Modeling exoplanet transits of rapid rotators

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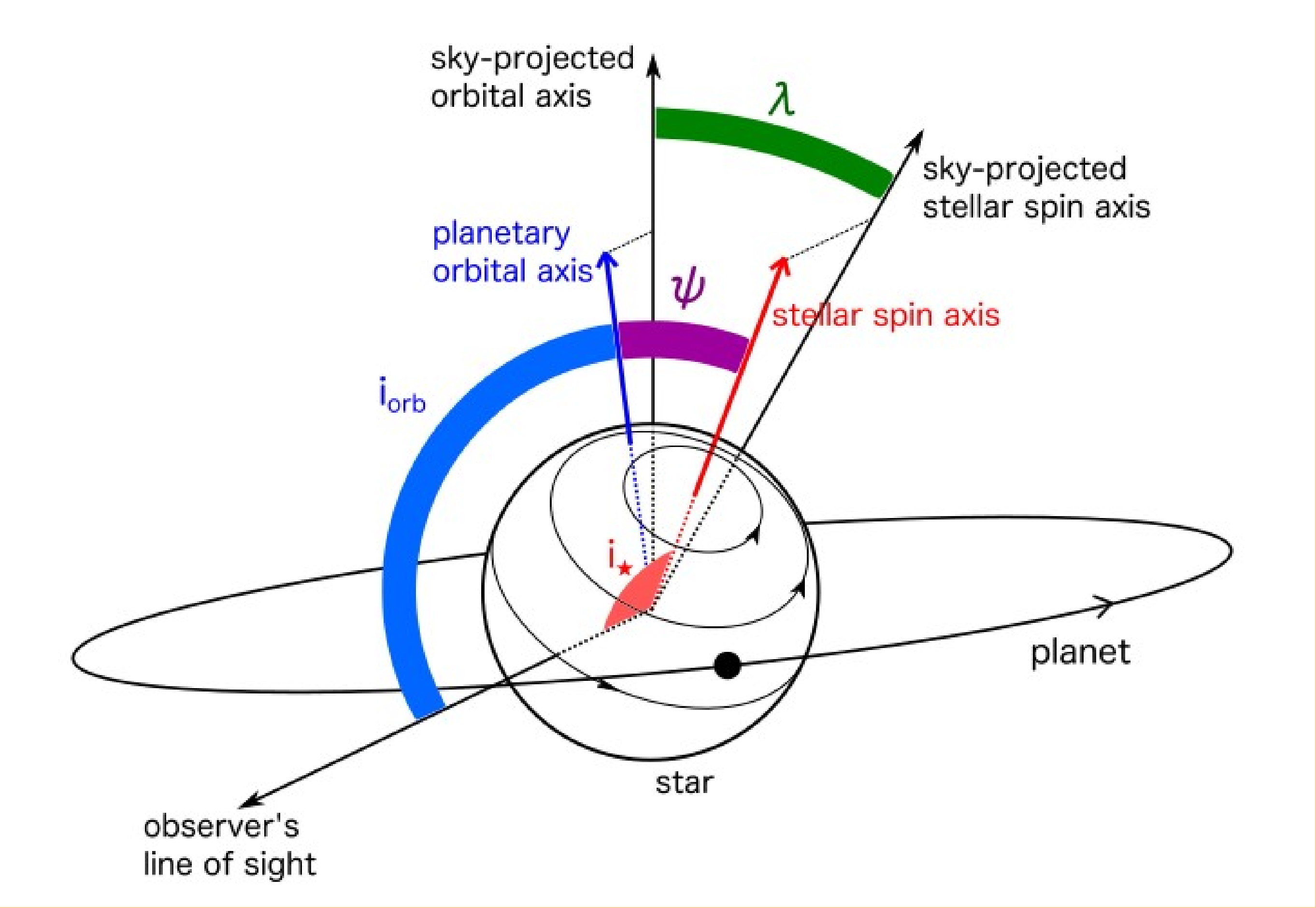
Rapidly rotating parent stars

- Spectral types A 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
- Tidal interaction => orbit and stellar precession => stellar quadruple moment J_2

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

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
- In spectroscopy projected (minimum) misalignment λ
- In photometry both λ and $i*$ thanks to gravity darkening or spots - only fast rotators with GD
- Possibility to measure differential rotation



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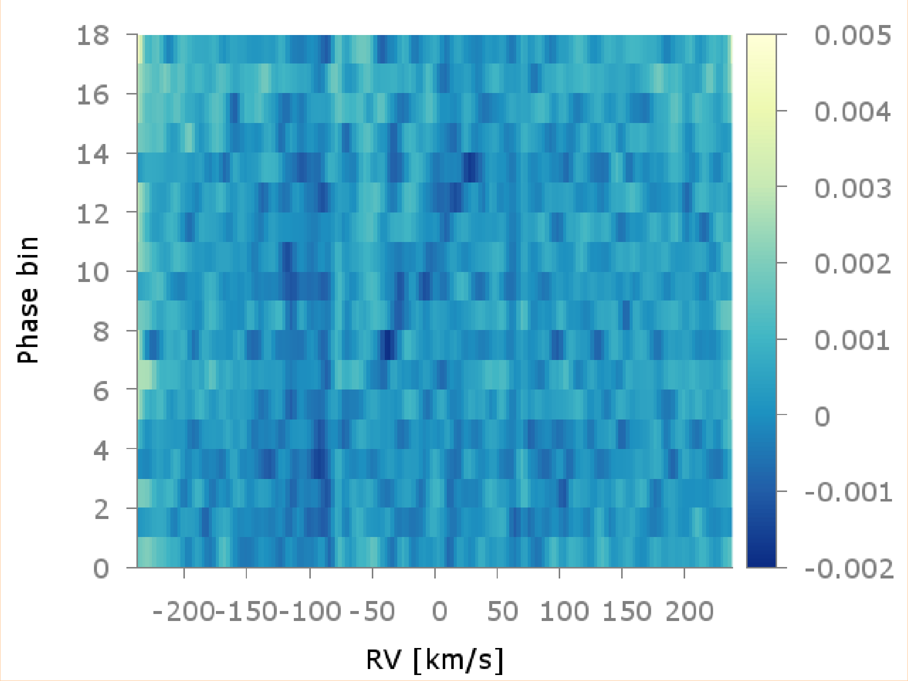
$$\cos\psi = \sin i_\star \cos i_{\rm orb} + \cos i_\star \sin i_{\rm orb} \cos\lambda$$

Kelt-7b



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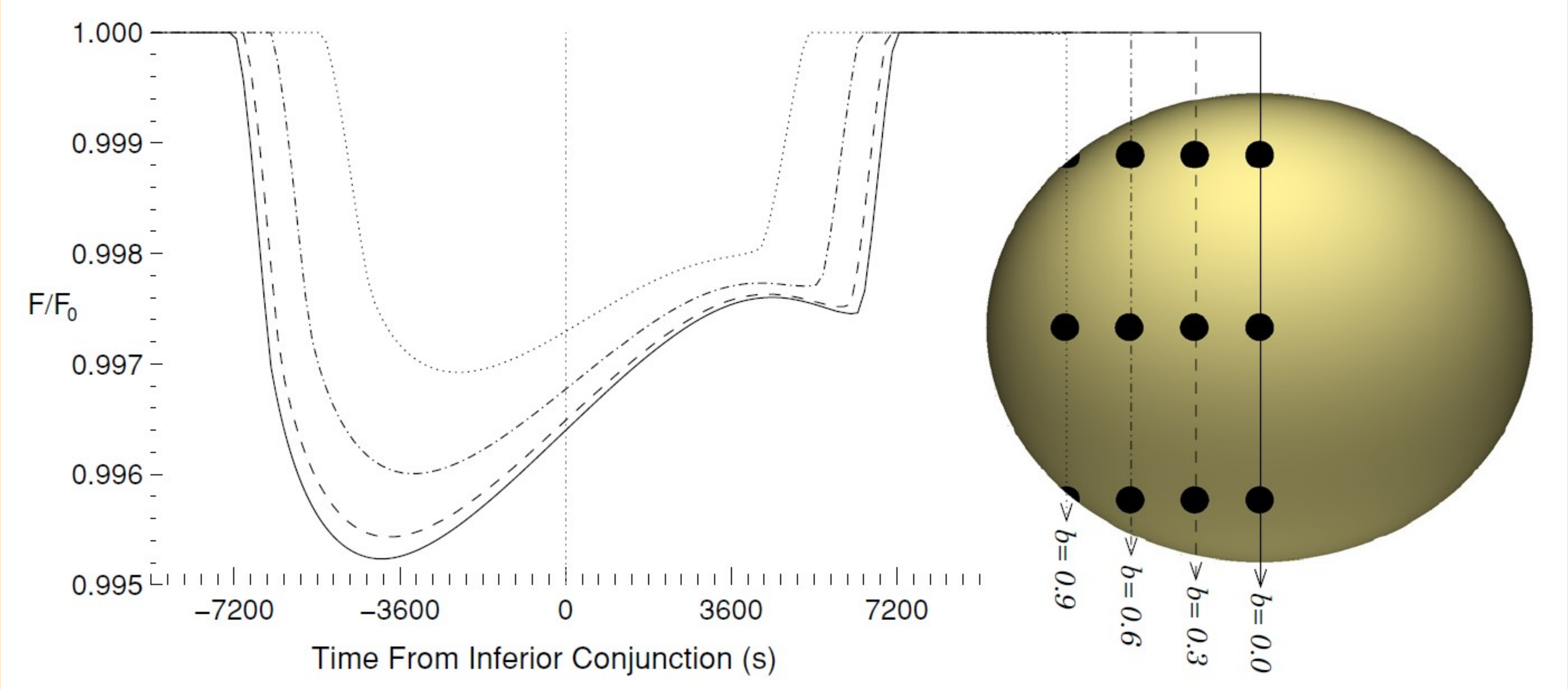
- V=8.54, F2V, v sin i* = 74 km/s, P = 2.735 days, T = 211 min
- 15-min exposures, SNR ~ 40, 1.3m@ Skalnaté Pleso
- Misalignment can be measured without extra stable spectrograph

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

A new code to model misaligned systems

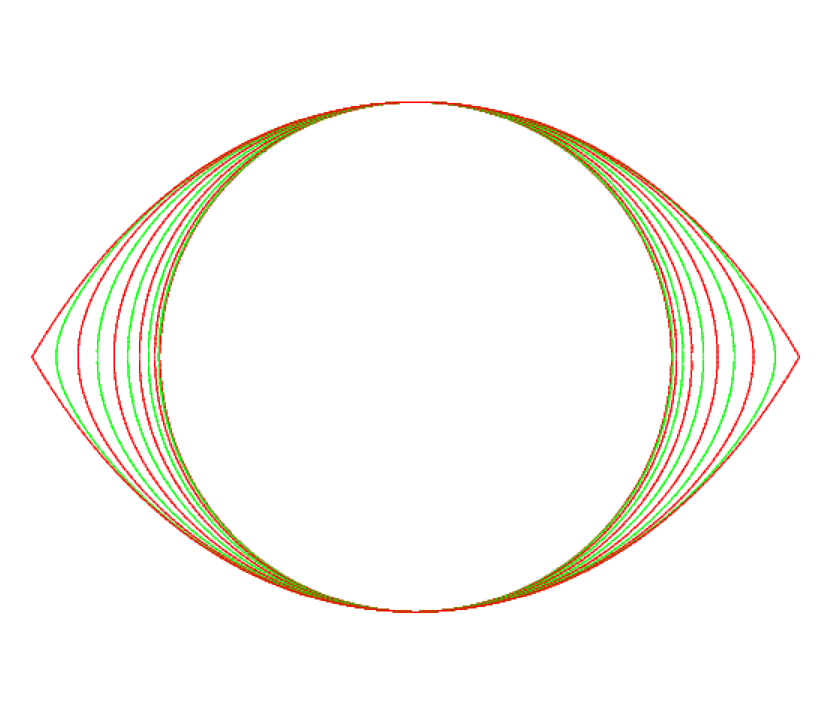
Modeling assumptions

- Roche surface geometry with the planet gravity neglected
- Solid-body rotation, $\Omega \neq \Omega(\theta)$
- Limb-darkening locally dependent on T^{eff} and g
- Doppler beaming, gravity darkening
- Eccentric orbits, third light
- Orbital precession

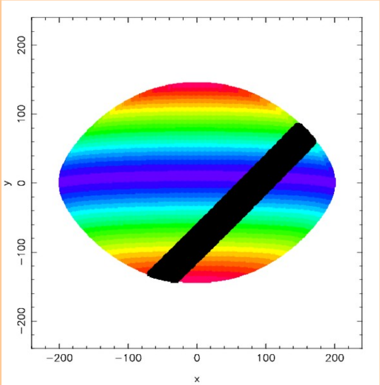
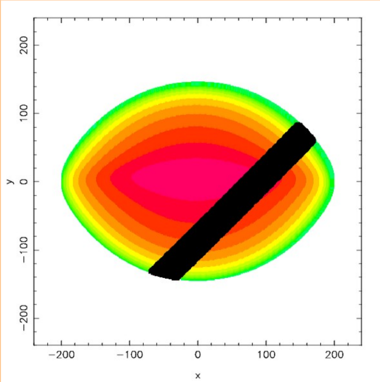
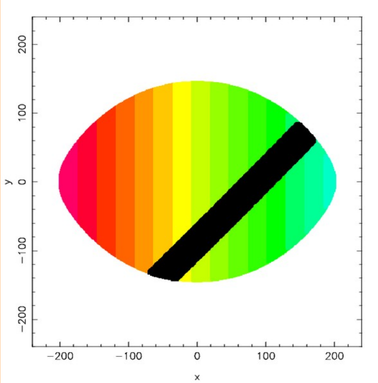
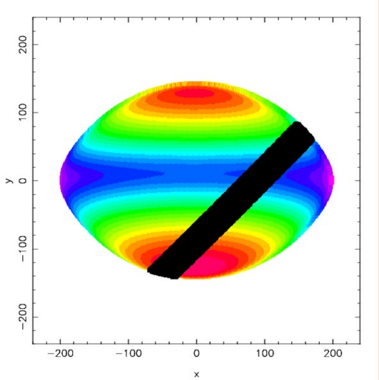
$$\Phi = -\frac{GM}{r} - \frac{1}{2}\Omega^2 r^2 \sin^2\theta$$

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

$$\frac{R_E}{R_P} = 1 + \frac{1}{2}f^2 = 1 + \frac{\Omega^2}{\Omega_{\mathrm{crit}}^2}$$



GD, DB, and LD effects

GD LD DB Σ

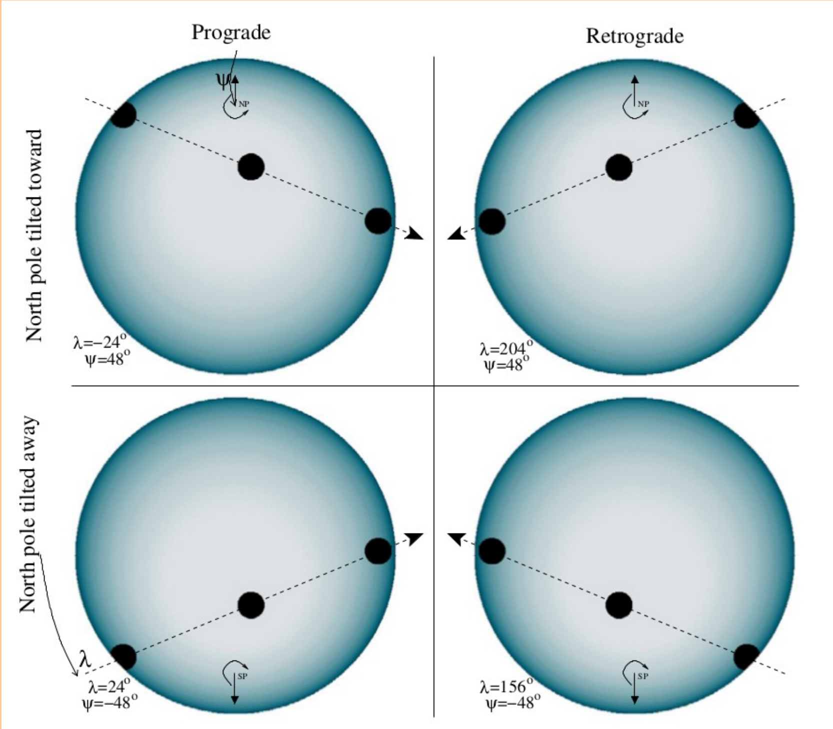
Rotational DB effect ~ few ppm, if detected, it would help to constrain λ

Gravity darkening: important only in rapid rotators

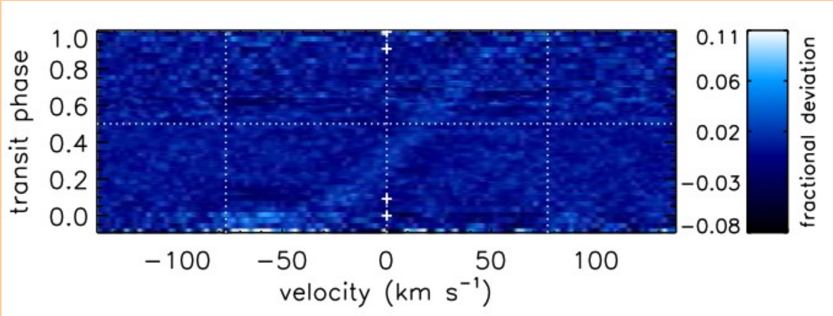
Precessing systems

KOI-13-A: precessing pin

- KOI-13 = ADS 12085AB, with ρ = 1.1″, V=9.70
- KOI-13A, A0V, v sin i* ~ 77 km/s
- Precession of the planetary orbit (Szabó et al., 2011)
- Barnes et al. (2011): 4 alternatives for λ and i*
- Orbital plane-spin misalignment λ=58.6±2.0° (Johnson et al., 2014)



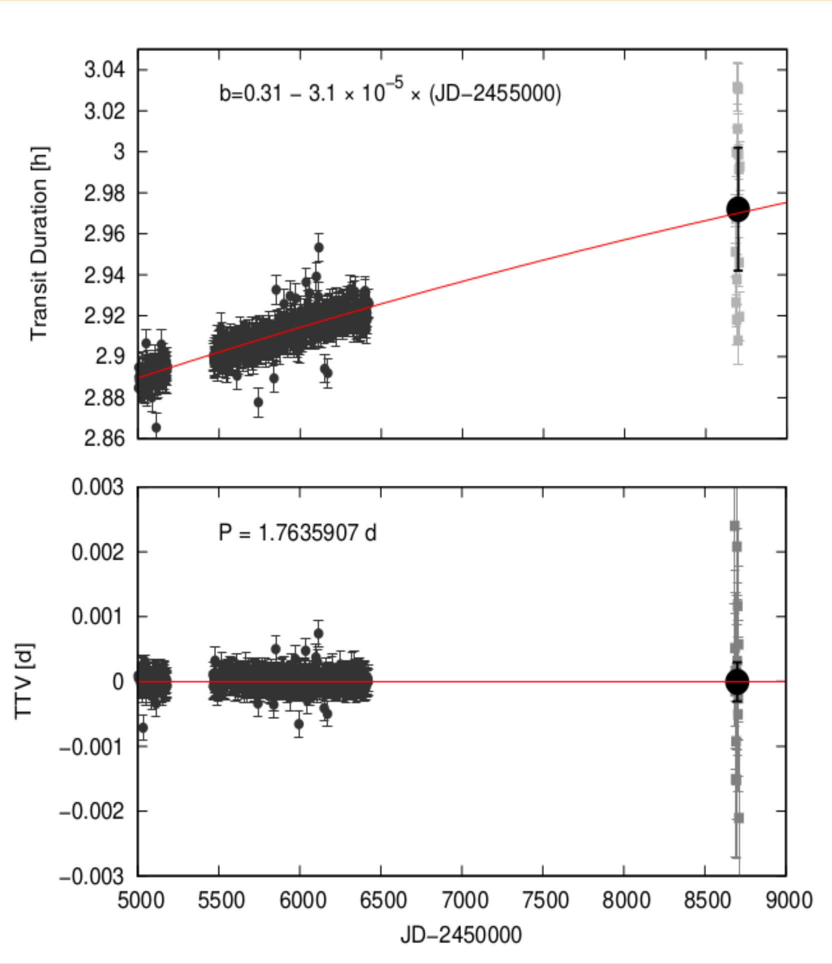
© Barnes et al., 2011, ApJS, 197, 10



© Johnson et al., 2014, ApJ, 790, 30

KOI-13-Ab: TTV+TDV

- New TESS LC in 2019
- Fitting individual transit light curves: TTV + TDV search
- No TTV found => no outer perturbers
- Linear TDV rate confirmed => orbital precession



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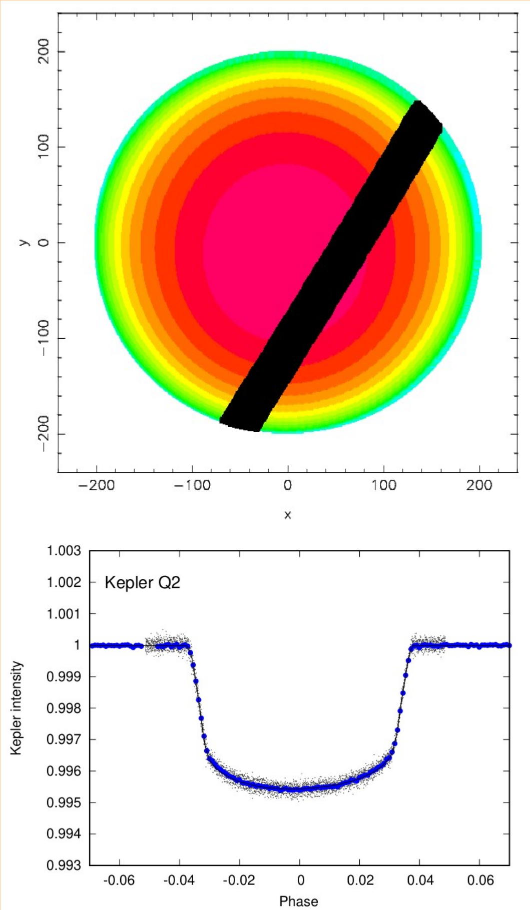
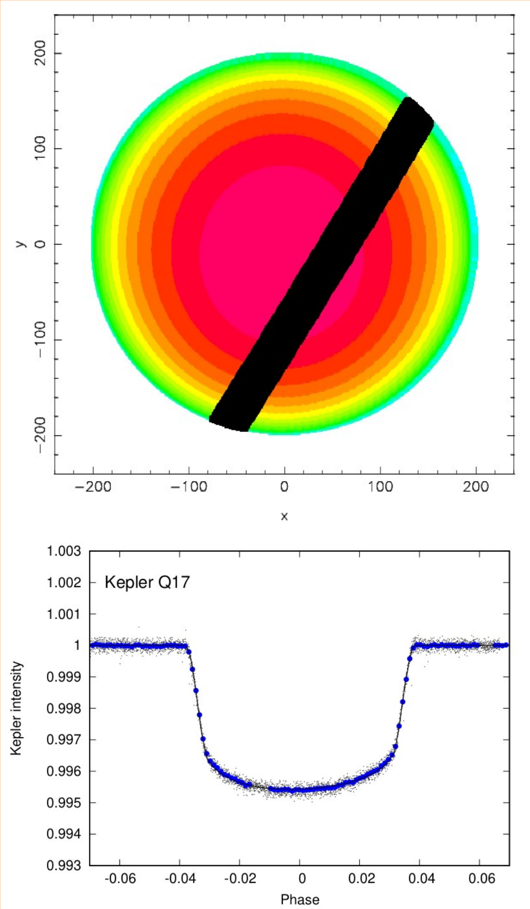
KOI-13-Ab: precession

Kepler KQ02



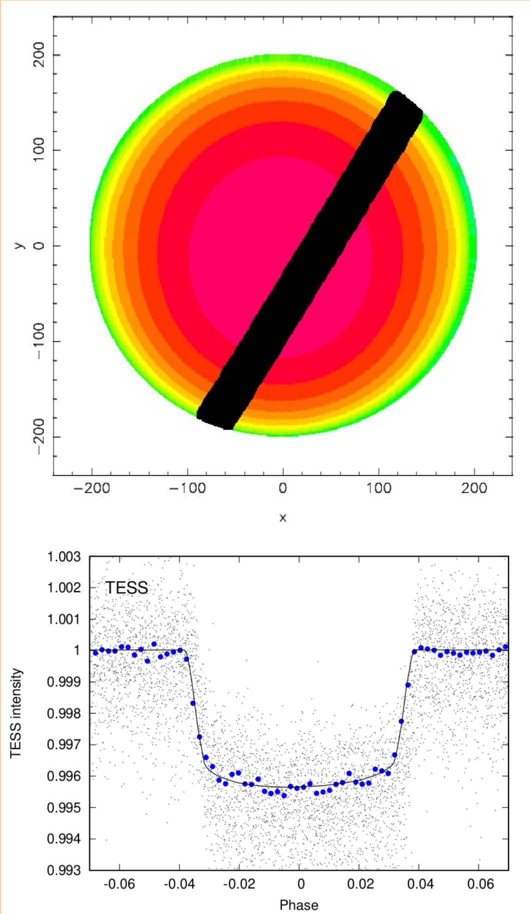
i = 86.29(4)°
b = 0.287(3)

Kepler KQ17



i = 86.82(4)°
b = 0.246(3)

TESS



i = 87.73(6)°
b = 0.176(5)

KOI-13-Ab: results

- Simultaneous fit to three LCs at different epochs and photometric bands: more reliable parameters
- Different chords and passbands break parameter degeneracies and LD and GD law dependence
- Conservation of the total AM ==> both orbital plane and spin axis precess: new Doppler tomography needed !

Parameter	unit	$T^{\rm eff} = 8600$K	$T^{\rm eff} = 8000$K
P	[day]	1.76358760(3)	1.76358762(3)
T_0	[HJD]	55 101.707254(12)	55 101.707249(13)
$R_\star/a$		0.22880(11)	0.22754(11)
$R_p/R_\star$		0.08632(3)	0.08606(3)
i_0	[deg]	85.738(18)	86.084(19)
$\mathrm{d}i/\mathrm{d}t$	[deg/day]	3.45(12) 10^{-4}	3.83(13) 10^{-4}
$i_\star$	[deg]	102.5(8)	100.5(8)
$\mathrm{d}b/\mathrm{d}t$	[day^{-1}]	−2.63(9) 10^{-5}	−2.93(10) 10^{-5}
χ^2		20924	20838
d.o.f.		13384	13384

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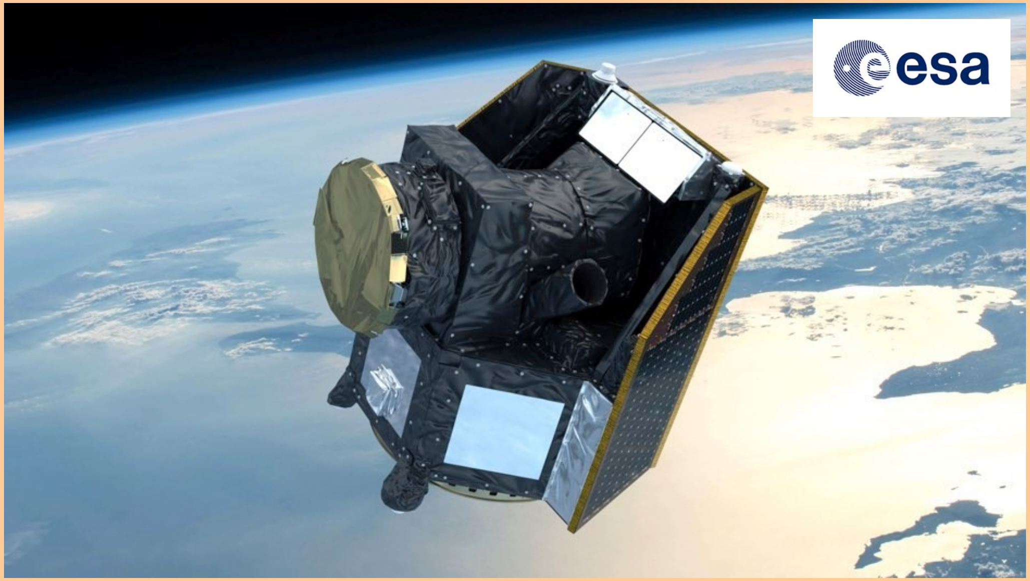
More precessing systems ?

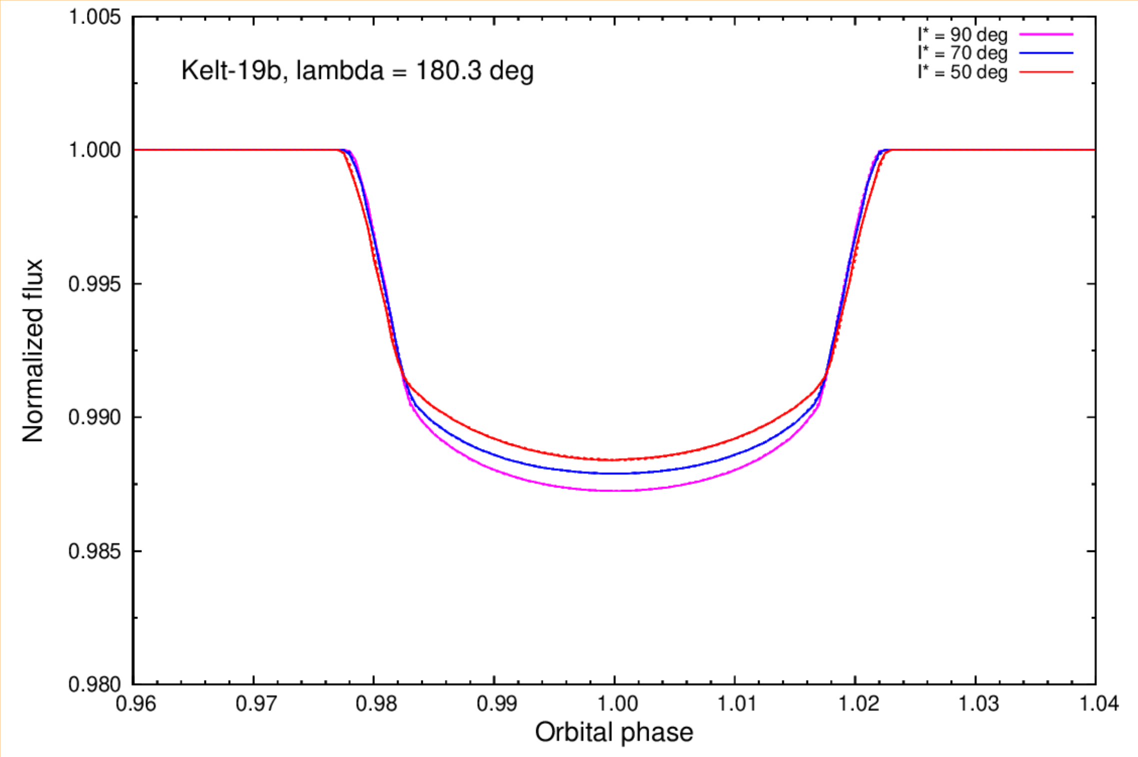
CHEOPS GO program

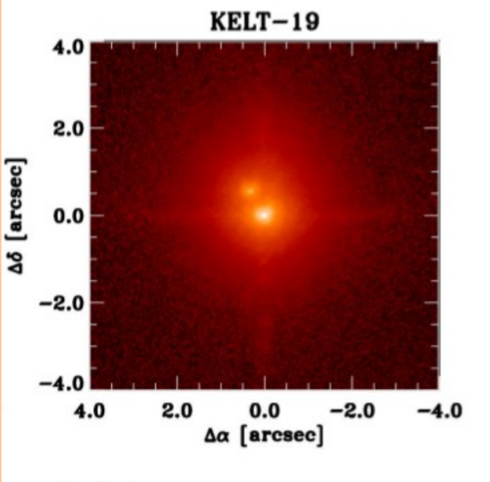
- Three early-type stars: Kelt-17b, Kelt-19Ab, Kelt-21b
- PI: Zoltán Garai
- Expected point-to-point scatter 200-300ppm
- 4 visits 2020/2021



30cm aperture, single-band CCD detector, SSO 100 min orbit, 280kg, launch Dec 17, 2019

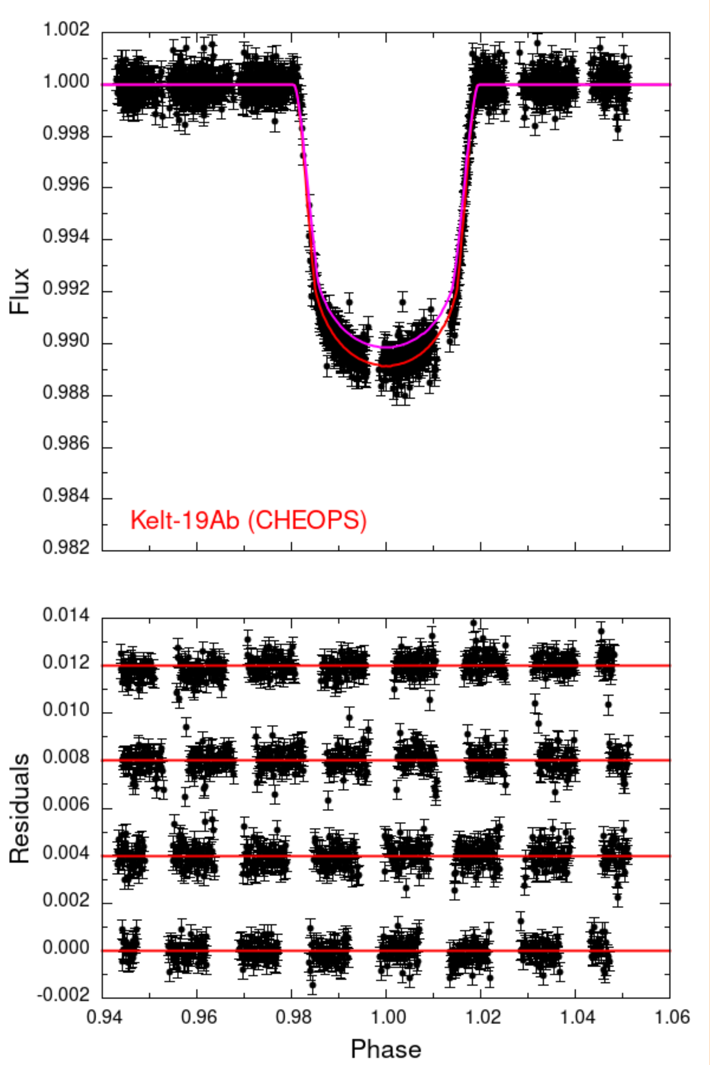
Kelt-19Ab



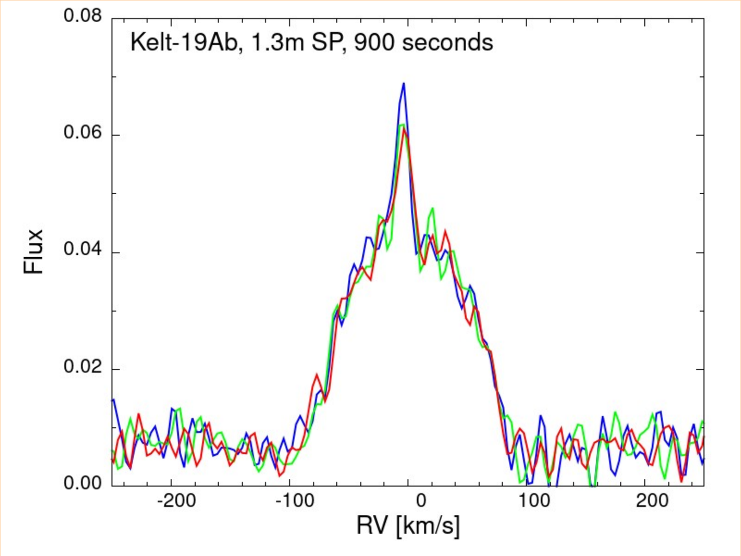


1.9 Mjup planet orbiting Am-type star, v sin i* = 84.8 km/s, λ = 180.3° (Siverd et al., 2018, AJ, 155, 35)

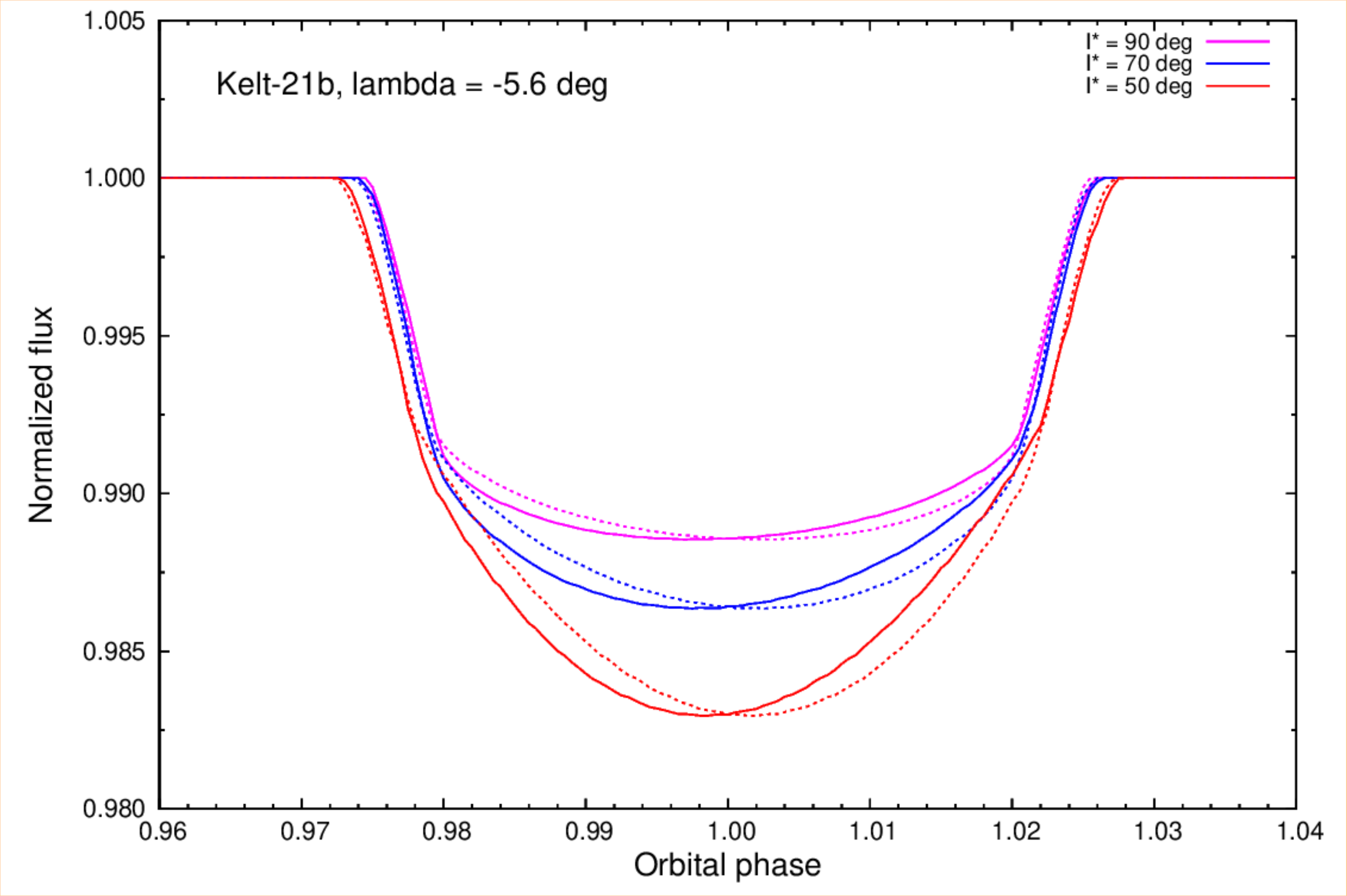
Kelt-19Ab with CHEOPS



- 4/4 visits done
- Real scatter 400ppm
- LC asymmetries below CHEOPS precision
- Transits now 10% deeper, real effect or light contamination

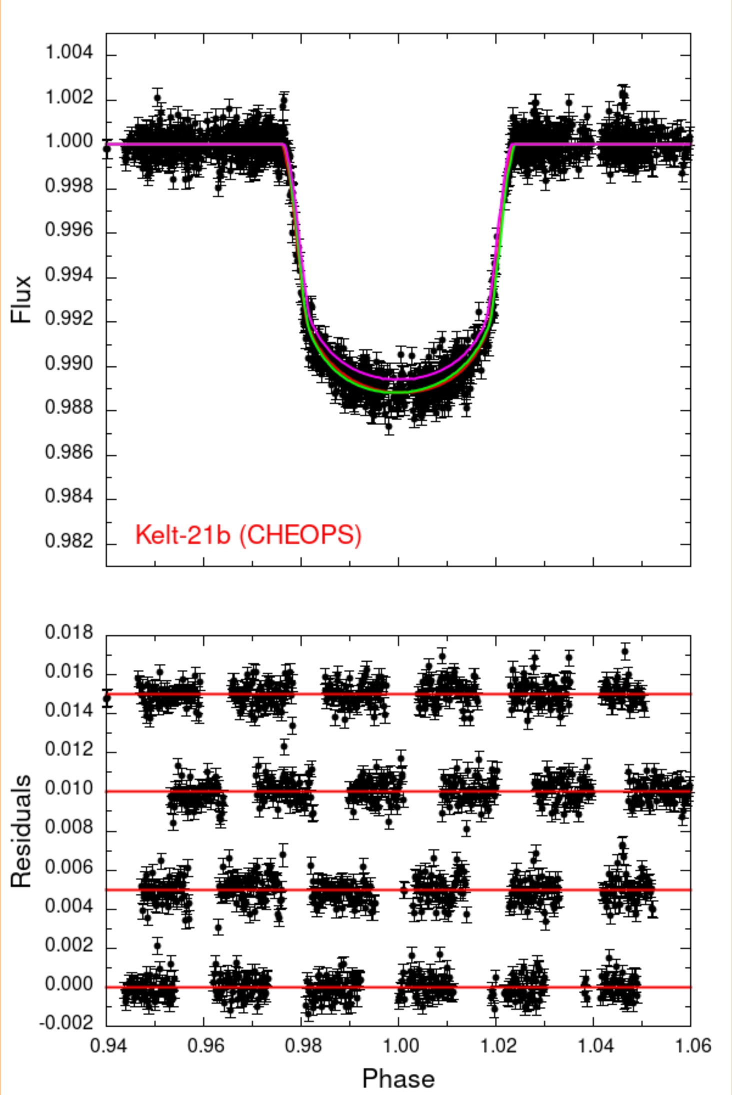


Kelt-21b

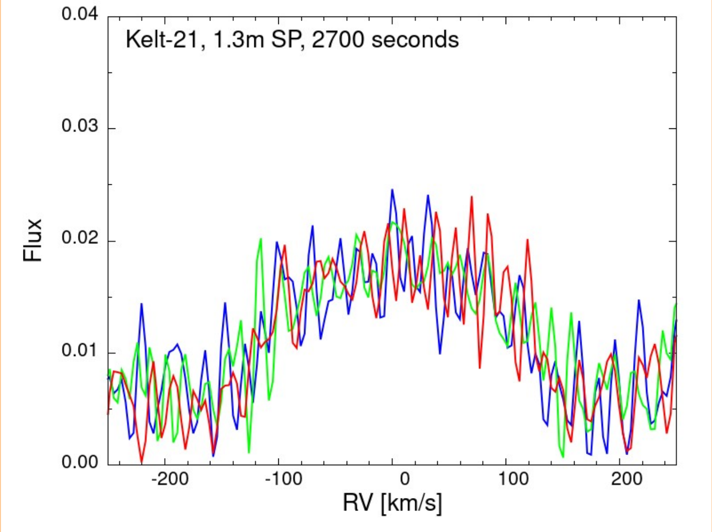


1.5 Mjup planet orbiting A-type star, v sin i*= 146 km/s, λ = -5.6°
(Johnson et al., 2018, AJ 155, 100)

Kelt-21b with CHEOPS



- 4/4 visits done
- Real scatter 600ppm
- LC asymmetries below CHEOPS precision
- Transits now 5% deeper, real effect or light contamination ?
- Stellar obliquity around i* = 70º
- Rotating at $\Omega \sim 0.38\ \Omega_{crit}$



Conclusions

- Rapidly-rotating early-type exoplanet parent stars are rare but important
- Possibility to measure spin-orbit misalignment without an extremely stable spectrograph
- Stellar spin axis misalignment via gravity darkening
- Combination of photometric & spectroscopic transit observations needed to find the true misalignment
- Rotational deformation: stellar spin - planet precession
- J2 gravitational quadruple moment - stellar structure
- More precise and multi-color data needed (ARIEL, 2029)

Thank you !