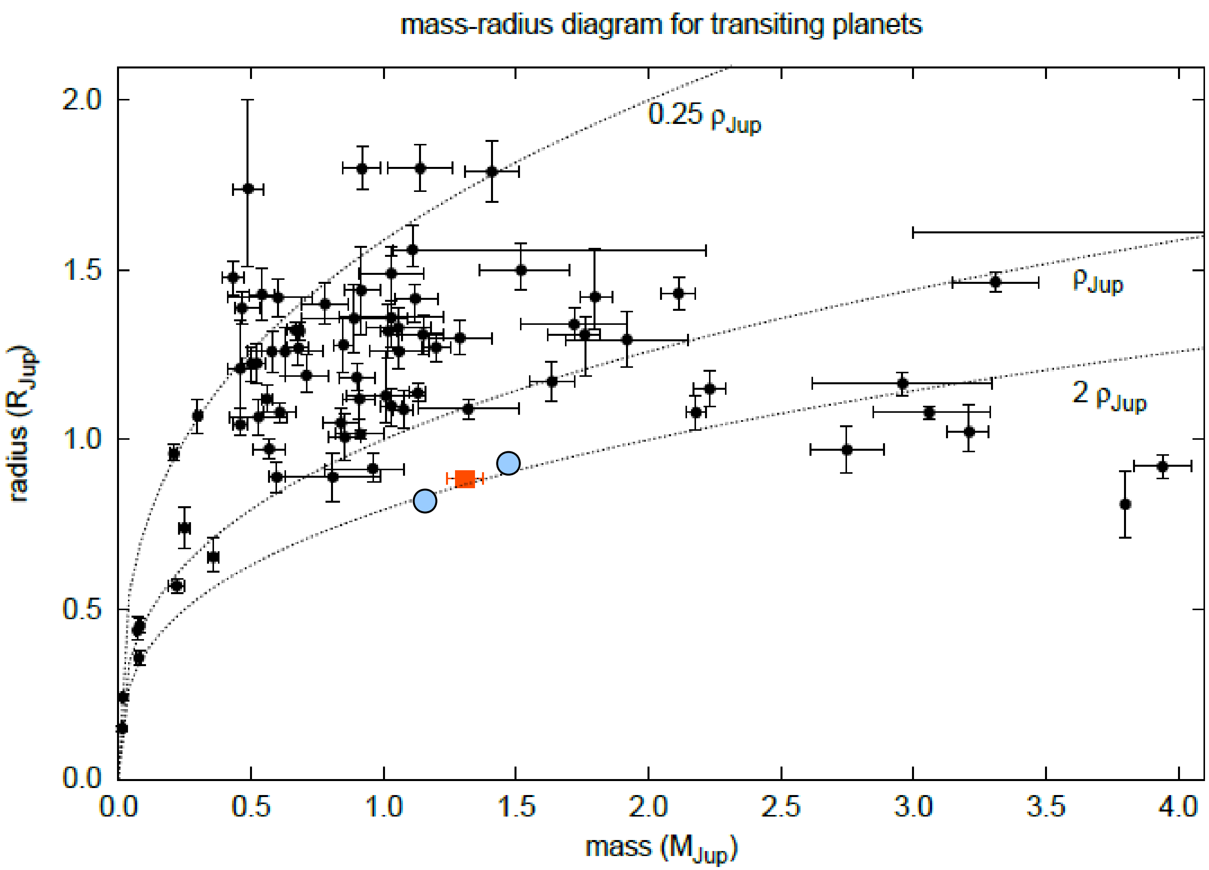


Figure from Neilson & Lester (2013)

Figure from

Cabrera et al. (2010)



~51% of heavy

elements (Cabrera et al)

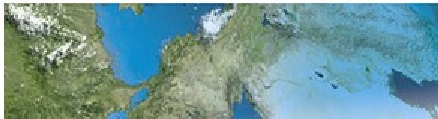
Meantime similar

systems found. e.g.:

WASP-64b,

KOI 1257Ab...

Fig. 8. Position of CoRoT-13b (square) among the other transiting planets in a mass-radius diagram.



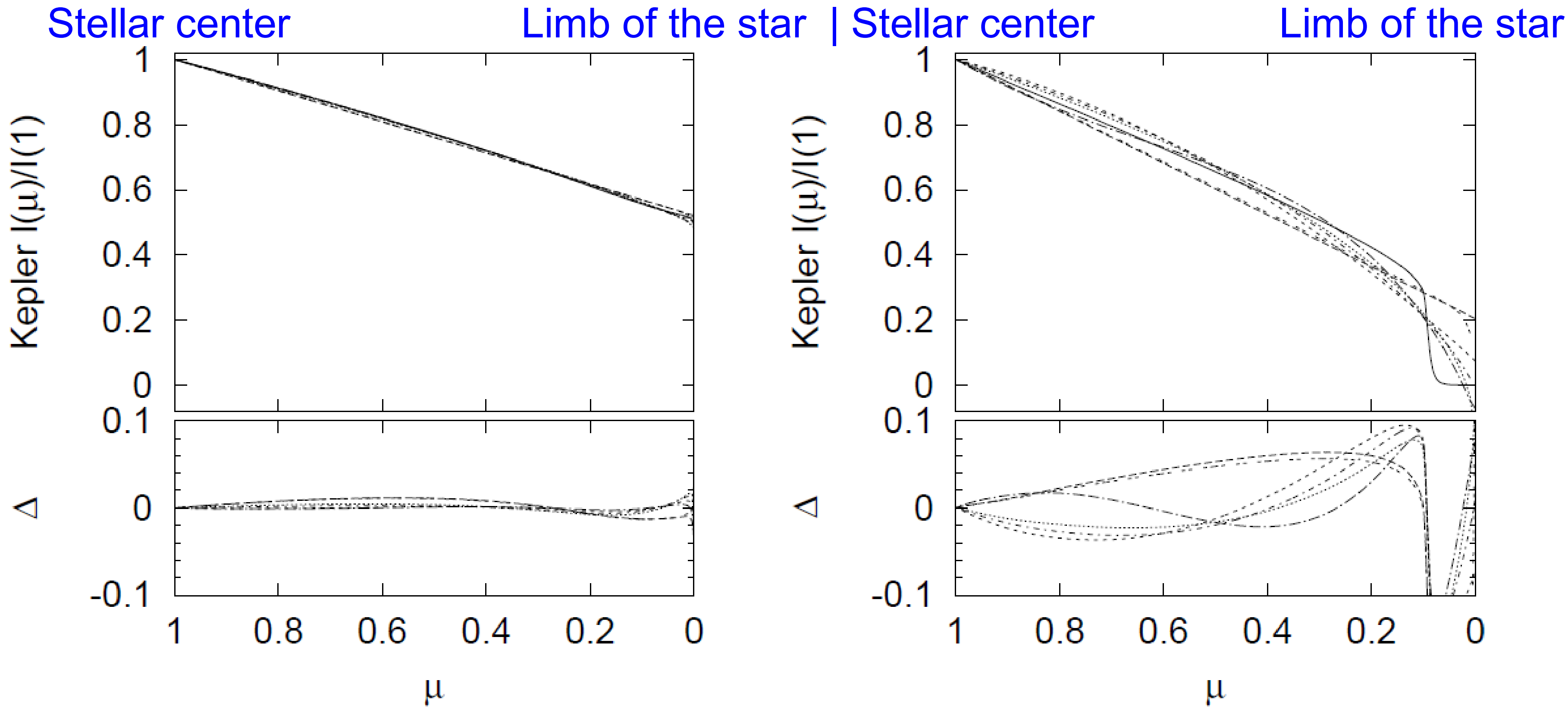
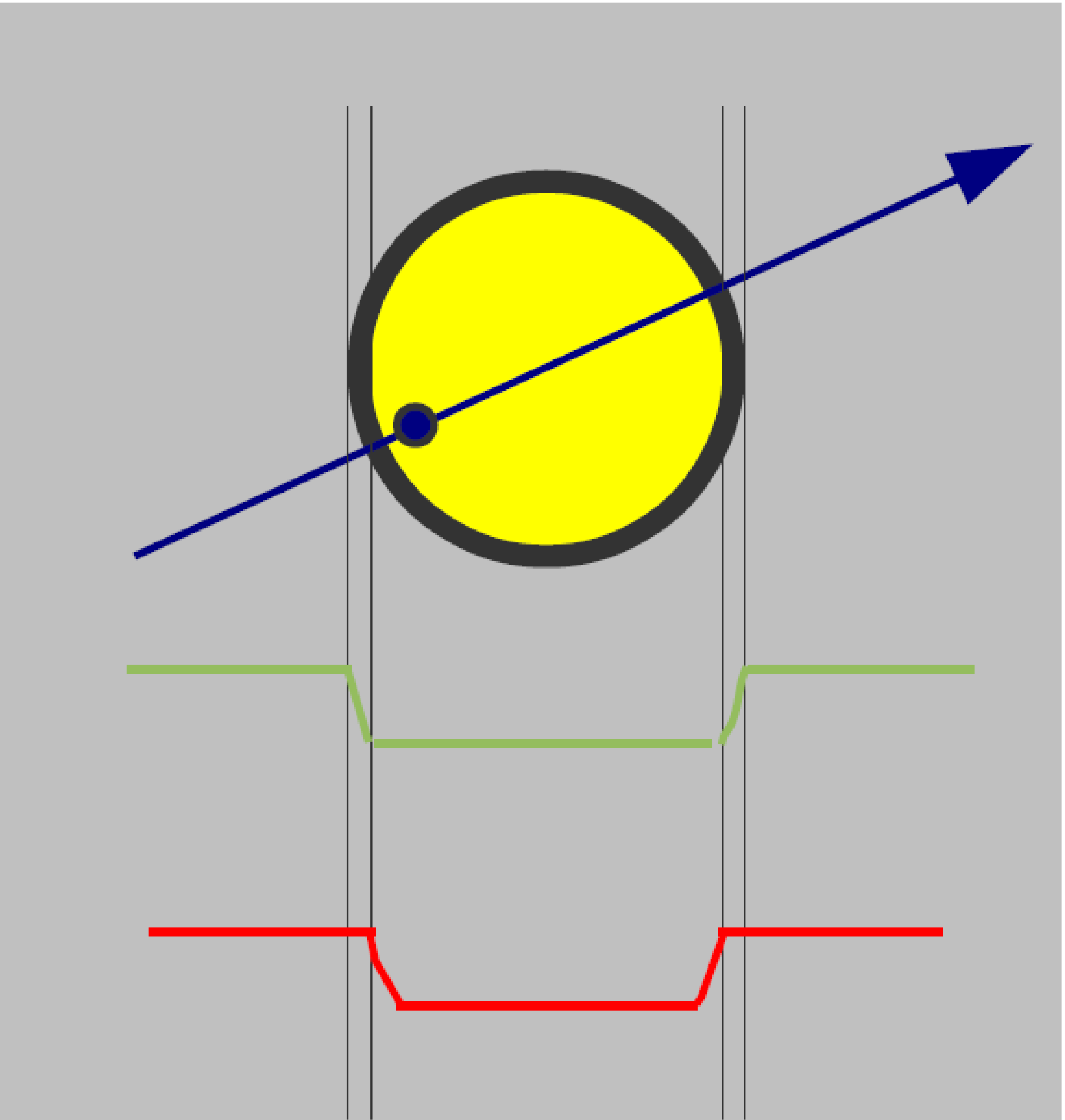
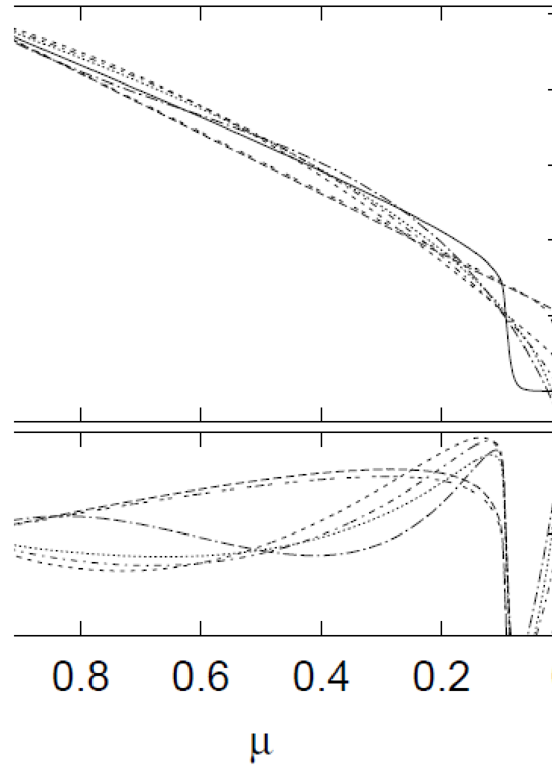


Fig. 1. *Kepler*-band model intensity profiles (black-solid) predicted for both plane-parallel (left) and spherically symmetric (right) model stellar atmospheres with $T_{\rm eff} = 5000$ K, $\log g = 2$ and $M = 10\ M_\odot$. Along with the intensity profiles, best-fit linear (green-dashed), quadratic (orange-short-dashed), square-root (blue-dotted), four-parameter (violet-long-dash-dotted), logarithmic (brown-short-dash-dotted), and exponential (grey-double-dash) limb-darkening relations are plotted. Bottom panels show the difference, $\Delta \equiv I_{\rm model} - I_{\rm law}$, between model intensities and best-fit limb-darkening laws.

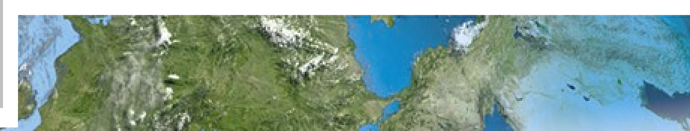
Neilson & Lester (2013ab, A&A)

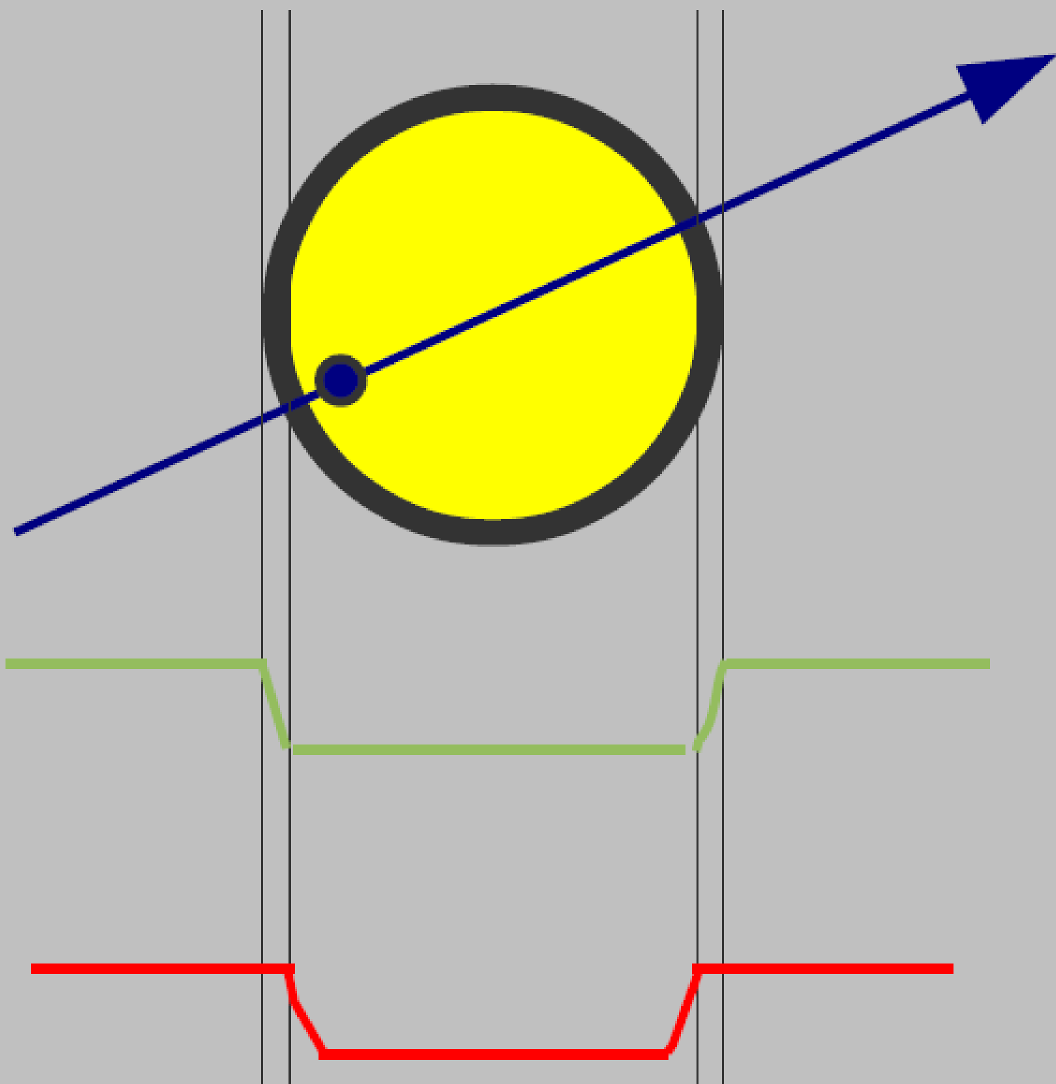
DLR

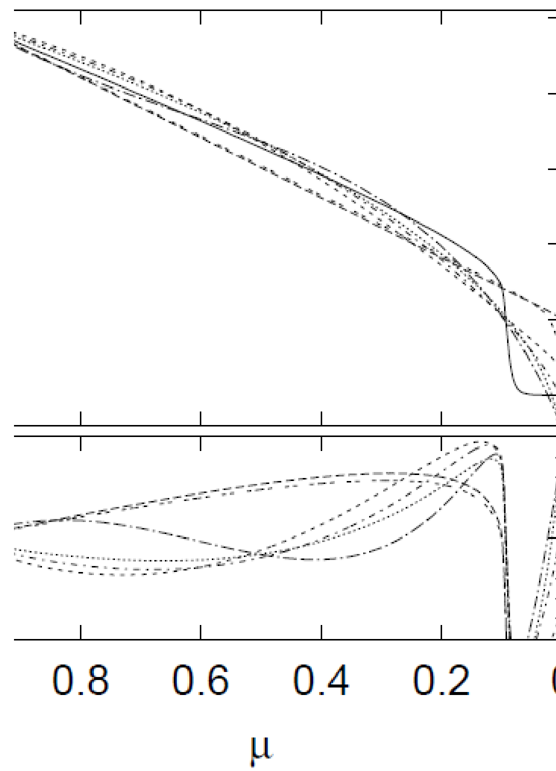




ɔarallel (left) and spherically symmetric (right)
vith the intensity profiles, best-fit linear (green-
(violet-long-dash-dotted), logarithmic (brown-
re plotted. Bottom panels show the difference,

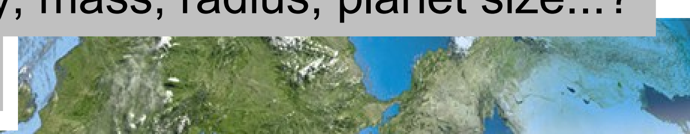






ɔarallel (left) and spherically symmetric (right)
/ith the intensity profiles, best-fit linear (green-
(violet-long-dash-dotted), logarithmic (brown-
re plotted. Bottom panels show the difference,

Are all a/Rs systematically affected? → Stellar density, mass, radius, planet size...?



modelling of planetary parameters:
impact of limb darkening when it is modified by spots

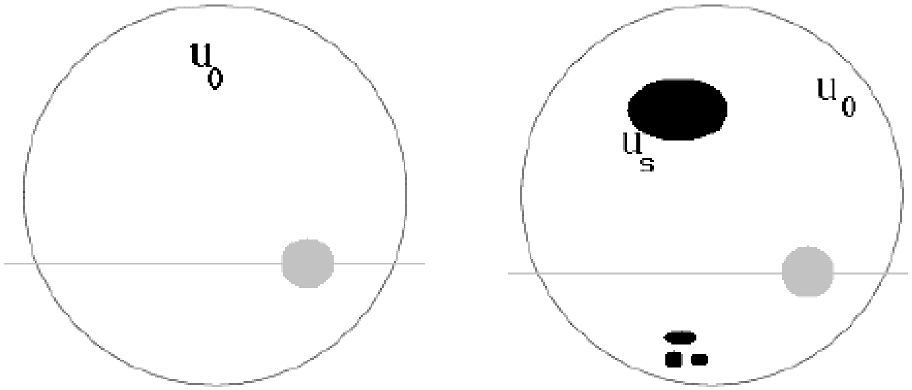


Fig. 4. Illustration of the effect of Type I spots. Left: the planet crosses an unmaculated star that is characterized with some limb darkening coefficient u_0. Right: the planet crosses the appareant stellar disc of a spotted star, where the spots and the planet have different impact parameters, as 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

DLR

Summary

TODAY:

1./ Stellar spots have impact on transit depth (it can be managed) and on temperature and radius determination (there is progress, but...), and they modify the observable limb darkening coefficients (maybe understood, Csizmadia et al. A&A 549, A9, 2013).

2./ Limb darkening tables are observationally not checked yet in a reliable way. (How can we fix something which is not tested yet?)

  - *3D models, improvements in convection theory, spherical models instead of plane-parallel models, including stellar activity and reliable observational checks and methods are needed at different wavelengths and on different objects.*

FUTURE:

A./ Gaia will provide distances, luminosities → empirical stellar radius on much bigger sample.

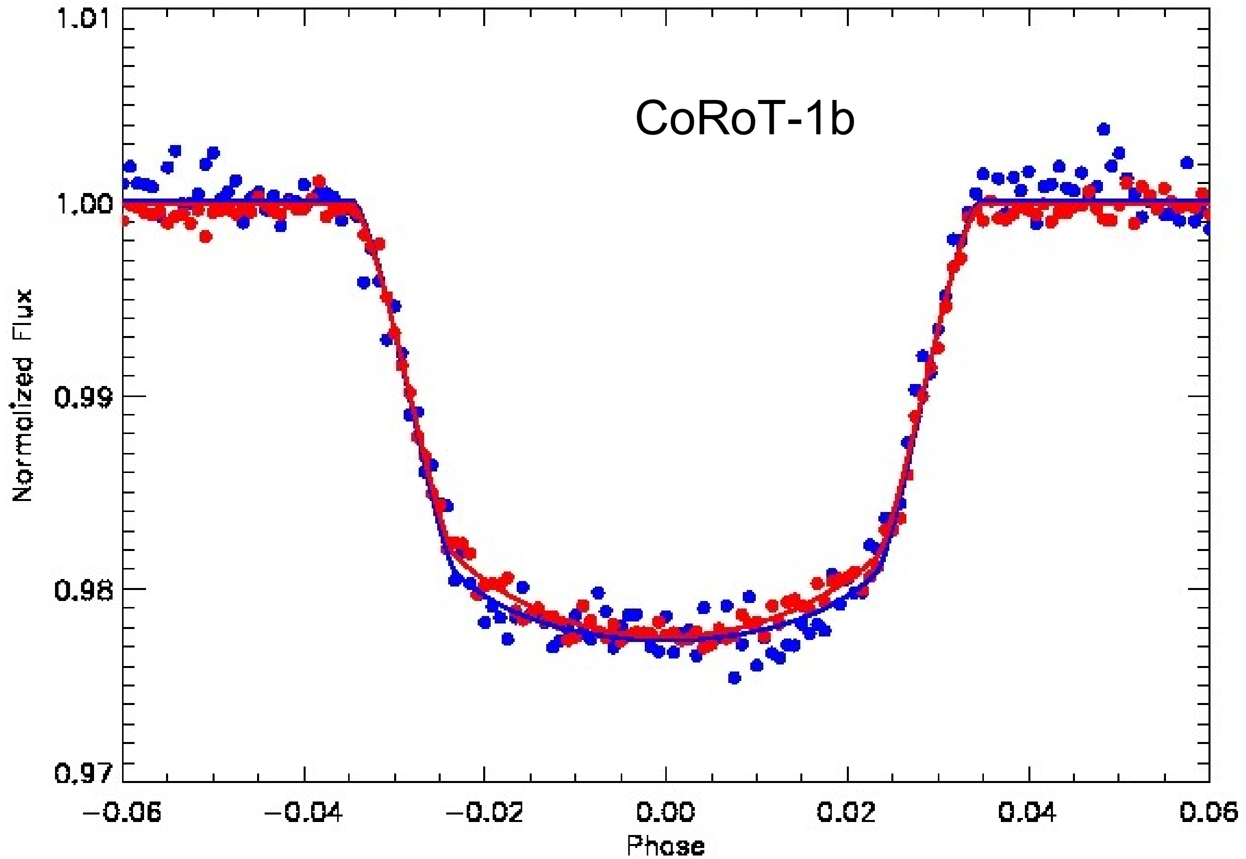
B./ Gaia + PLATO will provide much better stellar properties and hence better planetary parameters.

C./ Theoretical and observational improvements in limb darkening.

DLR

DLR

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.

DLR

Random and systematic errors in stellar parameters

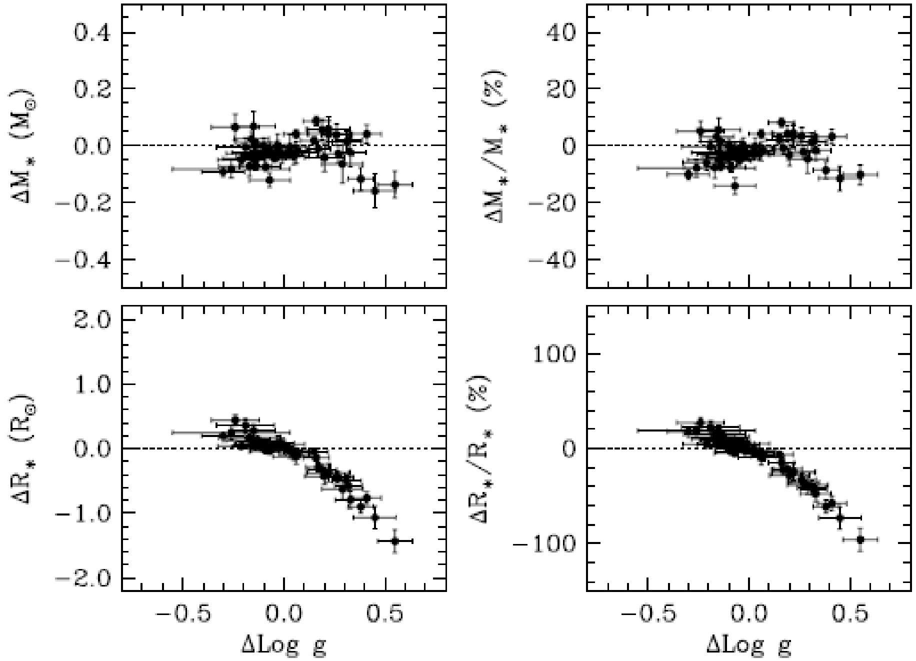


FIG. 10.— Mass and radius differences resulting from the use of constrained and unconstrained spectroscopic properties from SME along with stellar evolution models. Differences in the sense ⟨constrained minus unconstrained⟩ are shown in absolute units on the left, and as a percentage of $M_\star$ or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

Torres et al. (2012) ApJ, 757

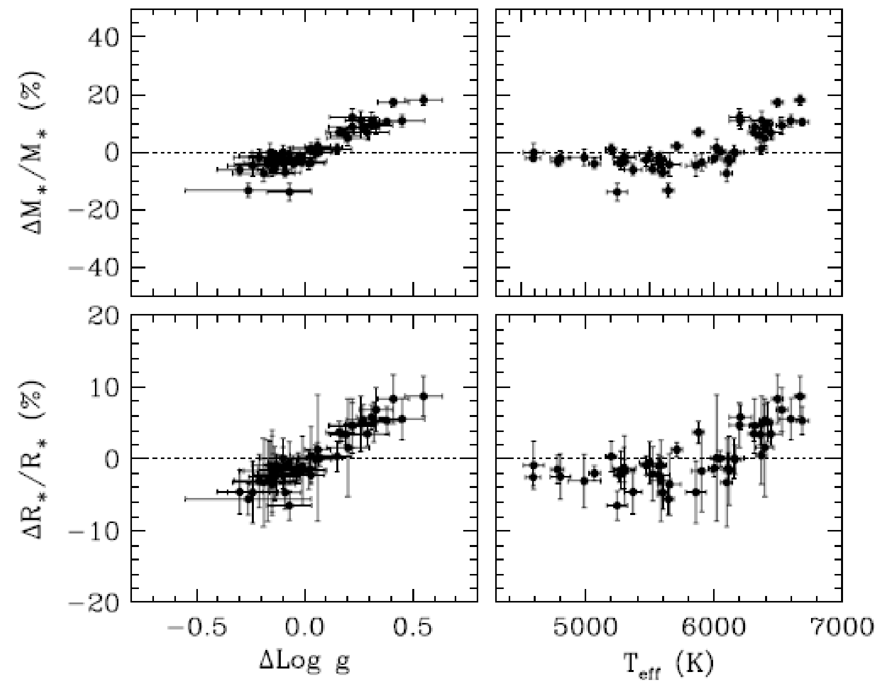


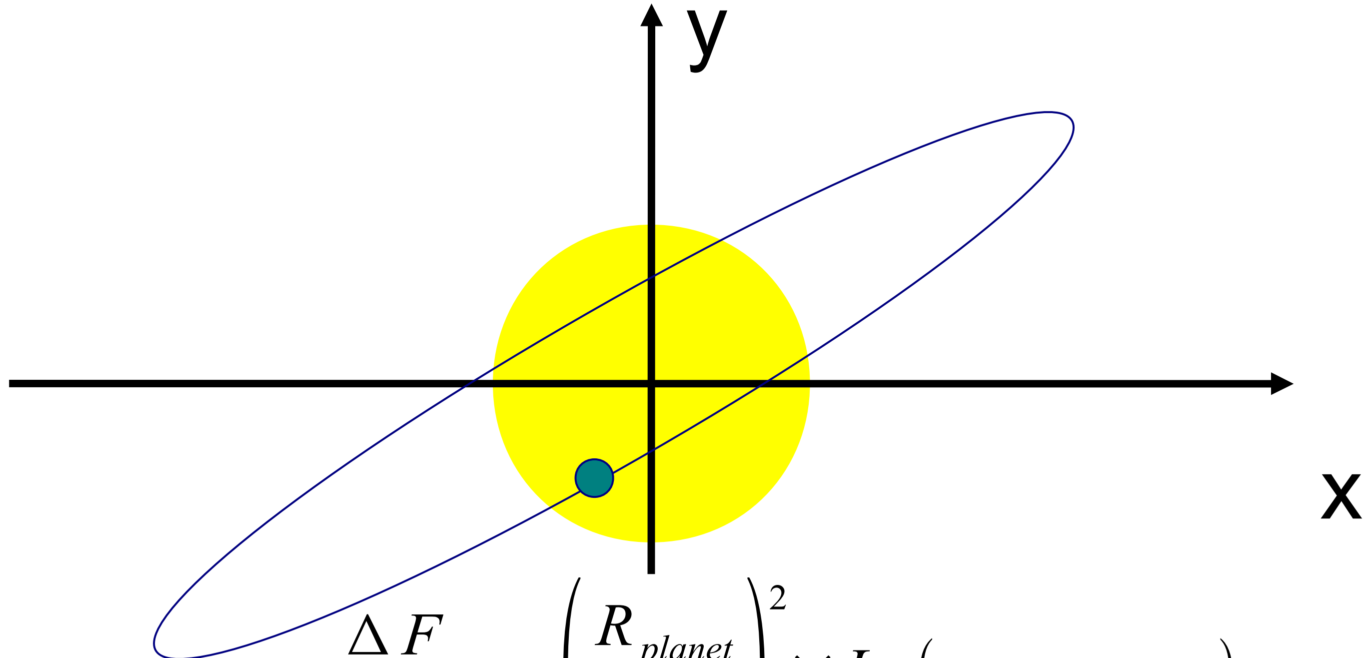
FIG. 11.— Systematic errors in the stellar mass and radius (expressed as a percentage) when using *unconstrained* values of $T_{\rm eff}$ and [Fe/H] from SME together with the external photometric constraint on $\log g$ from the mean stellar density. The differences shown are between the mixed usage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

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)}

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)…



$$\frac{\Delta F}{F + F_{cont}} = \left(\frac{R_{planet}}{R_{star}}\right)^2 \times L_D(u_a, u_b, x, y)$$

$$x, y = f_{x,y}(a/R_s, i, e, \omega, \tau, t)$$

Different approaches:
- fixed
- adjusted
- different mathematical formulation for L_D.

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