Detecting the spin-orbit misalignment of the super-Earth 55 Cnc e

Guillaume Hébrard[1,2] and Vincent Bourrier[3,1]

[1] Institut d'astrophysique de Paris, UMR7095 CNRS, Université Pierre & Marie Curie, 98bis boulevard Arago, 75014 Paris, France
[2] Observatoire de Haute-Provence, CNRS/OAMP, 04870 Saint-Michel-l'Observatoire, France
[3] Observatoire astronomique de l'Université de Genève, 51 chemin des Maillettes, 1290 Versoix, Switzerland

Abstract

Time-resolved spectroscopy of transits of the super-Earth 55 Cnc e was obtained with HARPS-N. The high precision and quality of the data allowed us to devise a correction for the "color-effect" on the radial velocities. Using that correction, we detected a signal that can be interpreted as a Rossiter-McLaughlin anomaly. This anomaly would have the smallest amplitude measured so far (~60 cm/s), and the super-earth 55 Cnc e would also be the smallest exoplanet with such a detection. The derived sky-projected obliquity is $\lambda = 72.4°$ (+12.7°/-11.5°), indicating that the planet orbit is prograde, highly misaligned and nearly polar compared to the stellar equator. The entire 55 Cancri system may have been highly tilted by the presence of a binary companion.

The 55 Cancri planetary system

- Host star 55 Cnc A: bright (V=5.9) G8V star;
- 55 Cnc B: M4V likely-bound companion;
- 5 detected exoplanets:

Planet	$M_p \sin i$ (M_{Jup})	Period (days)
e	0.03	0.74
b	0.80	14.7
c	0.16	44.4
f	0.17	261.2
d	3.54	4909

Transiting planet (planet e)

$M_p = 7.99 \pm 0.25\ M_{earth}$
$R_p = 1.99 \pm 0.08\ R_{earth}$

Butler et al. (1997); Marcy et al. (2002); McArthur et al. (2004); Fischer et al. (2008); Dawson & Fabrycky (2010); Winn et al. (2011); Demory et al. (2011); Endl et al. (2012); Gillon et al. (2012); Dragomir et al. (2014); Nelson et al. (2014)

Dynamical studies of that closely packed system in an binary system

- Coplanar?
- Dynamically stable?
- Misaligned?

Kaib et al. (2011)
Nelson et al. (2014)
Boué & Fabrycky (2014a,b)
Hansen & Zink (2015)

Measure the obliquity through RM anomaly!

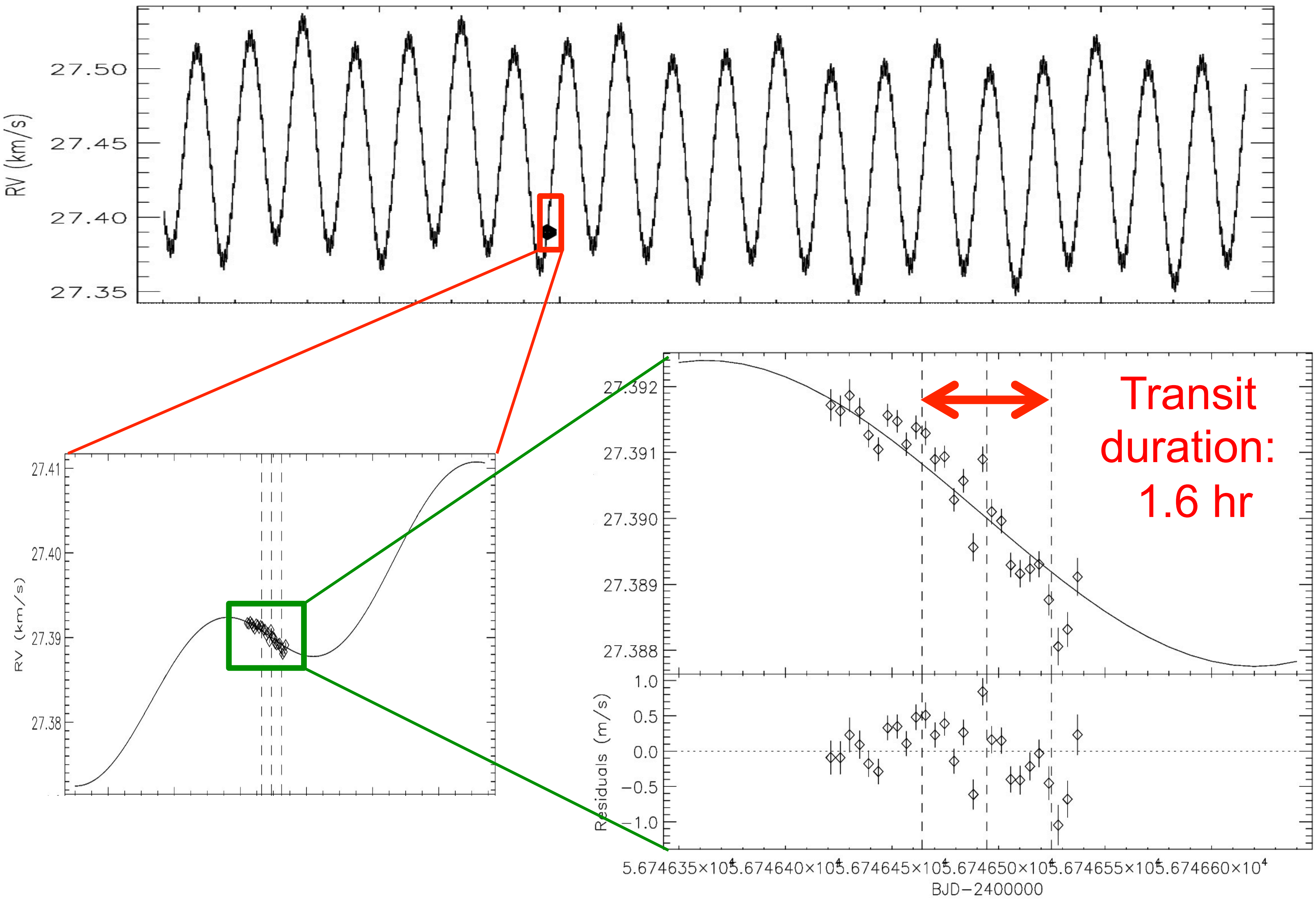
5 transits observed with HARPS-N

Run	Transit mid-time (UT)	Exposures†	Mode‡	Airmass††	S/N_392*	S/N_527*	S/N_673*
A	2012-12-26 at 02h54	27	ThAr**	1.10 – 1.00 – 1.35	56	261	150
B	2014-01-02 at 01h48	33	FP	1.00 – 1.43	70	342	260
C	2014-01-27 at 02h49	30	FP	1.00 – 1.38	27	144	131
D	2014-02-27 at 01h15	30	ThAr	1.00 – 1.39	16	92	93
E	2014-03-29 at 23h41	27	FP	1.01 – 1.36	73	354	269

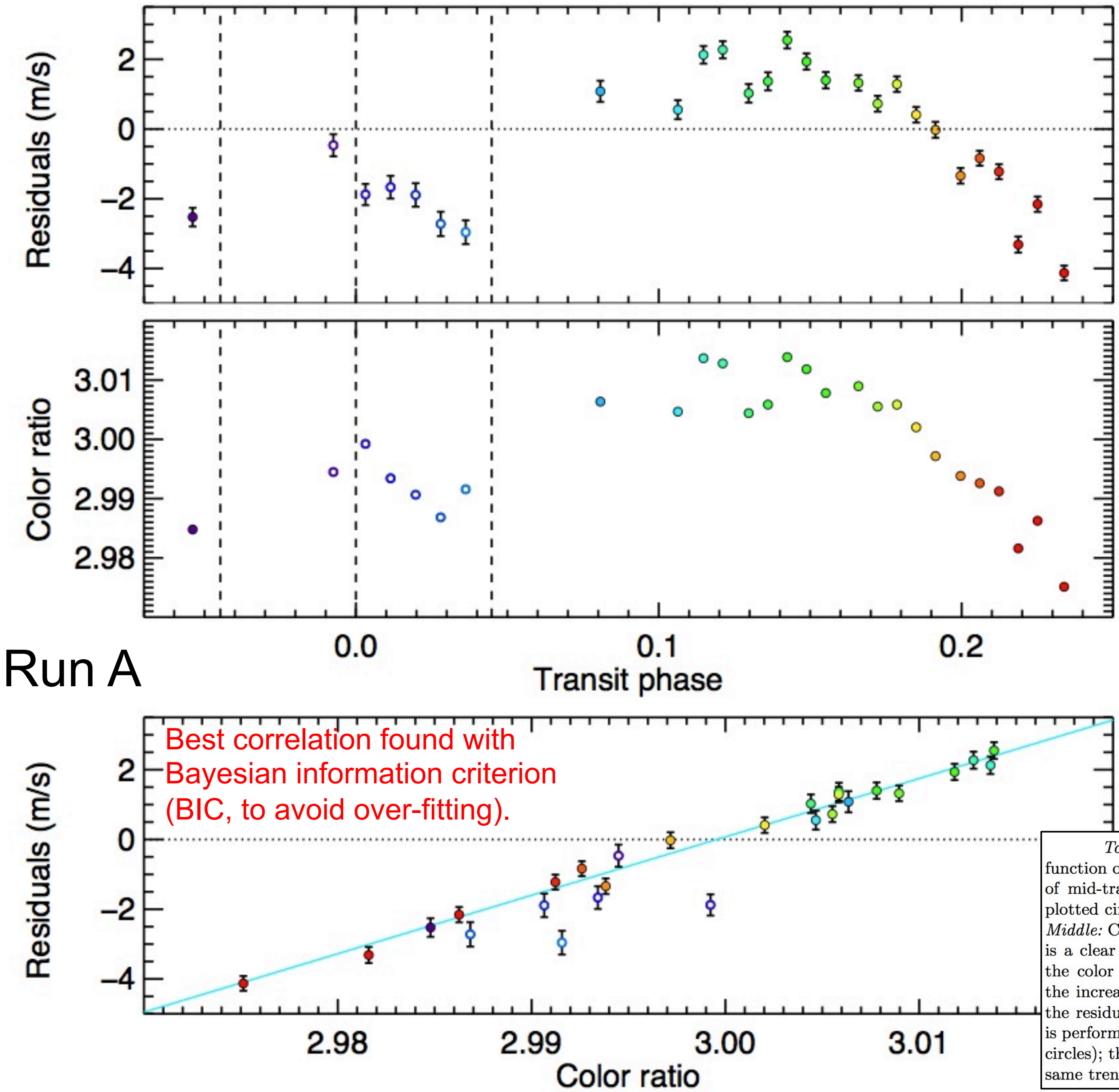
†: number of 6-minute individual exposures.
‡: simultaneous thorium-argon (ThAr) or Fabry Perot (FP) reference.
††: airmass evolution during the observation sequence.
∗: median of the signal-to-noise ratio per pixel at 392 Å (pipeline order # 2), 527 Å (# 42), and 673 Å (# 67).
∗∗: except for the two first exposures made without simultaneous reference.

S/N variations also during each run,
due to weather and airmass variations.

5-planet Keplerian model:



Empirical correction of the color effect



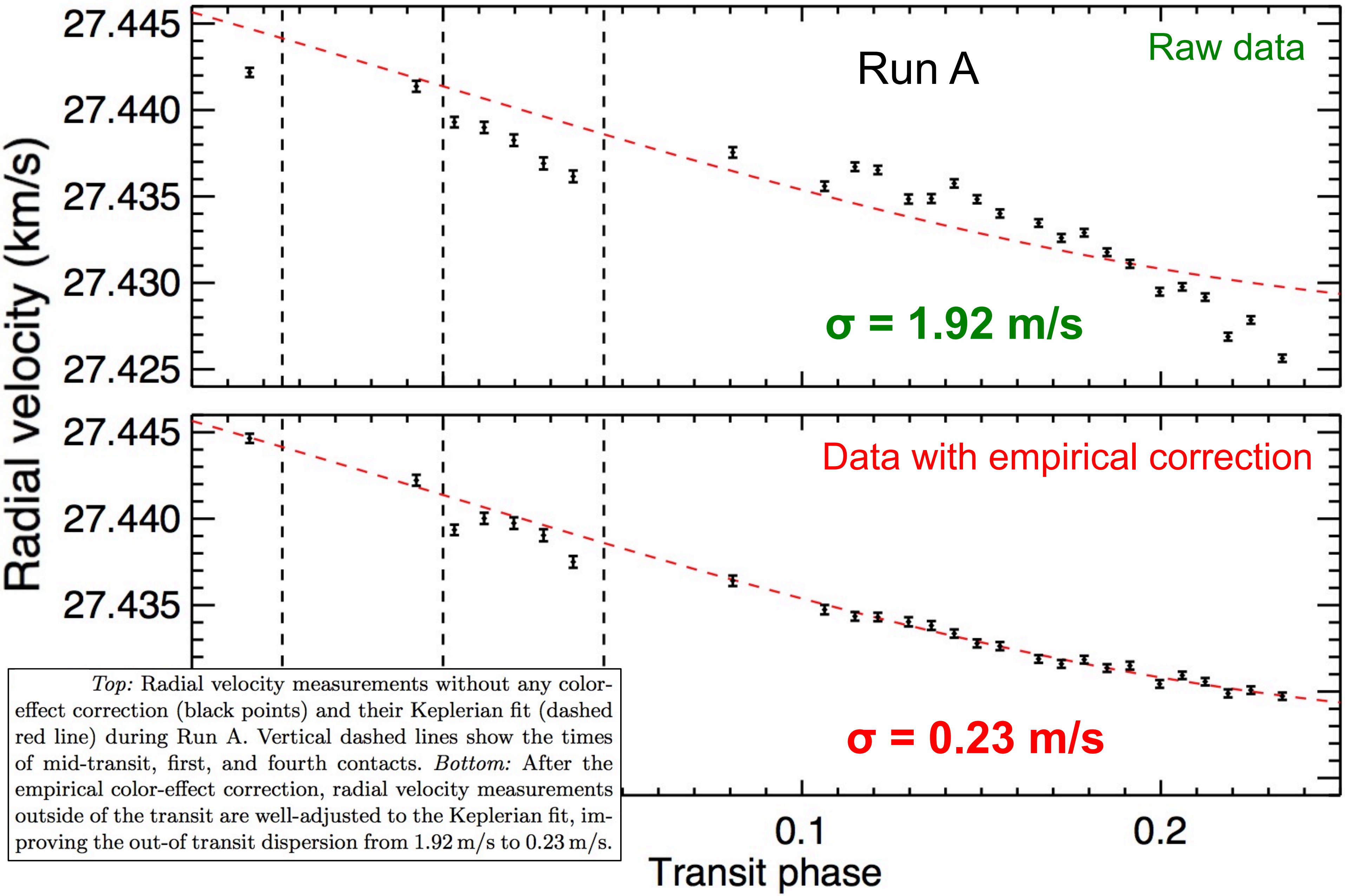
Color ratio:

$$C_{\mathrm{j1,j2}}^{\mathrm{i1,i2}}(\phi) = \frac{\sum_{i1}^{i2} S/N_{\mathrm{i}}(\phi)}{\sum_{j1}^{j2} S/N_{\mathrm{j}}(\phi)}$$

$S/N_{\mathrm{k}}(\phi)$: *S/N* in the spectral order *k* at orbital phase ϕ (*k*=[0-68] for HARPS-N).

Top: Residuals from the Keplerian fit in Dataset A as a function of orbital phase. Vertical dashed lines show the times of mid-transit, first, and fourth contacts. The colors of the plotted circles indicate the orbital phases of each observation. *Middle:* Color ratio $C_{32,32}^{28,30}$ as a function of orbital phase. There is a clear correlation with the RV residuals. The decrease in the color ratio at the end of the sequence is mainly due to the increase in the airmass. *Bottom:* Linear relation between the residuals of the Keplerian fit and the color ratio. The fit is performed on the measurements outside of the transit (filled circles); those in the transit (empty circles) roughly follow the same trend.

Empirical correction of the color effect



Top: Radial velocity measurements without any color-effect correction (black points) and their Keplerian fit (dashed red line) during Run A. Vertical dashed lines show the times of mid-transit, first, and fourth contacts. *Bottom:* After the empirical color-effect correction, radial velocity measurements outside of the transit are well-adjusted to the Keplerian fit, improving the out-of transit dispersion from 1.92 m/s to 0.23 m/s.

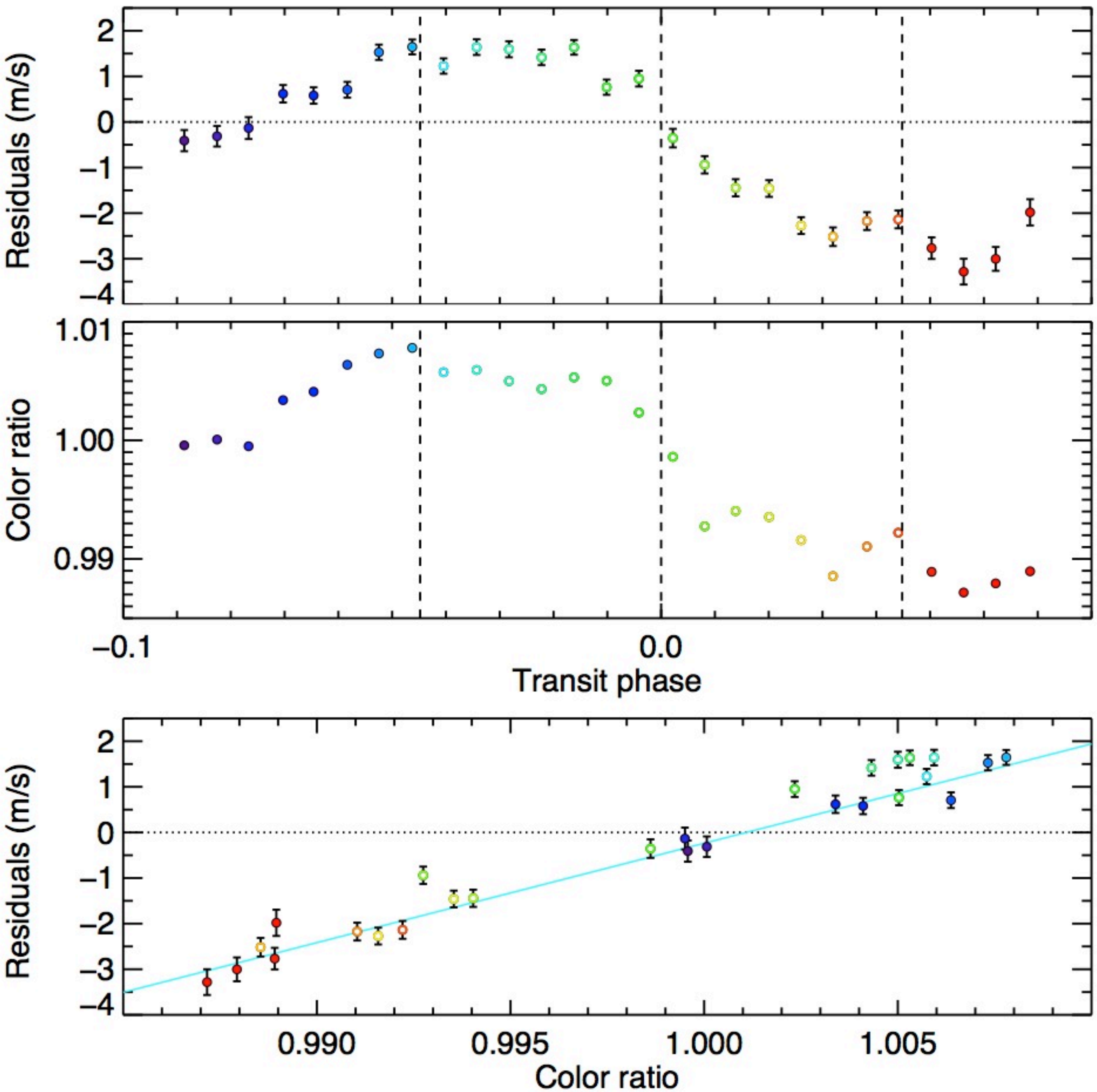
For each Run, the empirical correction allows the dispersion to be significantly reduced (factor 1.7 to 8.3 improvement on σ).

	Empirical correction			*DRS standard correction*	*Without correction*
Run	Color ratio [i1,i2]/[j1,j2]	Polynomial degree	Dispersion (m/s)	Dispersion (m/s)	Dispersion (m/s)
A	[28,30]/[32,32]	1	0.23	-	1.92
B	[15,17]/[12,12]	3	0.32	0.73	2.57
C	[14,16]/[13,13]	1	0.67	0.95	1.11
D	[6,7]/[4,5]	1	0.60	1.52	1.39
E	[21,21]/[28,28]	1	0.28	0.43	1.86

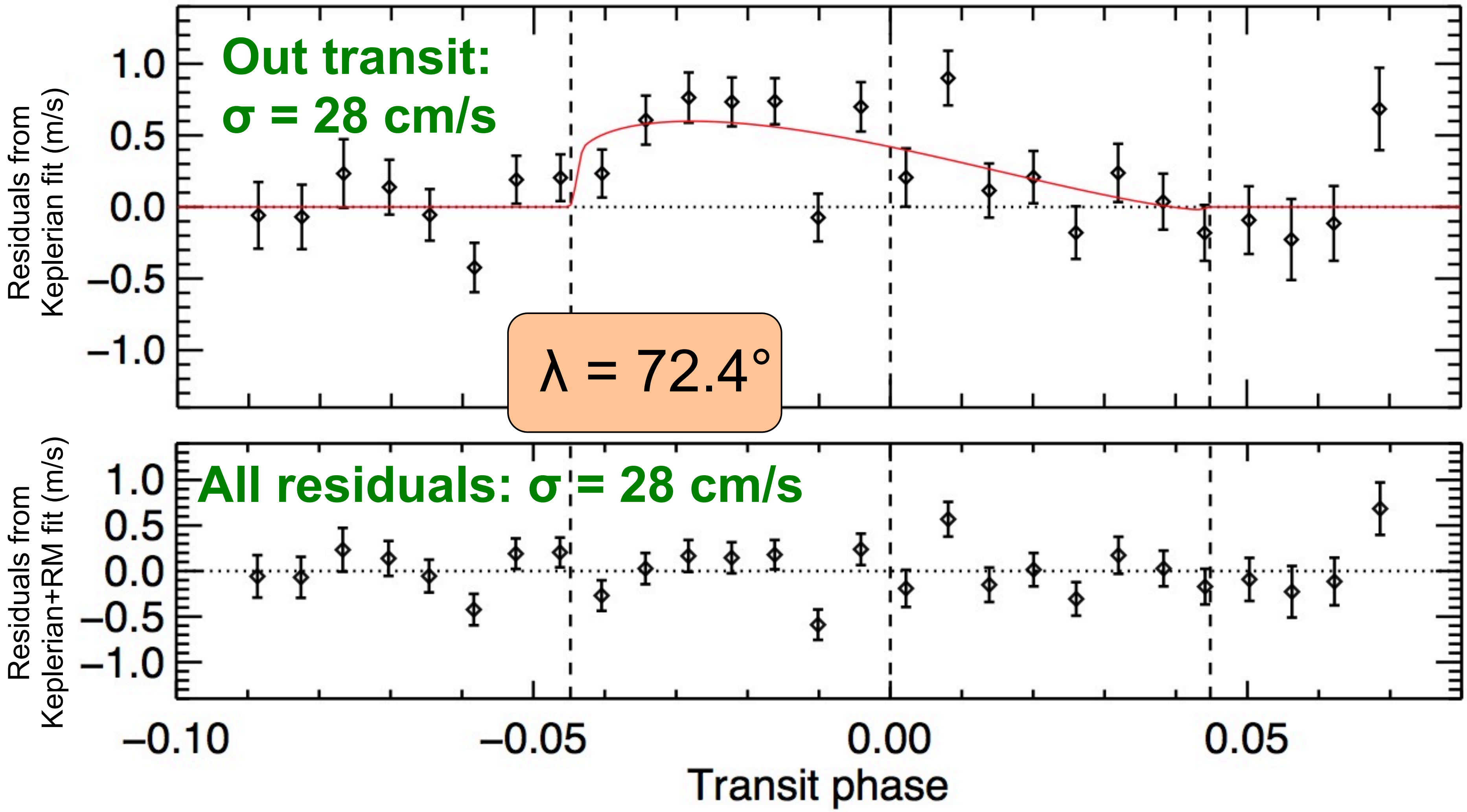
For each Run, the empirical correction also allows a reduction of the dispersion by comparison with the standard DRS color correction (factor 1.4 to 2.5 improvement on σ).

Notes: Dispersion is calculated outside of the transit on the residuals to the Keplerian fit.
The corrections refer to the different color-effect corrections on the radial velocities.

Run E



Best color ratio:
SNR_{21}/SNR_{28}



F-test: >90% probability that the fit improvement is due to RM detection.

Accuracy on systemic RV: ±8 cm/s.

Parameters for the Rossiter-McLaughlin analysis of 55 Cnc e.

Parameter	Symbol	Value	Unit
Fixed†			
Transit epoch	T_0	$2455962.0697^{+0.0017}_{-0.0018}$	BJD
Transit duration	$t_{\rm d}$	$0.0660^{+0.0035}_{-0.0028}$	day
Orbital period	P	$0.7365417^{+0.0000025}_{-0.0000028}$	day
Planet-to-star radii ratio	$R_{\rm p}/R_*$	$0.01936^{+0.00079}_{-0.00075}$	
Scaled semi-major axis	$a_{\rm p}/R_*$	$3.523^{+0.042}_{-0.040}$	
Orbital inclination	$i_{\rm p}$	$85.4^{+2.8}_{-2.1}$	deg
Stellar reflex velocity	K	6.3±0.21	$\rm m\,s^{-1}$
Measured‡			
Sky-projected obliquity	λ	$72.4^{+12.7}_{-11.5}$	deg
Projected stellar rotation velocity	$v\sin i_*$	$3.3^{+0.9}_{-0.9}$	$\rm km\,s^{-1}$
Systemic velocity	γ	27.40949±0.00008	$\rm km\,s^{-1}$

†: All parameters were taken from Dragomir et al. (2014), except for K taken from Endl et al. (2012).
‡: Values are calculated in Section 4. See also Sect. 5.1 for the uncertainties.

Validation tests on Run E

- BIC or $\Delta\chi_2$;
- Resampling of observations (Kipping 2010);
- Ephemeris (T_0, P, $t_{duration}$):
  - ± 1σ values;
  - T_0 from Gillon et al. (2012) 8 min later than Dragomir et al. (2014);
- Model parameters:
  - Limb darkening;
  - Convective blueshift;
  - Keplerian parameters of the 5 planets;
  - Transit parameters of 55 Cnc e;

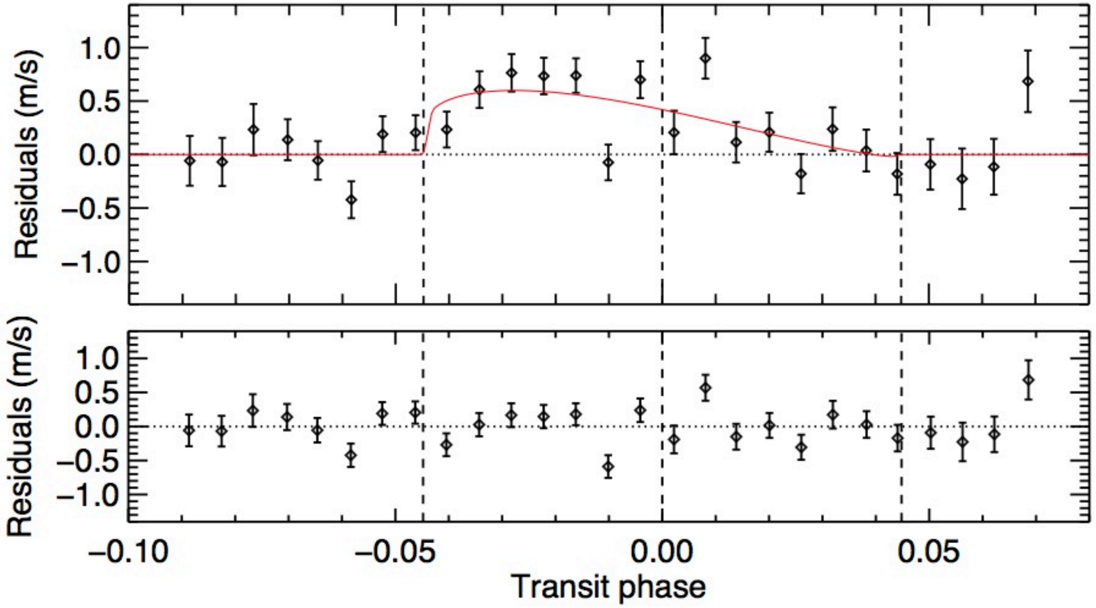
→ no significant changes.

Color-effect empirical correction

$\lambda = 72.4°^{+7.4°}_{-9.0°}$

$v \sin i_* = 3.3 \pm 0.9$ km/s

$\sigma = 28$ cm/s

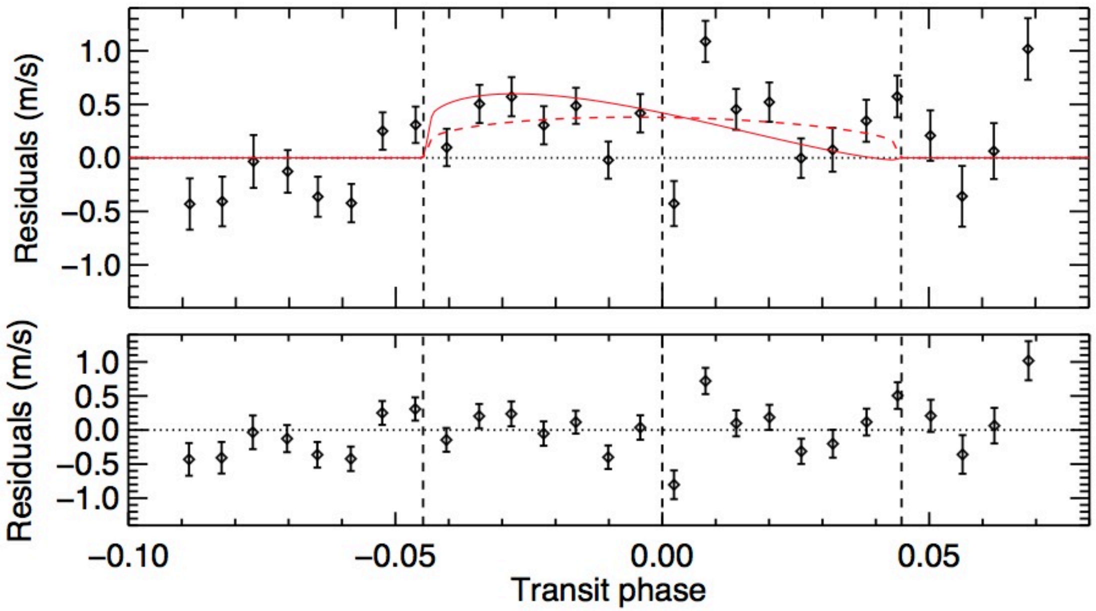


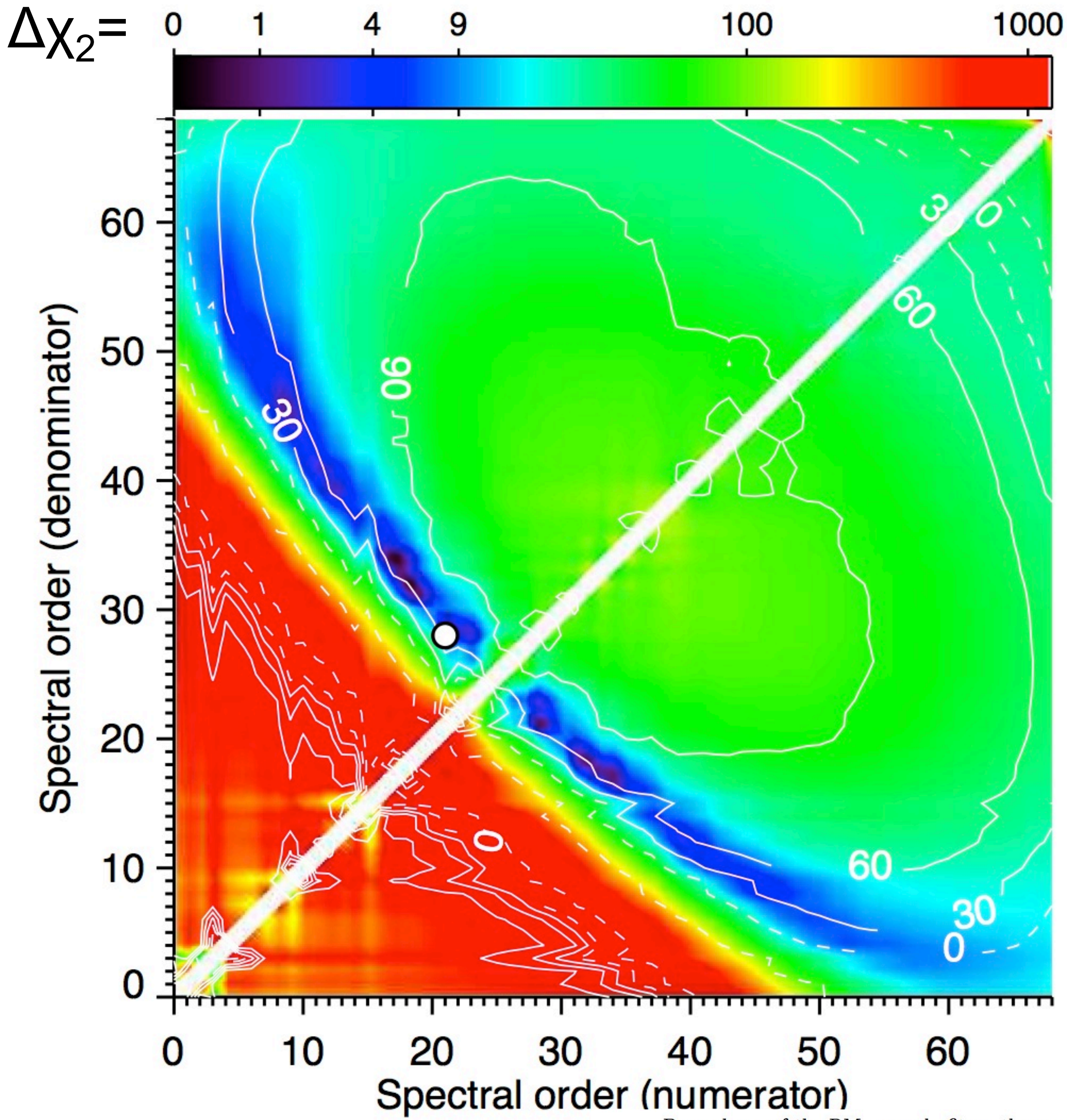
Color-effect standard DRS correction

$\lambda = 88.6°^{+9.3°}_{-9.9°}$

$v \sin i_* = 2.9 \pm 1.3$ km/s

$\sigma = 39$ cm/s





- Symmetrical
- 50° < λ < 110°
- 0.5 < *v* sin *i*$_*$ < 5 km/s

Dependence of the RM anomaly fit on the spectral orders used to compute the color-effect correction (Run E). Two different spectral orders must be used to quantify the color, which explains the white diagonal line where no fits can be done. White contours show the spin-orbit angles obtained for each color ratio (solid lines for positive values, dashed lines for negative values). The colorscale corresponds to the χ^2 difference with respect to the best fit, obtained with the spectral orders 21 and 28 (white disk) and λ=72.4°. Color ratios in the red part of the diagram show no significant correlation between the residuals of the Keplerian fit and the color ratio. Fits at less than about 3σ from the best fit are found in the localized blue area.

According their accuracies, Runs A-D agree with the Run-E detection.

- All runs:
λ = 68.3° +/- 6.6°

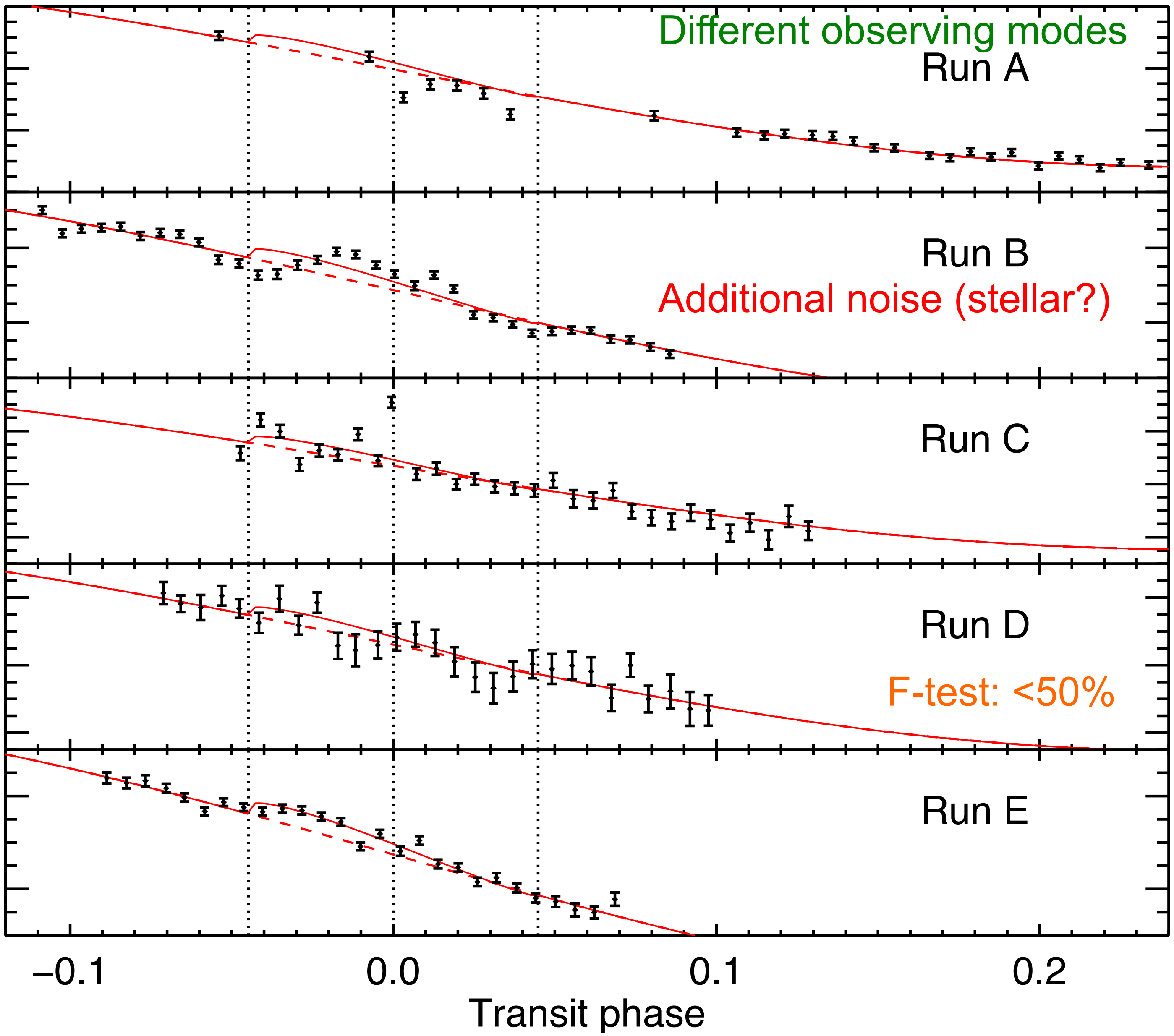
- Run A only:
bad fit

- Run B only:
λ = 77.1° +/- 7.3°

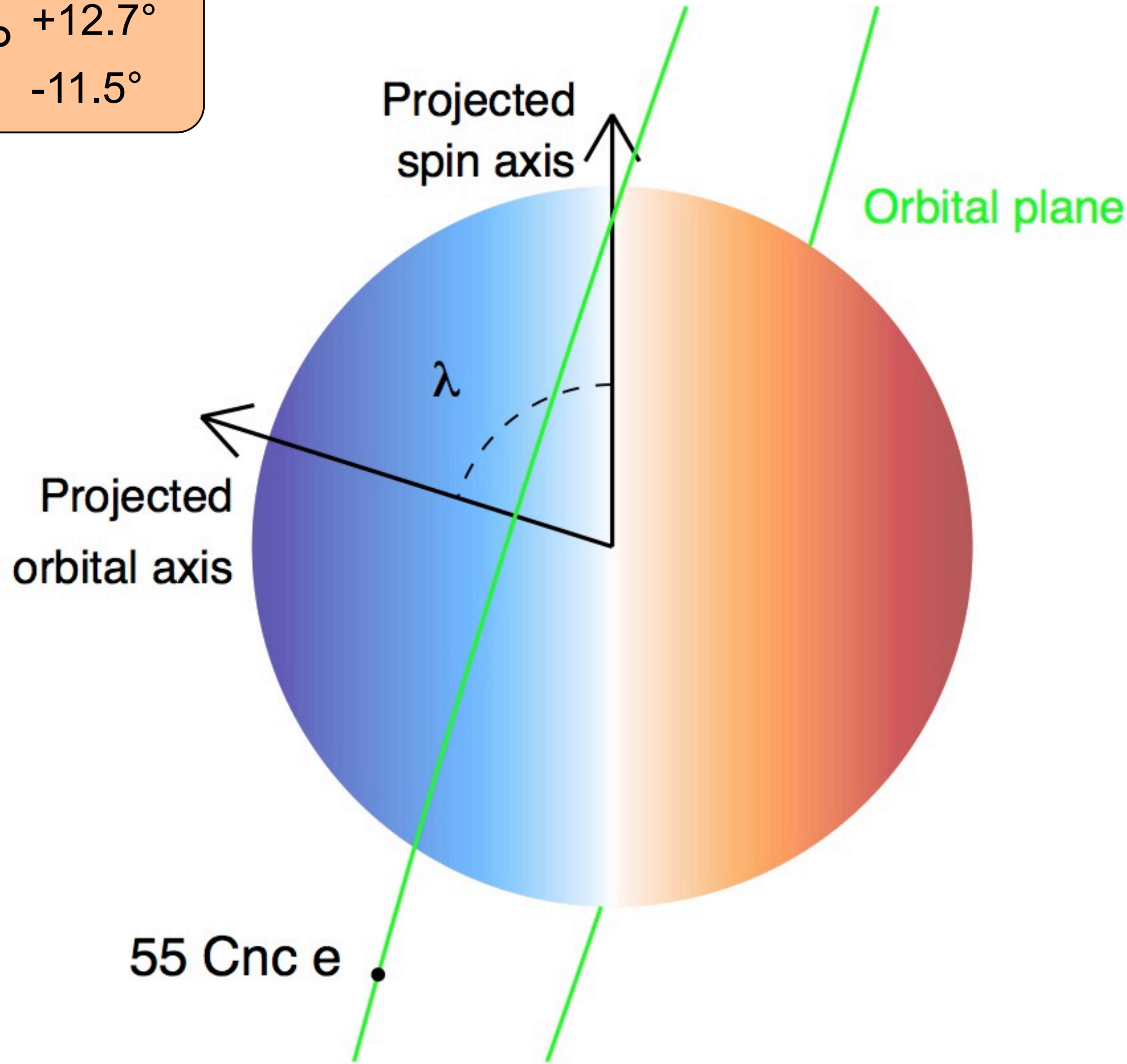
- Run C only:
λ = 65.9° +/- 15.2°

- Run D only:
no detection

- All runs but E:
λ = 65.2° +/- 8.4°



$$\lambda = 72.4^{\circ}\,{}^{+12.7^{\circ}}_{-11.5^{\circ}}$$

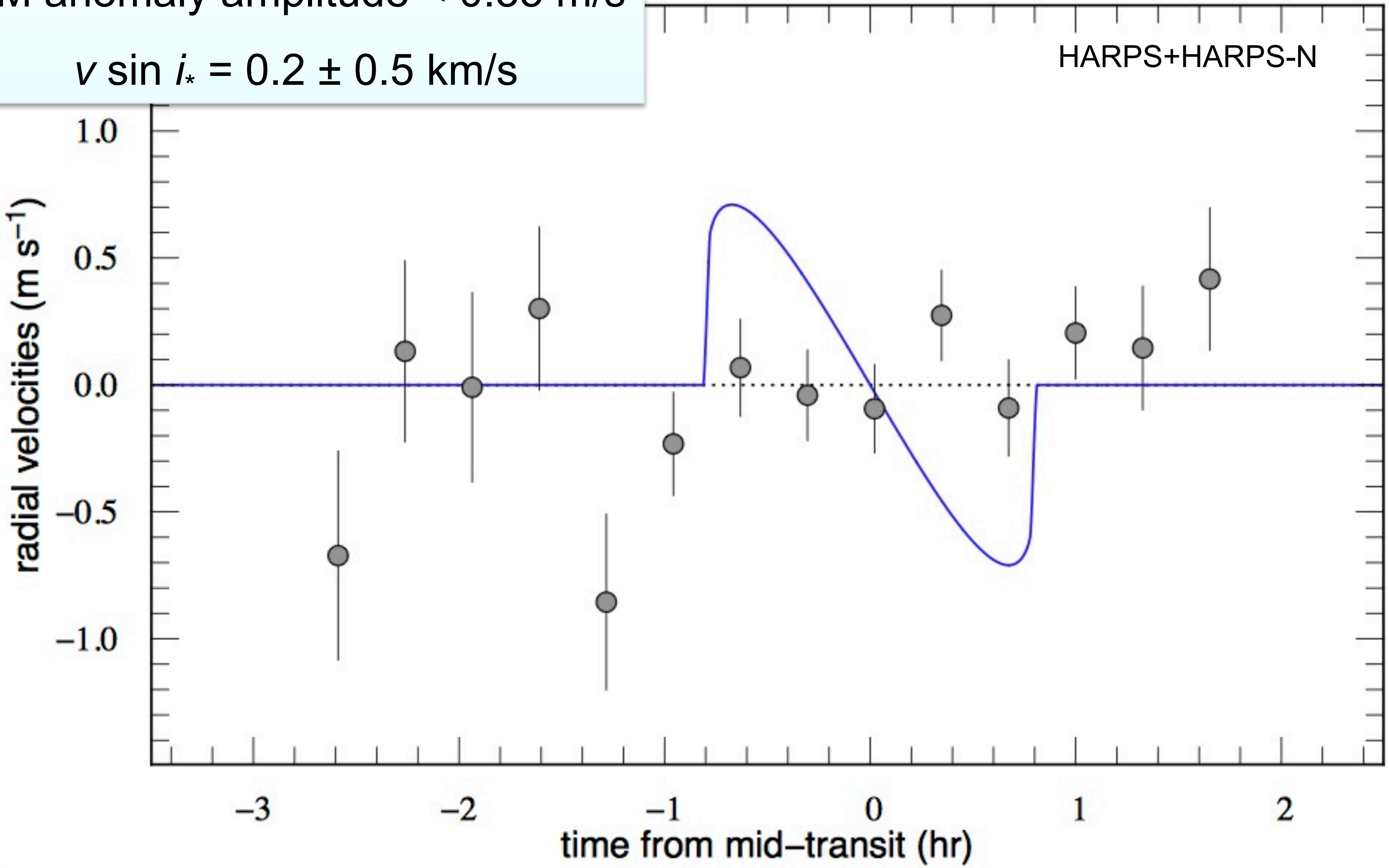


López-Morales et al. (2014):
6 additional transits of 55 Cnc e (4 with HARPS-S, 2 with HARPS-N)

No detection!

RM anomaly amplitude < 0.35 m/s

$v \sin i_* = 0.2 \pm 0.5$ km/s



Conclusions

- Possible detection of the smallest Rossiter-McLaughlin anomaly amplitude of an exoplanet so far (~60 cm/s).

- The super-Earth 55 Cnc e would be the smallest exoplanet with a Rossiter-McLaughlin anomaly detection.

- $\lambda = 72.4°$ (+12.7/-11.5): the planet orbit is prograde, highly misaligned and nearly polar compared to the stellar equator.

- The entire 55 Cancri system may have been highly tilted by the presence of a stellar companion.

- The detection mainly stand on one observation: it should be confirmed with other transit observations in good weather conditions.

- We devised an empirical correction for the “color effect” on the spectra, which significantly improves accuracy of radial velocities, below 30 cm/s.

- The potential of this correction on long-term RV measurements could be explored.