Precession of the orbital planes in transiting exoplanets

Theodor Pribulla

(in collaboration with Z. Garai, Ľ. Hambálek, S. Kálmán, & G. Szabó)

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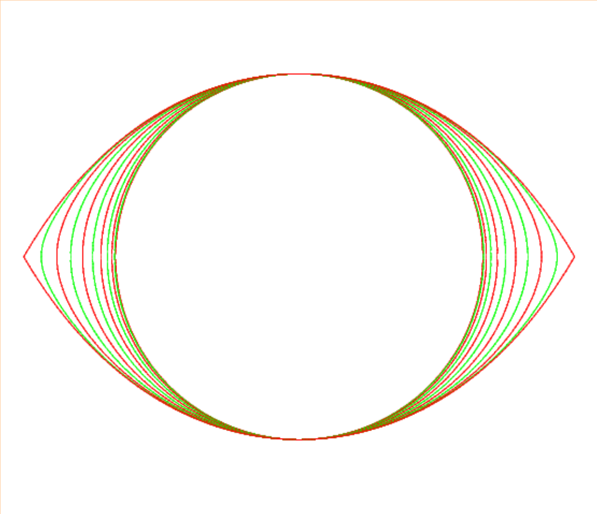
Rapidly rotating parent stars

- Early-type stars to mid-F
- ~ 30 hosts with T_{eff} > 7000 K showing transits
- Difficult to measure RVs - rotational-line broadening, stellar pulsations => often only the upper mass limit
- Confirmation: detection of planet "shadow" in line profiles during the transits



$$\Phi = -\frac{GM}{r} - \frac{1}{2}\Omega^2 r^2 \sin^2\theta$$

$$\Omega_{\rm crit} = \sqrt{\frac{8GM}{27R_P^3}} = \sqrt{\frac{GM}{R_E^3}}$$

$$\frac{R_E}{R_P} = 1 + \frac{1}{2}f^2 = 1 + \frac{\Omega^2}{\Omega^2_{\rm crit}}$$

Spin-orbit misalignment

- Spin-orbit misalignment: planet formation/migration history
- Systems with hot parent stars show isotropic orientations, late-type stars are typically aligned
- Can be measured only in transiting systems
- Spectroscopy: projected (minimum) misalignment λ
- Photometry: both λ and i* - fast rotators with GD

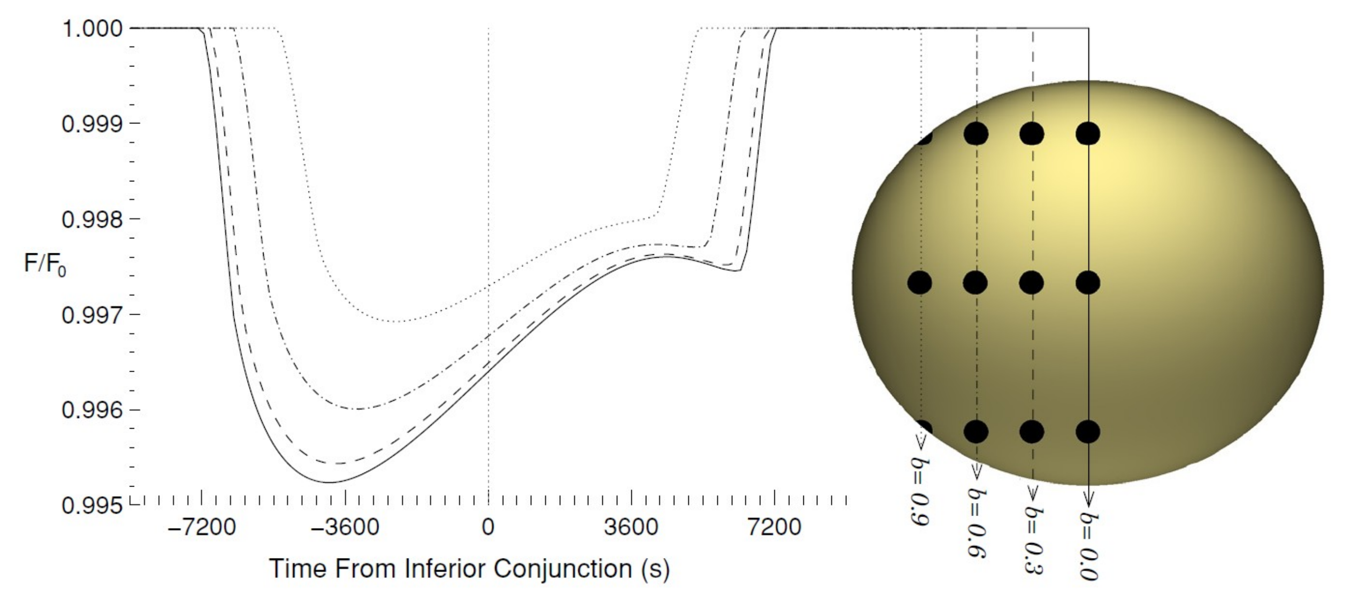
$$\cos\psi = \sin i_\star \cos i_{\rm orb} + \cos i_\star \sin i_{\rm orb} \cos\lambda$$

Precessing systems

- Misaligned close systems + rotationally deformed stars: precession of stellar spin axis and orbital plane of the planet
- Tidal interaction => orbital and stellar precession => stellar quadruple moment J_2
- Typically $L_{orb} << L_*$ ==> precession of the star negligible
- Three precessing systems known, Kepler-13Ab (Szabó et al., 2012, MNRAS, 421, L122), WASP-33b (Johnson et al., 2015, ApJ 810, L23) and Kelt-9b (Stephan et al., 2022, ApJ 931, 111)

$$\dot{\Omega}_{\rm p} = -\frac{3}{2} J_2 \frac{2\pi}{P} \cos\psi \left(\frac{R_\star}{a}\right)^2$$

GD LC asymmetry

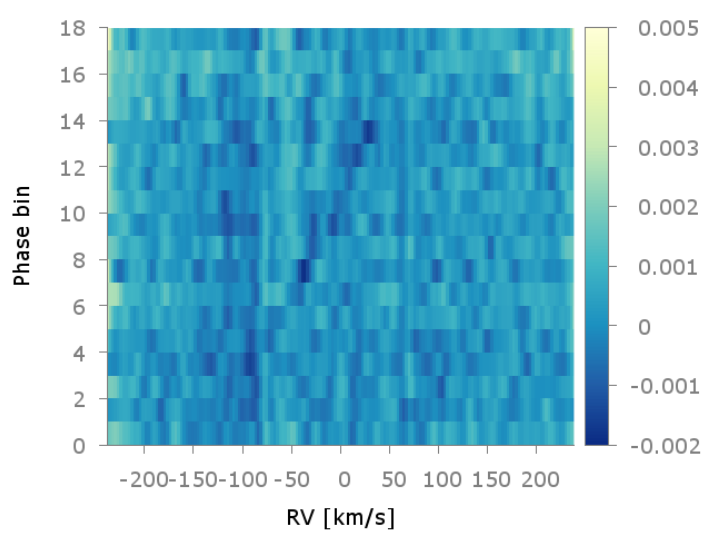


Synthetic LCs of a transiting 1 Rjup planet in a 0.05 a.u. orbit around an Altair-like star with obliquity i* = 60° and λ = 270°.

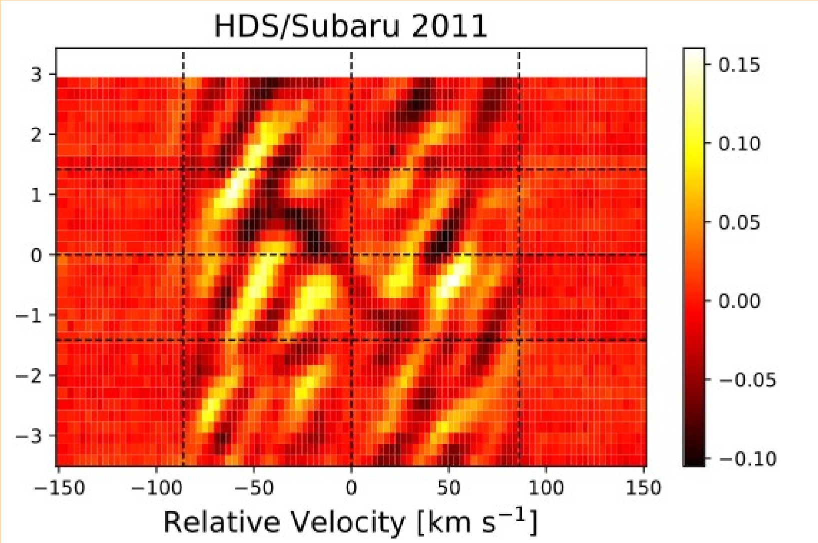
© Barnes, 2009, ApJ, 705, 683

$$T_{\rm eff} = \left(\frac{F}{\sigma}\right)^{1/4} = \left(\frac{L}{4\pi\sigma GM}\right)^{1/4}\sqrt{\frac{\tan\vartheta}{\tan\theta}}\,g_{\rm eff}^{1/4}$$

Transit tomography



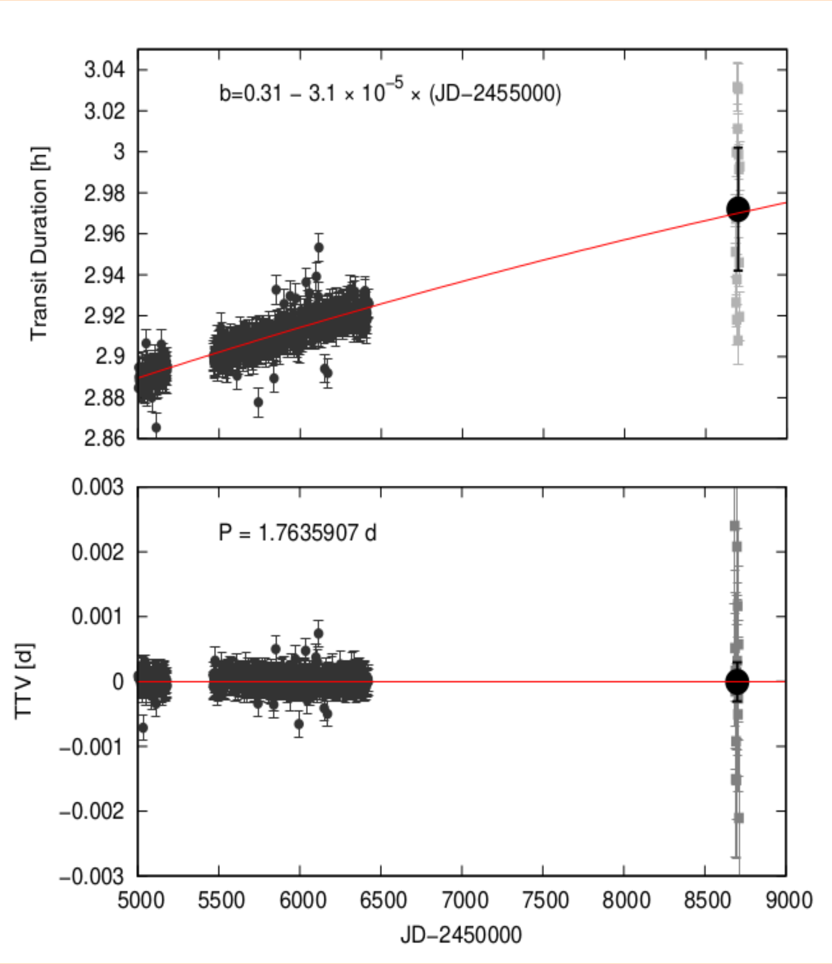
KELT-7b
V=8.54, F2V, v sin i* = 74 km/s,
P = 2.735 days, T = 211 min
15-min exposures, SNR ~ 40,
1.3m@ Skalnaté Pleso (2018)
© Cseh+, 2019, CAOSP, 49, 556



WASP-33b
V=8.14, F4V, v sin i* = 87 km/s,
P =1.220 days, T = 163 min
10-min exposures,
8.2m@ Mauna Kea (2011)
© Watanabe+, PASJ, 72, 19 (2020)

KOI-13Ab: precessing pin

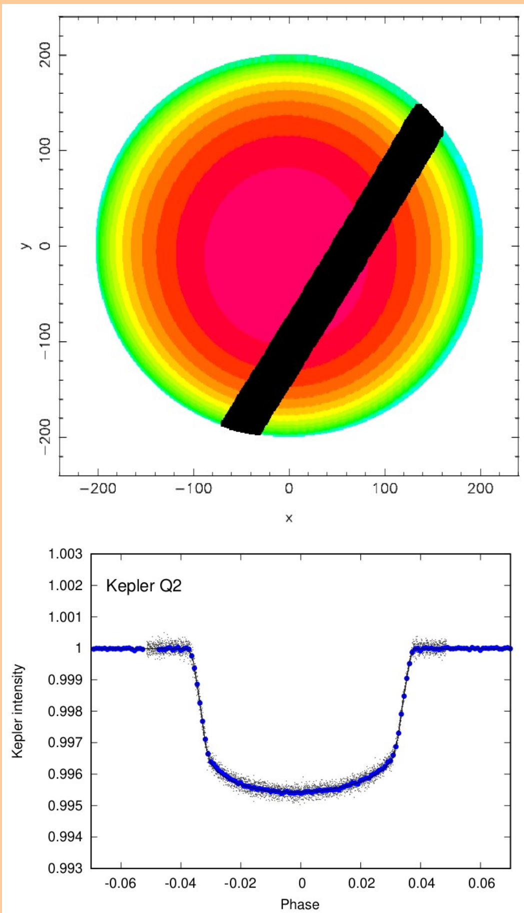
- KOI-13 = ADS 12085AB, with ρ = 1.1″, V=9.70
- A0V, v sin i* ~ 77 km/s
- Precession of the planetary orbit (Szabó et al., 2011)
- Fitting individual transit light curves: TDV !
- No TTV found => no outer perturbers
- Linear TDV rate confirmed => orbital precession
- New TESS data in 2022 !



©Szabó, Pribulla et al., MNRAS, 492, L17 (2020)

KOI-13-Ab: precession

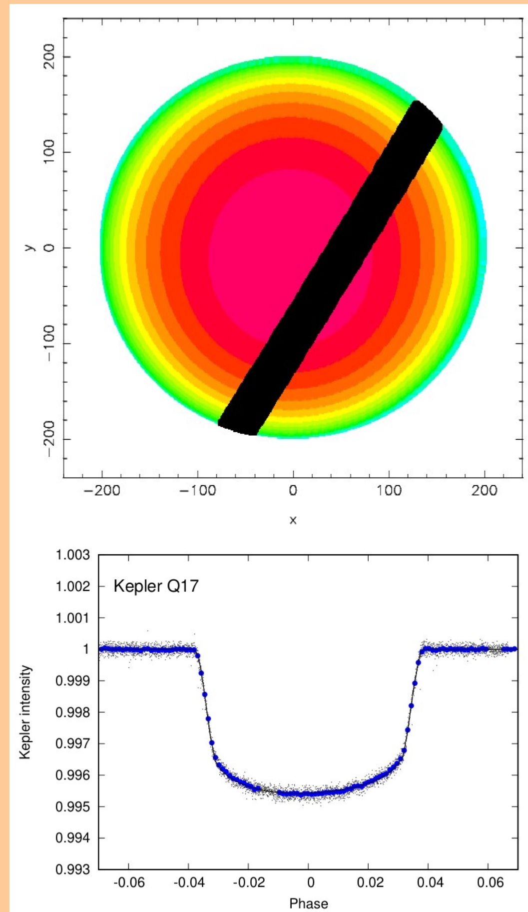
Kepler KQ02



$i = 86.29(4)^\circ$

$b = 0.287(3)$

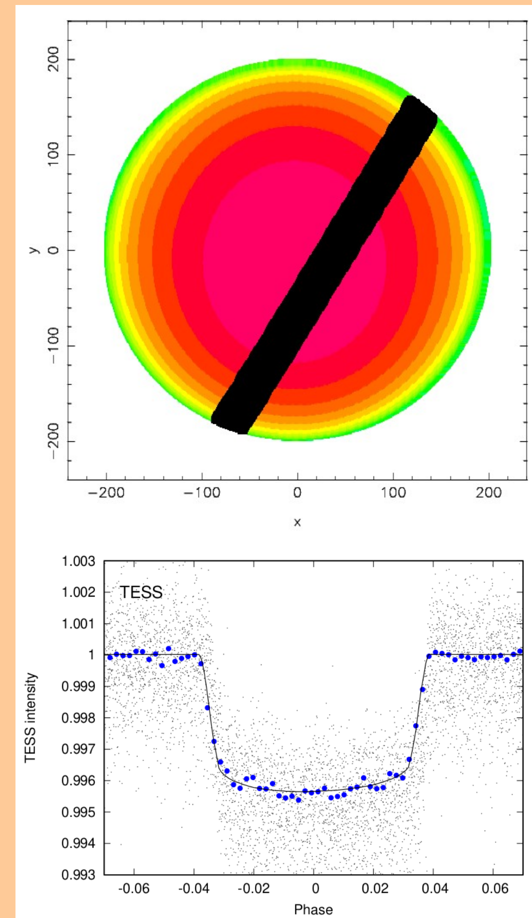
Kepler KQ17



$i = 86.82(4)^\circ$

$b = 0.246(3)$

TESS

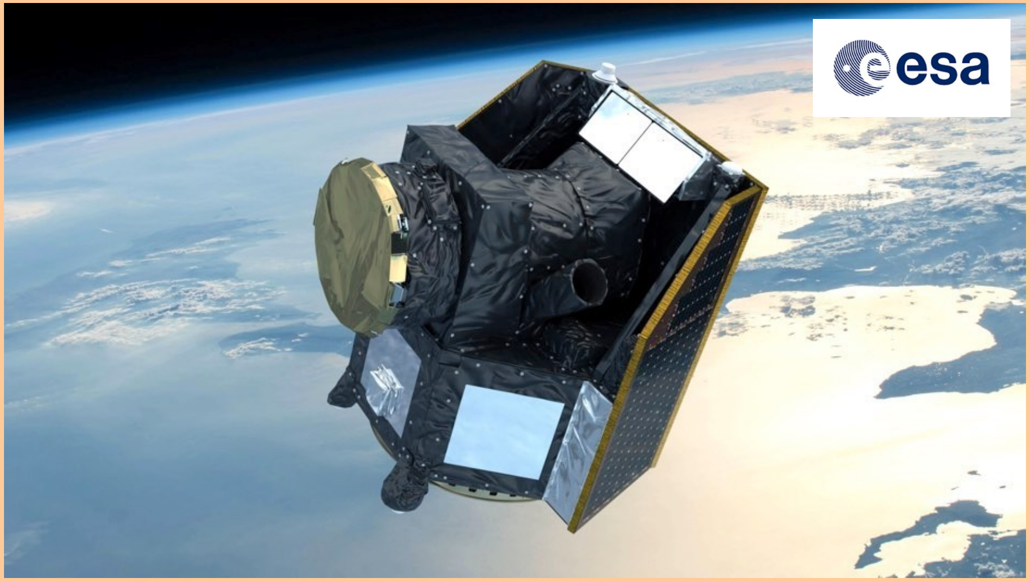


$i = 87.73(6)^\circ$

$b = 0.176(5)$

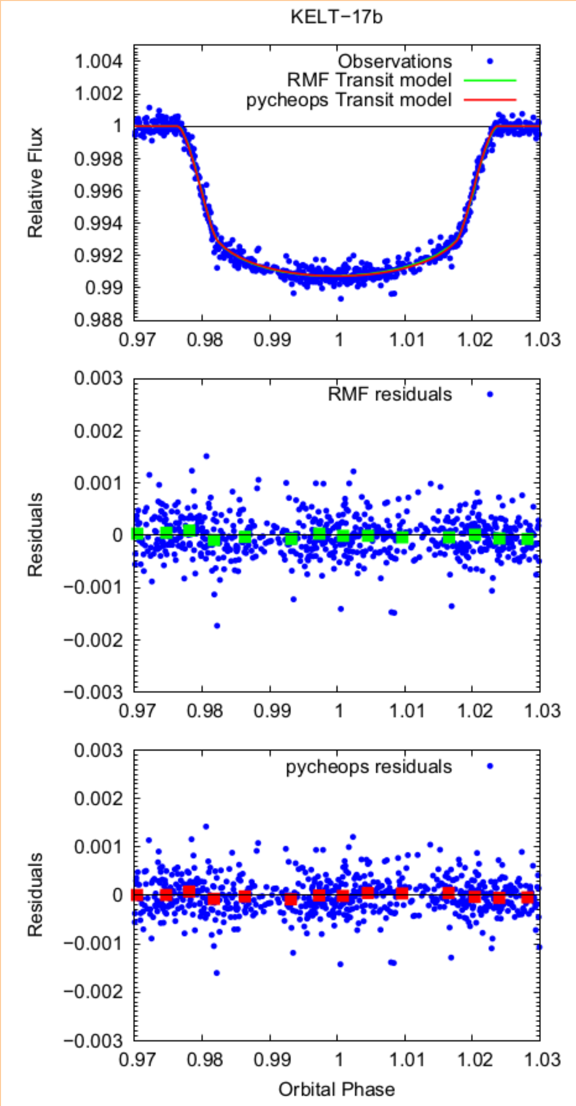
CHEOPS GO program

- Three early-type stars: Kelt-17b, Kelt-19Ab, Kelt-21b
- PI: Zoltán Garai
- Expected point-to-point scatter 200-300ppm
- See Garai, Pribulla et al., MNRAS 513, 2822 (2022)

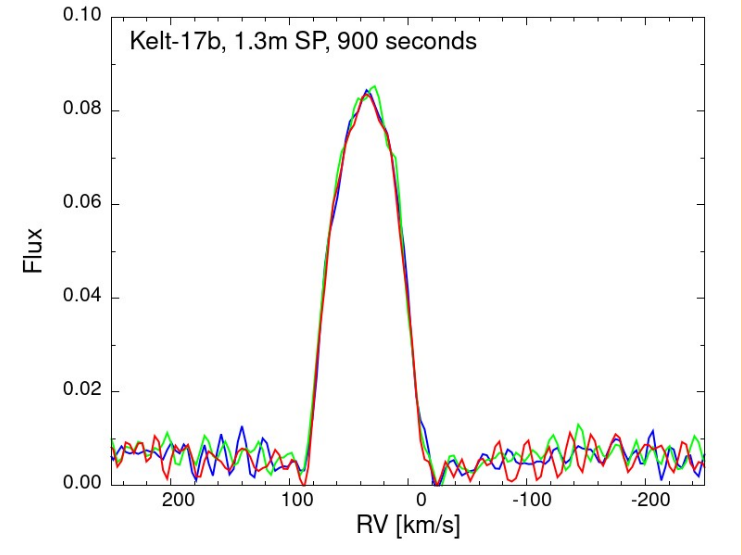


32cm aperture, single-band CCD detector, SSO 100 min orbit, 280kg, launch Dec 17, 2019

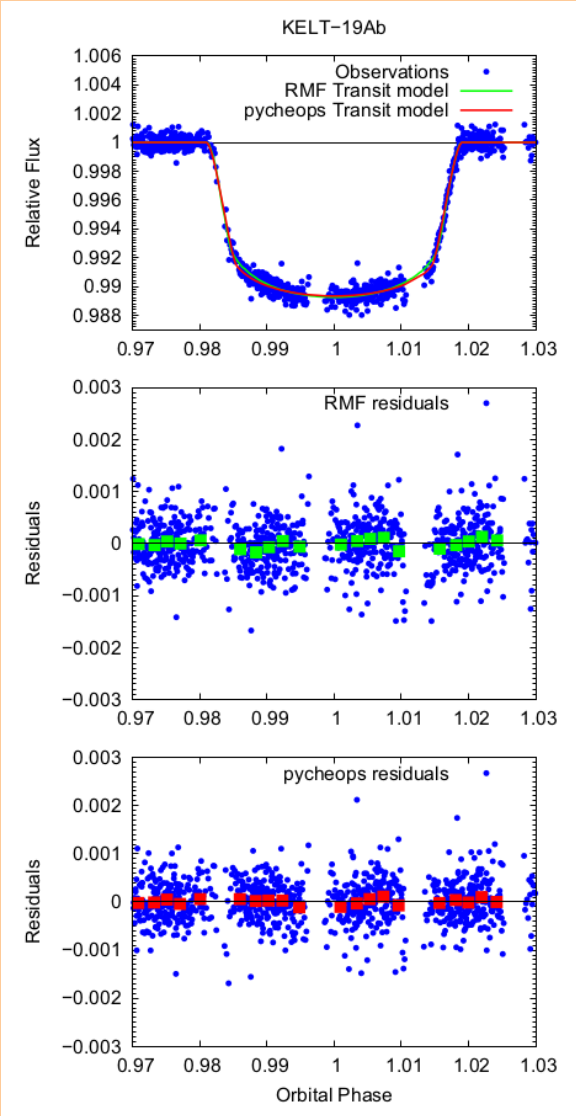
Kelt-17b with CHEOPS



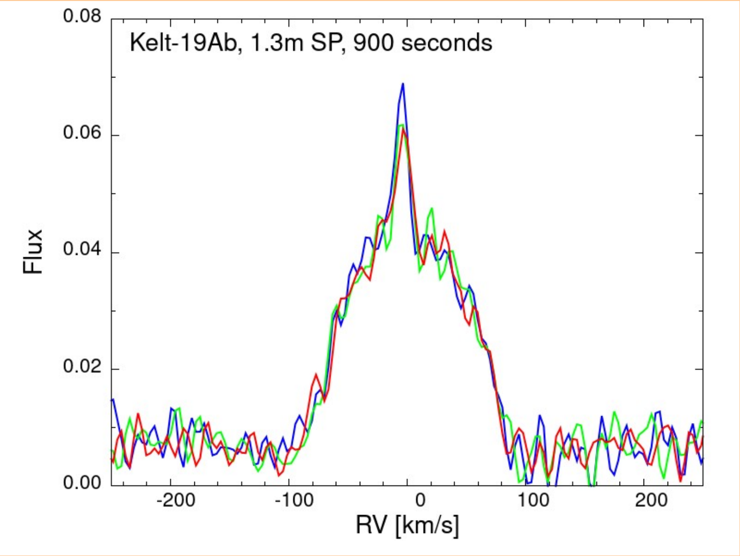
- 1.5 Mjup planet orbiting A-type star, V = 9.23, v sin i*= 44.2 km/s, λ = -115° (Zhou et al., 2016, AJ, 152, 136)
- LC asymmetries below CHEOPS precision (400ppm)
- Parameter improvement, no significant change of the transit

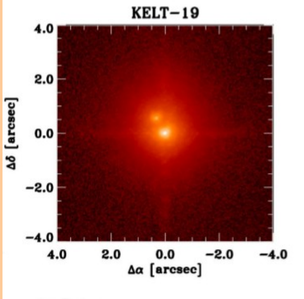


Kelt-19Ab with CHEOPS

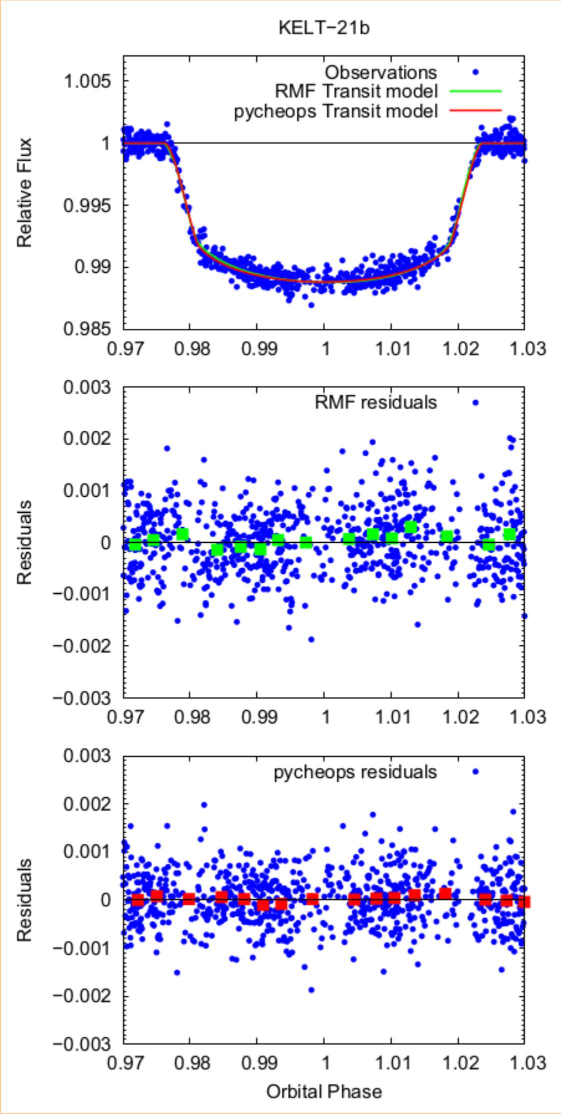


- 1.9 Mjup planet orbiting Am-type star, v sin i* = 84.8 km/s, λ = 180.3° (Siverd et al., 2018, AJ, 155, 35)
- LC asymmetries below CHEOPS precision (400ppm)
- Transits now 10% deeper, real effect or light contamination

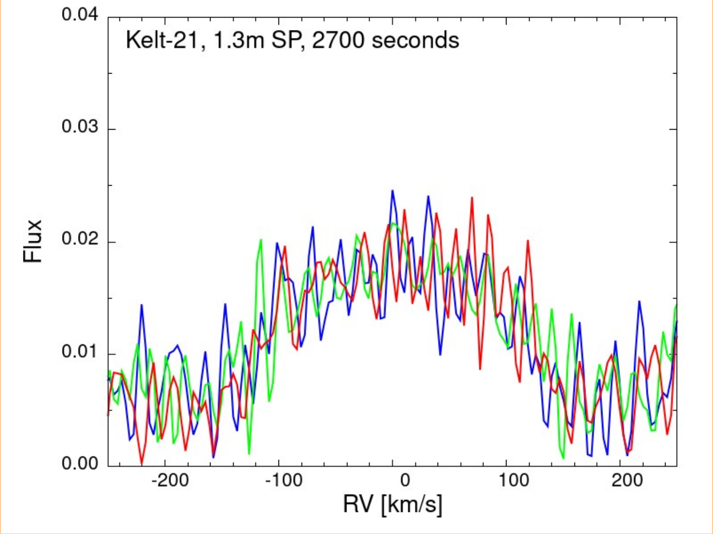




Kelt-21b with CHEOPS



- 1.5 Mjup planet orbiting A-type star, v sin i*= 146 km/s, λ = -5.6° (Johnson et al., 2018, AJ 155, 100)
- LC asymmetries below CHEOPS precision (600ppm)
- Transits now 5% deeper, real effect or light contamination ?
- Stellar obliquity around i* = 70º
- Rotating at $\Omega \sim 0.38\ \Omega_{crit}$



Precessing objects in TESS

- Diploma thesis of D. Orikhovskyi (FMFI UK, Bratislava)
- Search for: (i) misaligned systems, (ii) TDV & precession
- TESS TOI catalog lists 137 planetary candidates, confirmed planets or known planets with T < 12mag, transit depth > 3mmag and Teff > 7000 K

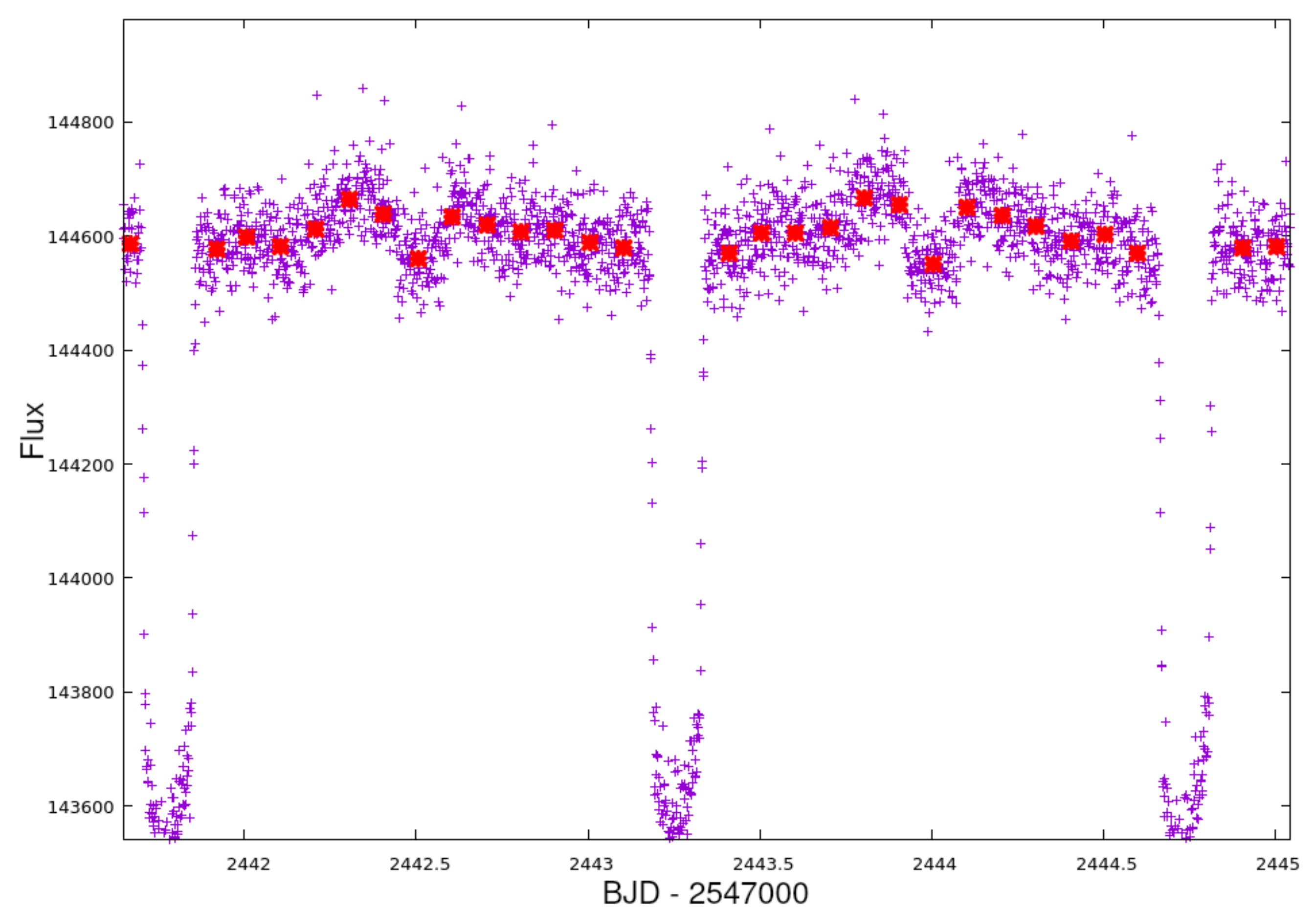
4x 10cm aperture, single-band CCD detector, eccentric orbit P = 13.70 days, 362kg,

launch April 18, 2018

Methods

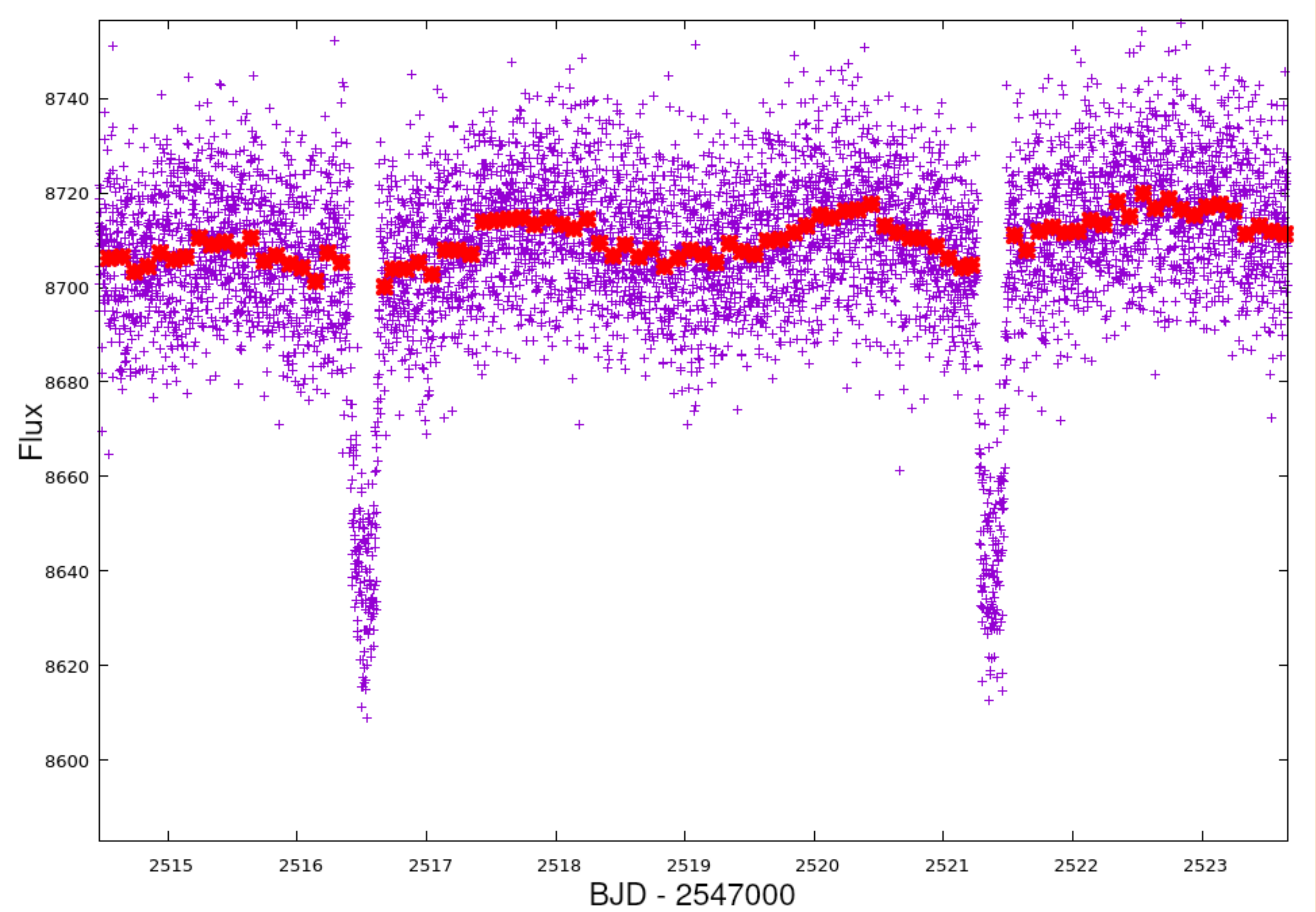
- Selection of objects with 2 min cadence only: 85 objects
- SAP (simple aperture photometry used), SPOC (Science Processing Operations Center) data
- Median detrending of LCs, 0.1 day bins, transit regions excluded for the trend build-up
- Linear interpolation between out-of-transit points
- Problems: short-period pulsations, spot-like variability, incorrect ephemerids

Interesting by-products (i)



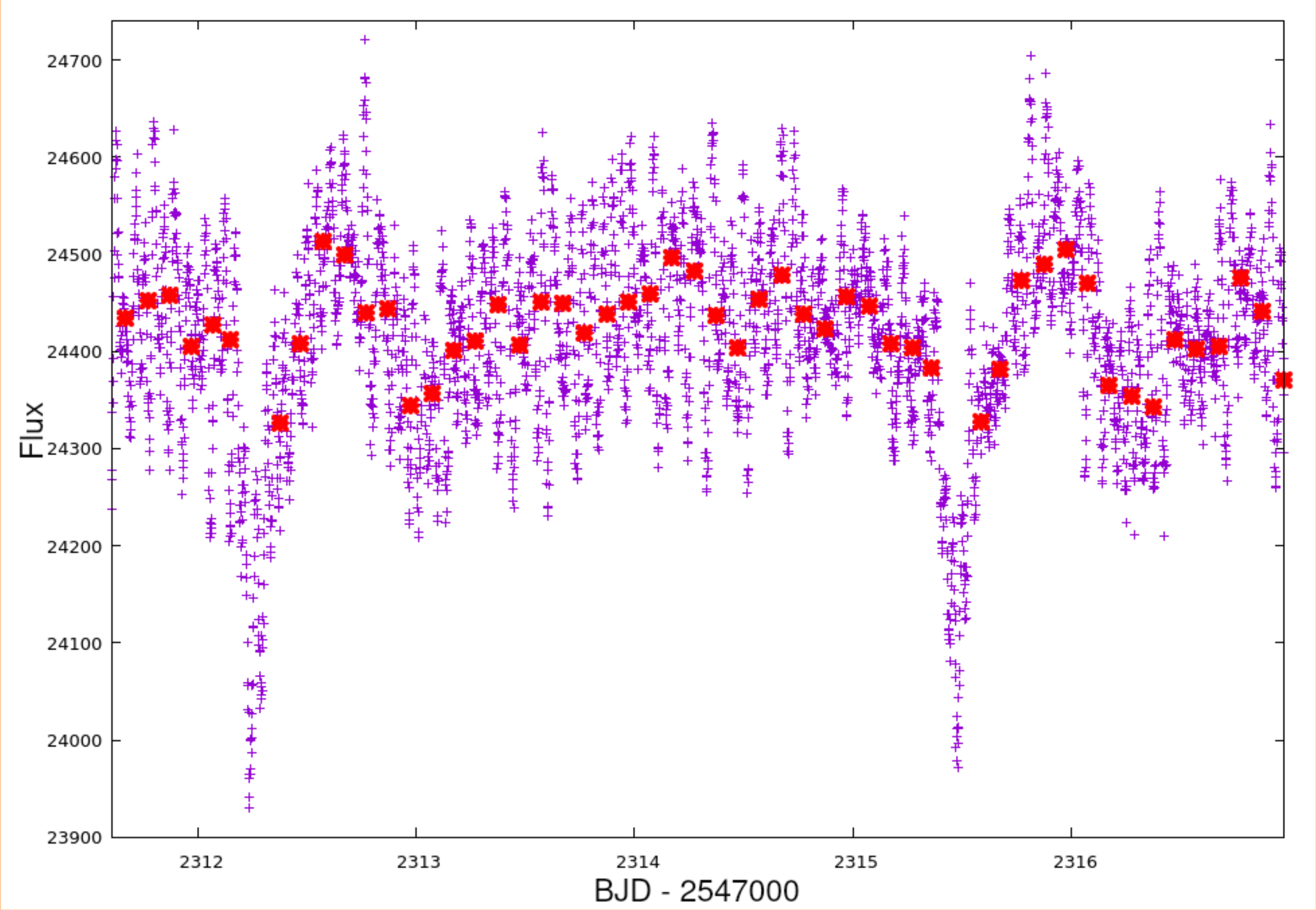
Strongly illuminated planet, or a sdB+M dwarf system

Interesting by-products (ii)



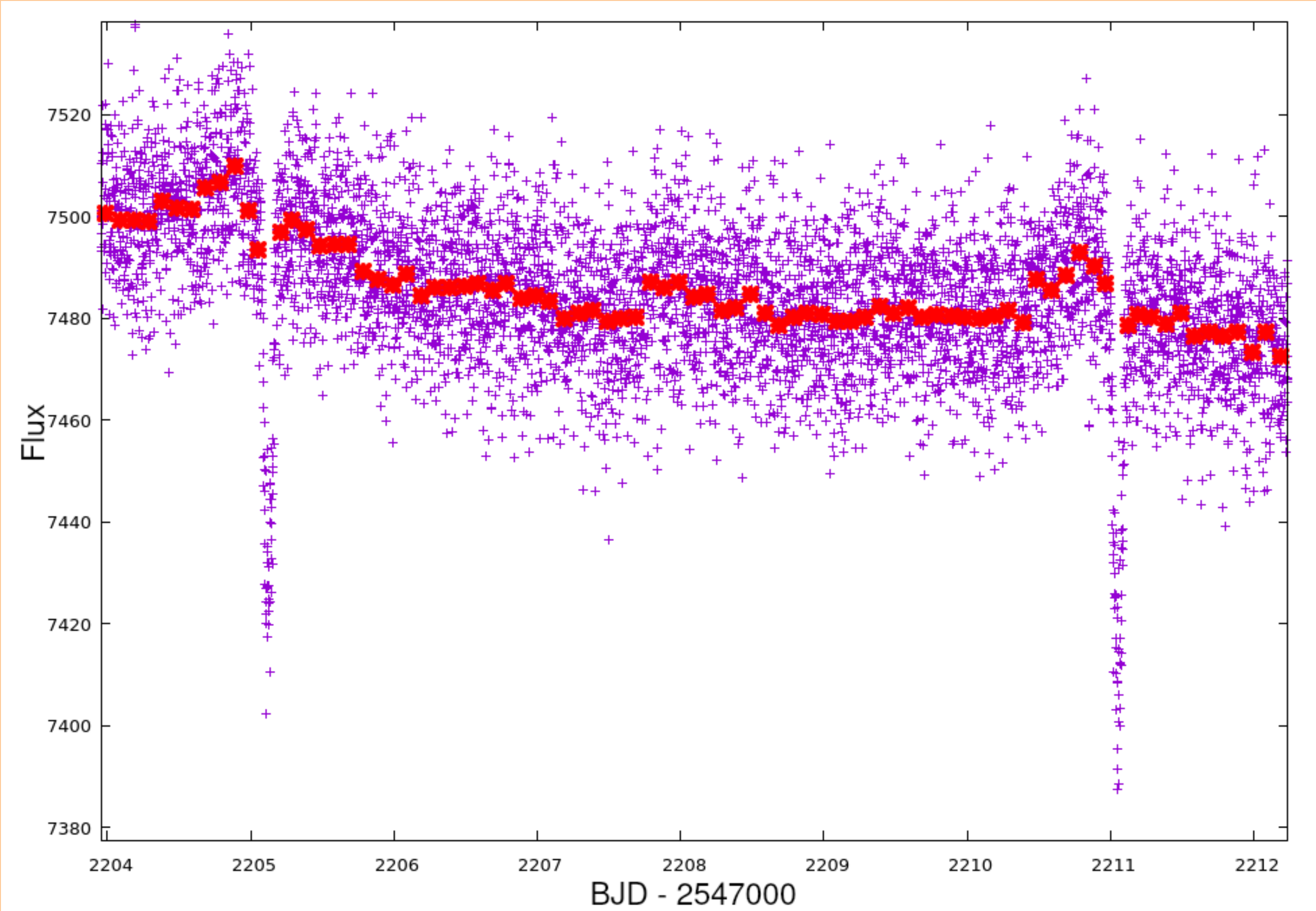
Ellipsoidal out-of-eclipse variability, a close binary

Interesting by-products (iii)



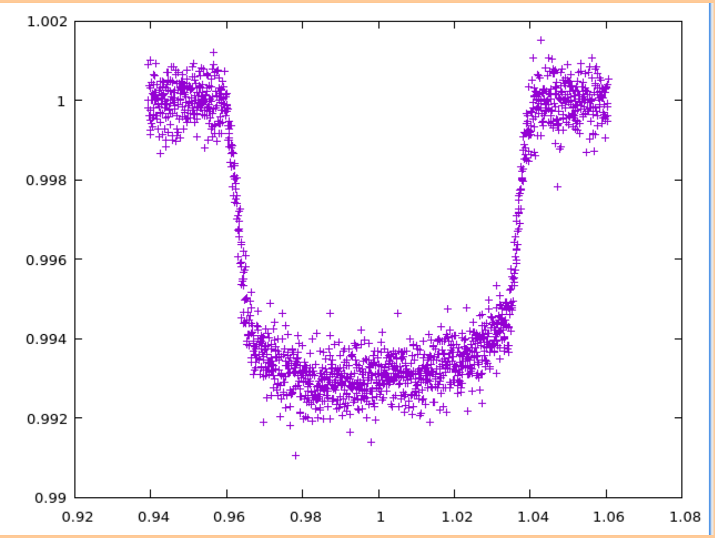
Heartbeat ecc. binary, fast oscillation, TEOs ?

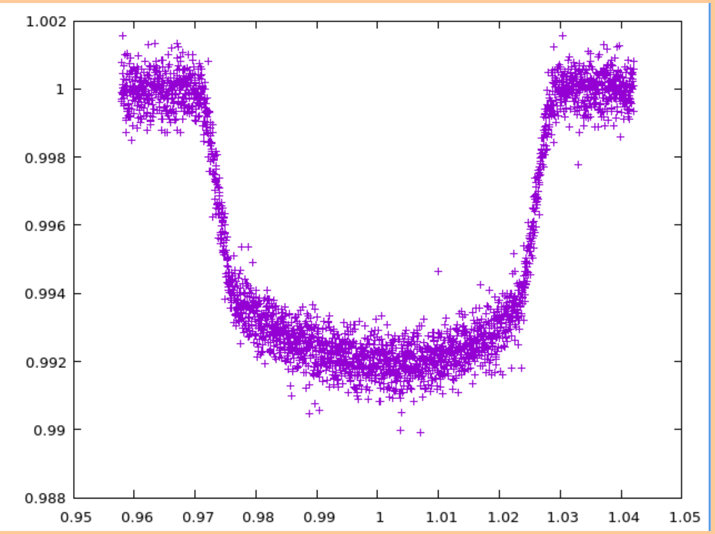
Interesting by-products (iv)

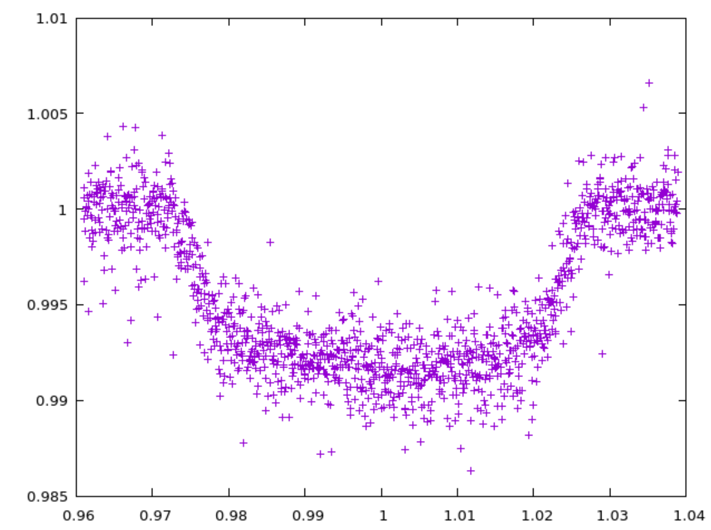


Pre-transit brightening

Best candidates







Conclusions

- Rapidly-rotating early-type exoplanet parent stars are rare but important: formation and migration history
- Possibility to measure spin-orbit misalignment without an extremely stable spectrograph
- Stellar obliquity via GD
- Combination of photometric & spectroscopic transit observations needed to find the true misalignment
- Rotational deformation: planetary orbital precession
- TESS: three candidates for misaligned systems found + treasure trove of interesting objects

Thank you !