Multiple and multiply-eclipsing stellar systems

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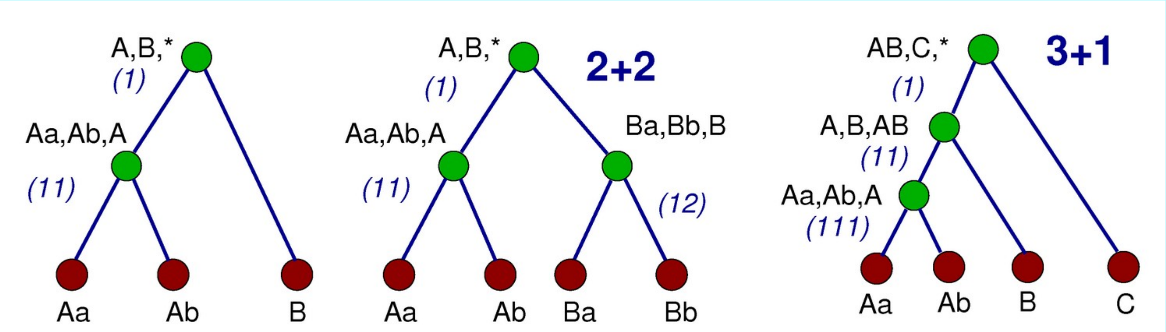
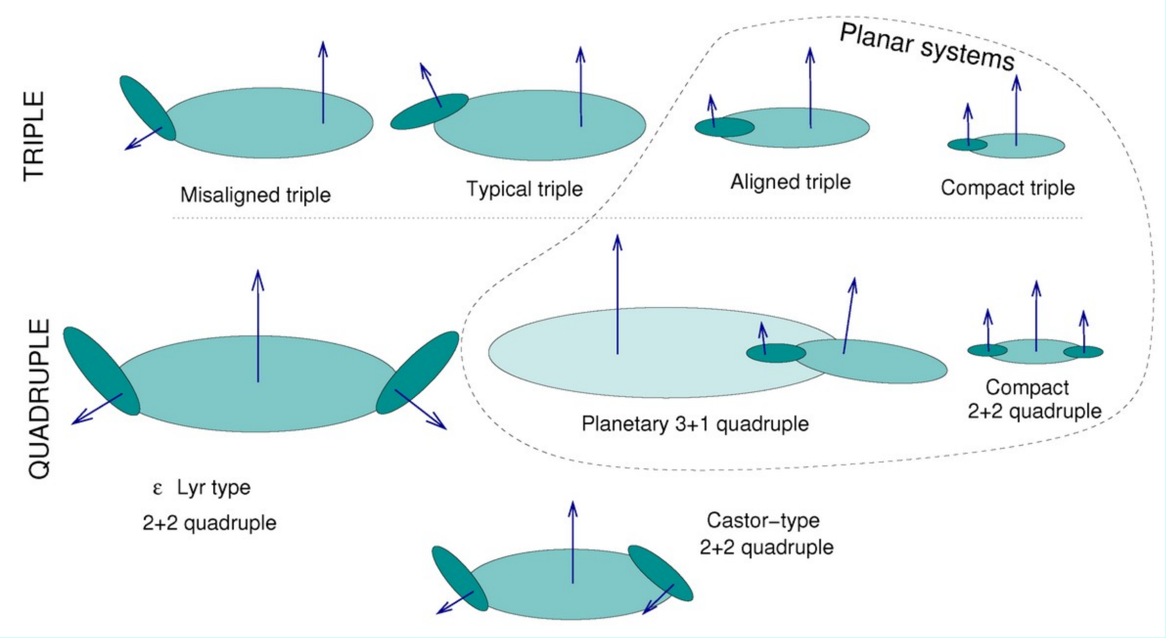
Multiple stellar systems

* Triple, quadruple, quintuple etc. groups of stars
* Hierarchy, hierarchical multiple stars
* Stability and perturbations of the orbits
* Open questions: formation, evolution, existence of sub-stellar bodies

Hierarchy & configuration





Tokovinin (2021, Universe)

Orbital perturbations

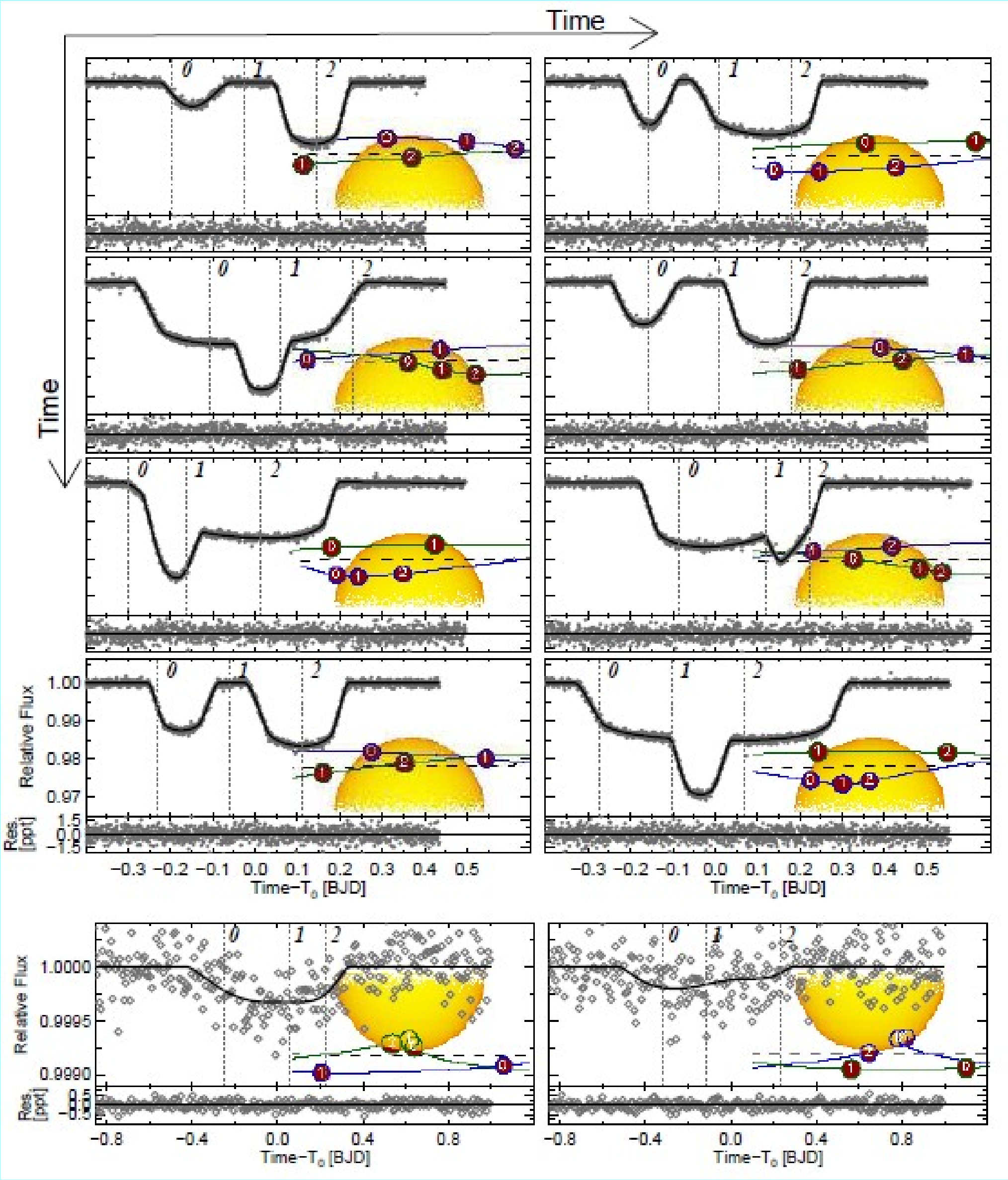
- In triples short-term, long-term, secular perturbations with characteristic periods: P_{12}, P_3, P_3^2/P_{12} and amplitudes $(P_{12}/P_3)^2$, P_{12}/P_3, 1
- The tighter the system the larger short and long-term perturbations
- Secular effects most-easy to detect (apsidal motion, nodal-line precession)

Multiply-eclipsing multiples

- First such system known: V994 Her (Lee et al., 2008, MNRAS)
- Complicated eclipse shapes + dynamical perturbations
- Photometry enables to determine absolute parameters
- TYC 7037-89-1: a Sextuply Eclipsing Sextuple Star (Powell et al., 2021, AJ)

KOI-126

- ✶ Multiply-eclipsing
- ✶ G dwarf + 2 M dwarfs with $M = 0.2 M_\odot$
- ✶ $P_3 = 33.9$ d, $P_{12} = 1.8$ d
- ✶ Inner orbit precession with $P \sim 1000$ d ==> changes in the eclipse geometry
- ✶ Masses determined with 1%, radii with 0.5% precision

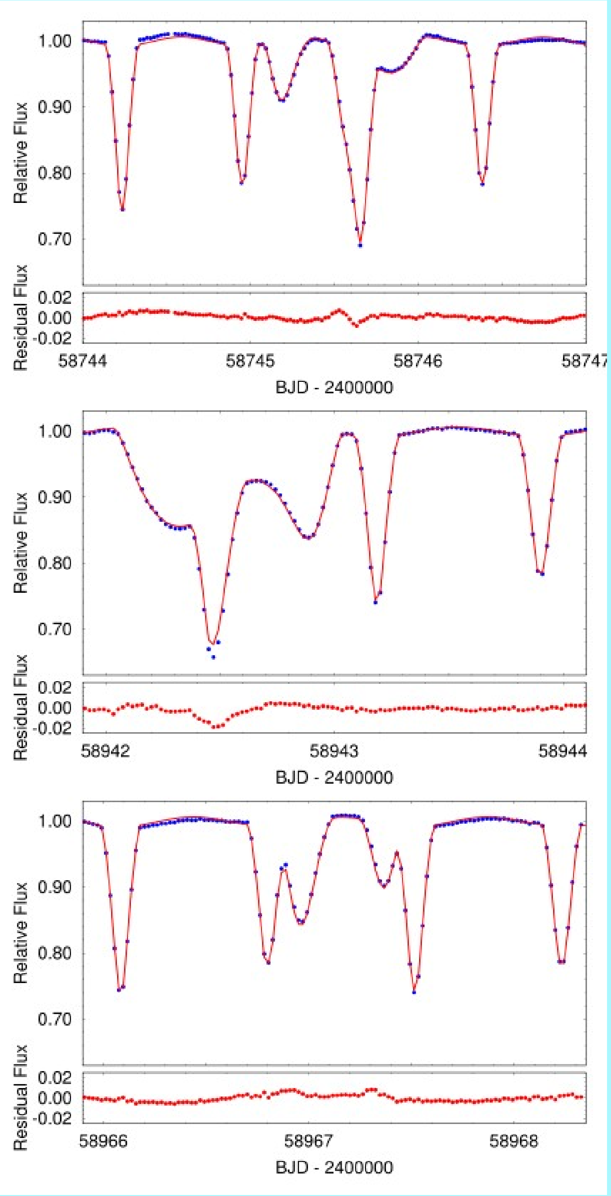


Carter et al. (2011, Science)

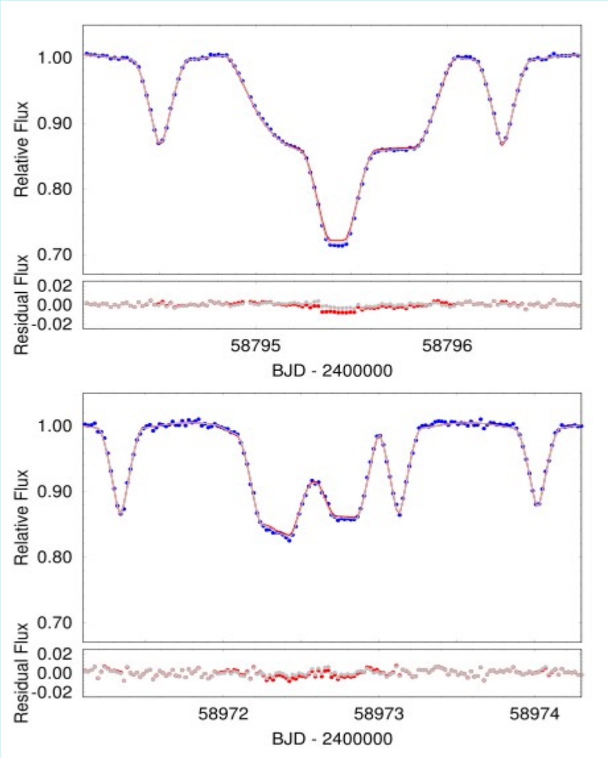
Three new triply eclipsing triples

New and discovery data

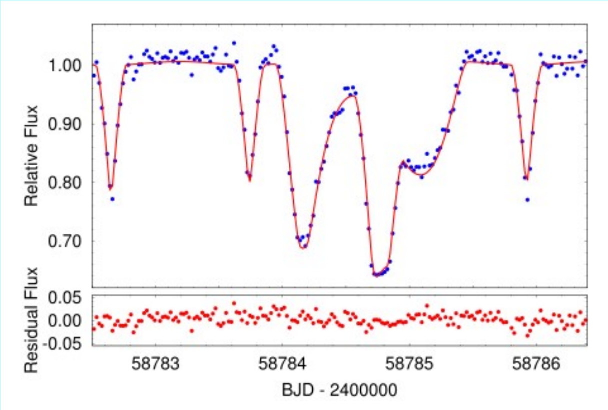
- TIC193993801, P_{12} = 1.4313 d, P_3 = 49.28 d
- TIC388459317, P_{12} = 2.1847 d, P_3 = 89.86 d
- TIC052041148, P_{12} = 1.7862 d, P_3 = 177.0 d
- Combination of the TESS and ASAS-SN enabled to find the outer orbital periods, P_3
- Spectroscopy from Astelco 1.3m and MUSICOS for TIC 193993801 (V = 11.27 ==> problematic)
- Photometry from ASA800 (0.8m, f/8, griz system) at Szombathely (HU), and other telescopes



TIC193993801

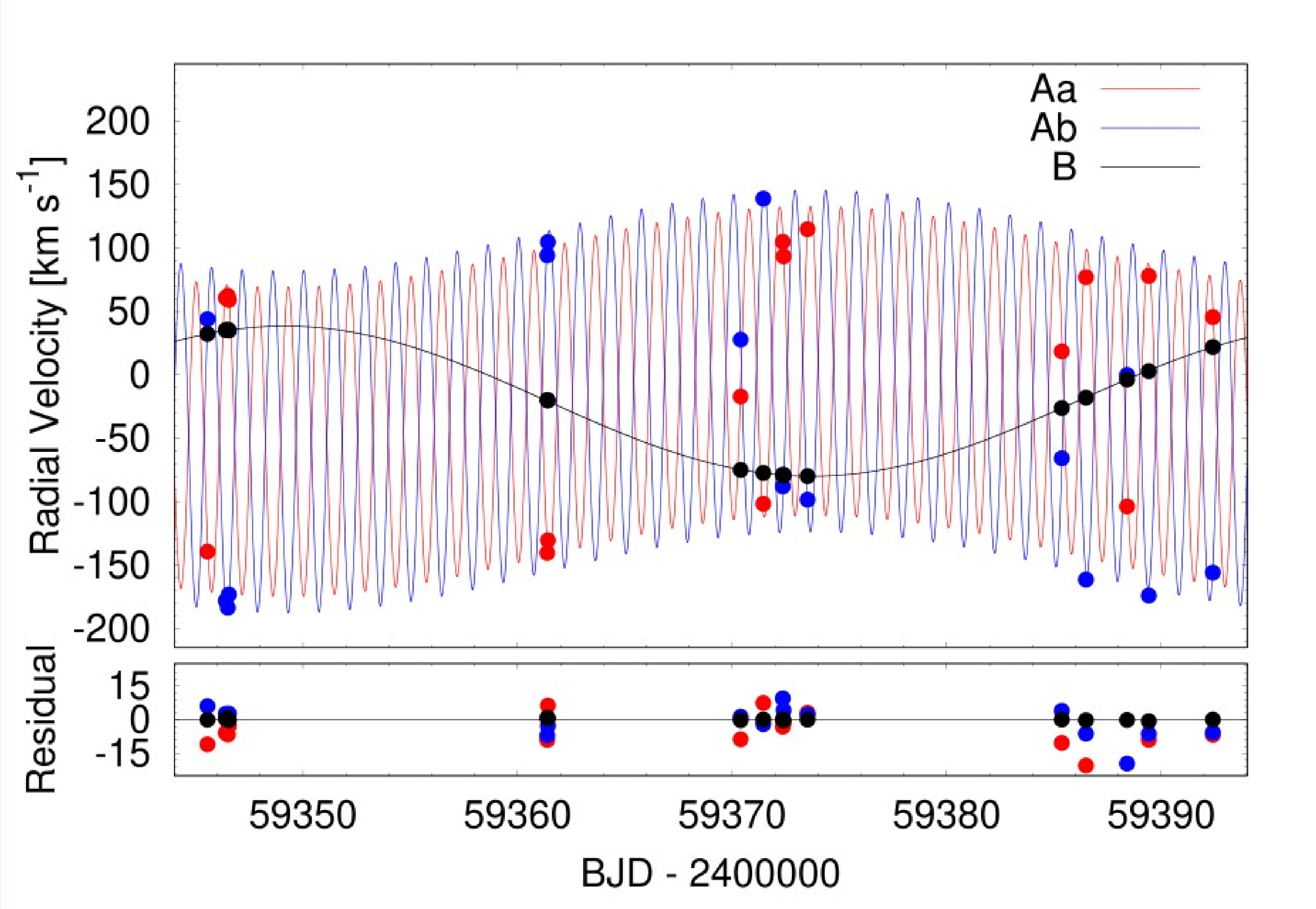


TIC052041148



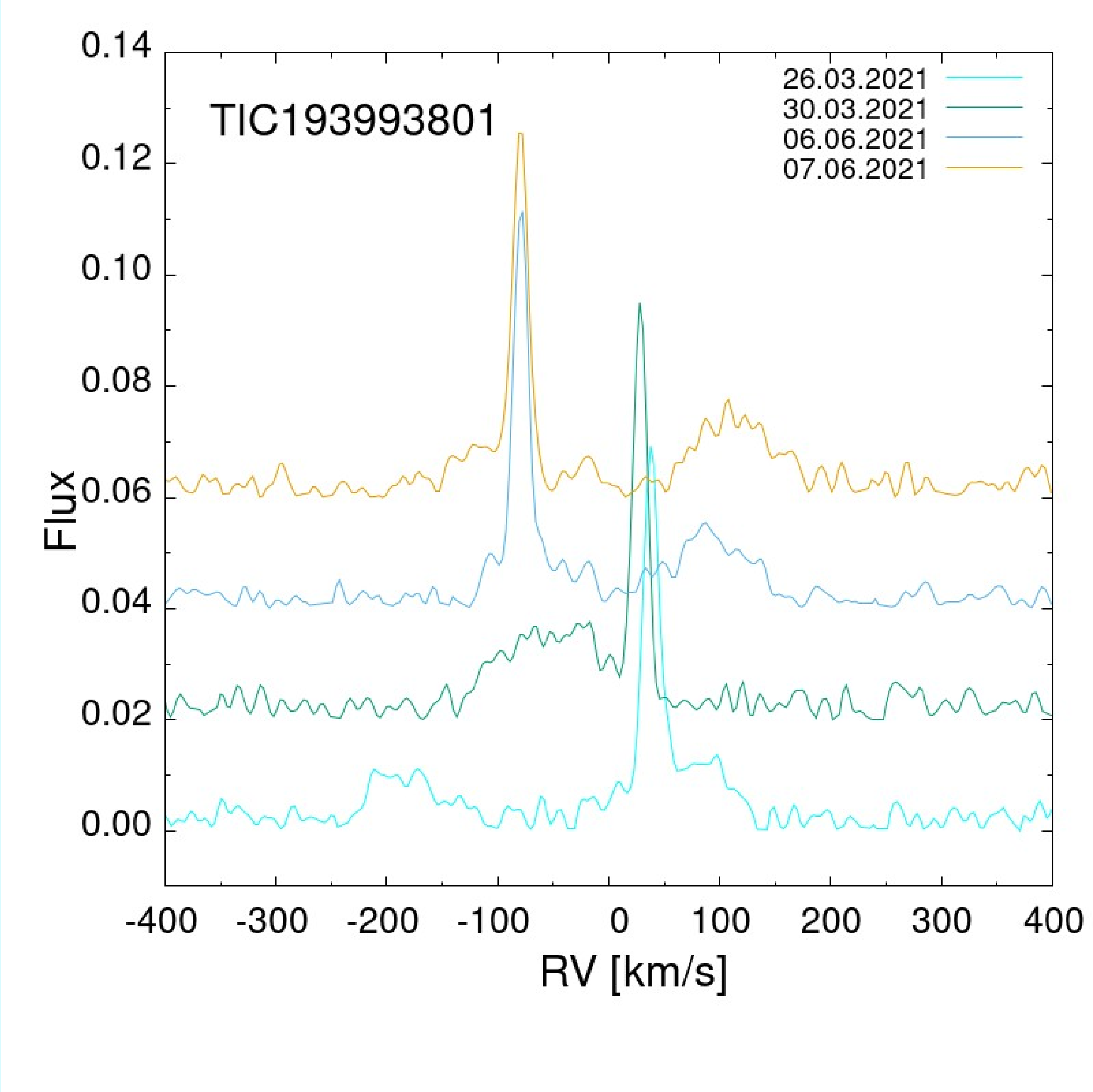
TIC388459317

Outer-orbit eclipses observed by TESS
and their best photodynamic fits



RV curve of TIC193993801 obtained from the spectroscopic observations with MUSICOS at SP 1.3m

BFs



MUSICOS spectra with SNR 15-18, F8V template, 4900-6100 Å range used, eclipsing pair noisy

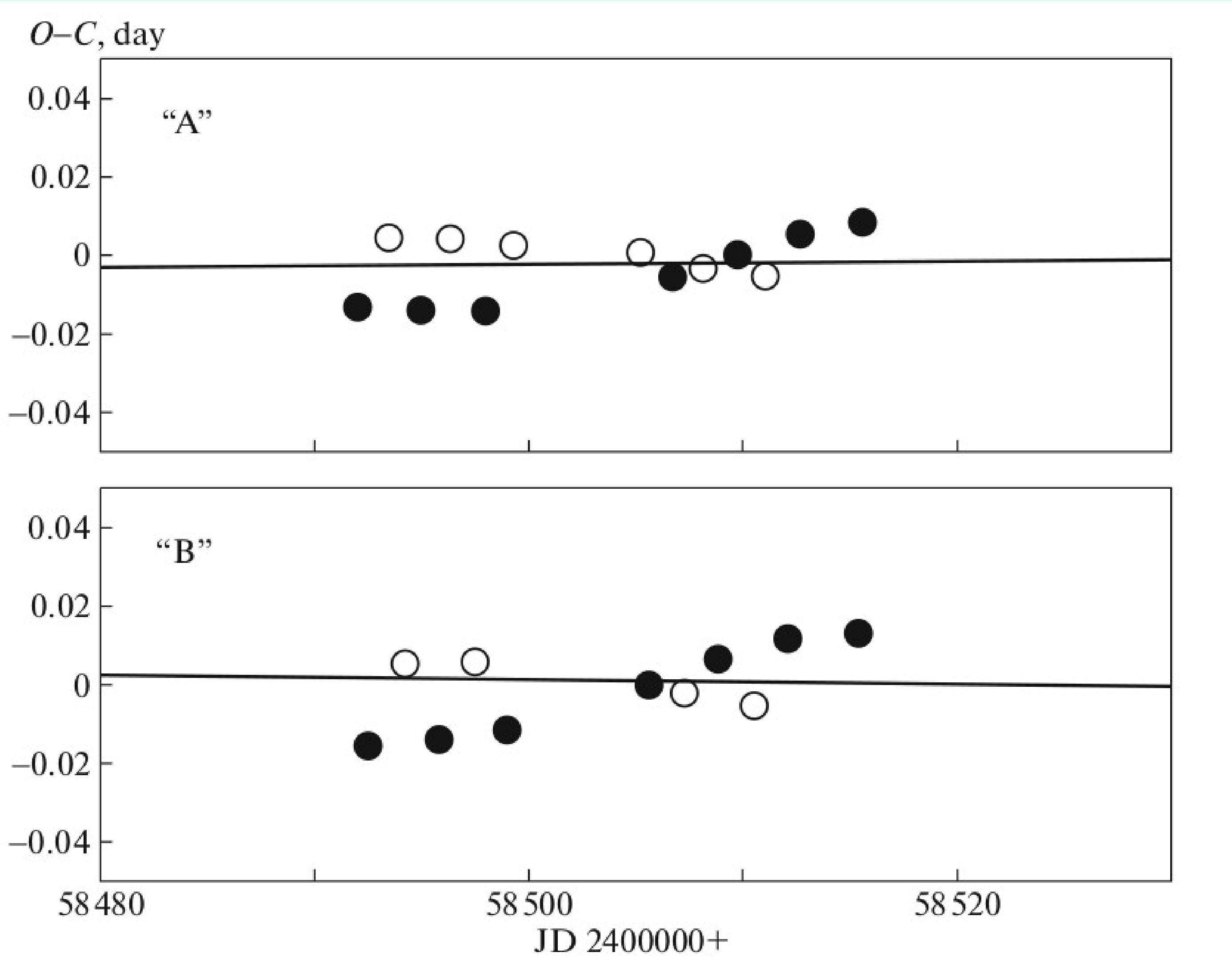
Analysis & results

- Multi-body numerical integrator, multi-band LC, ETV and RV, SED synthesis
- MCMC analysis to determine posterior distribution of parameters
- Main result: 3-10% absolute parameter accuracy without RV data, 1-3% with RVs (TIC193993801)
- All systems are co-planar within 1-3°
- Vast range of outer-orbit eccentricities 0.003, 0.1, 0.62 ==> different formation ?
- Published in Borkovits et al. (2022, MNRAS)

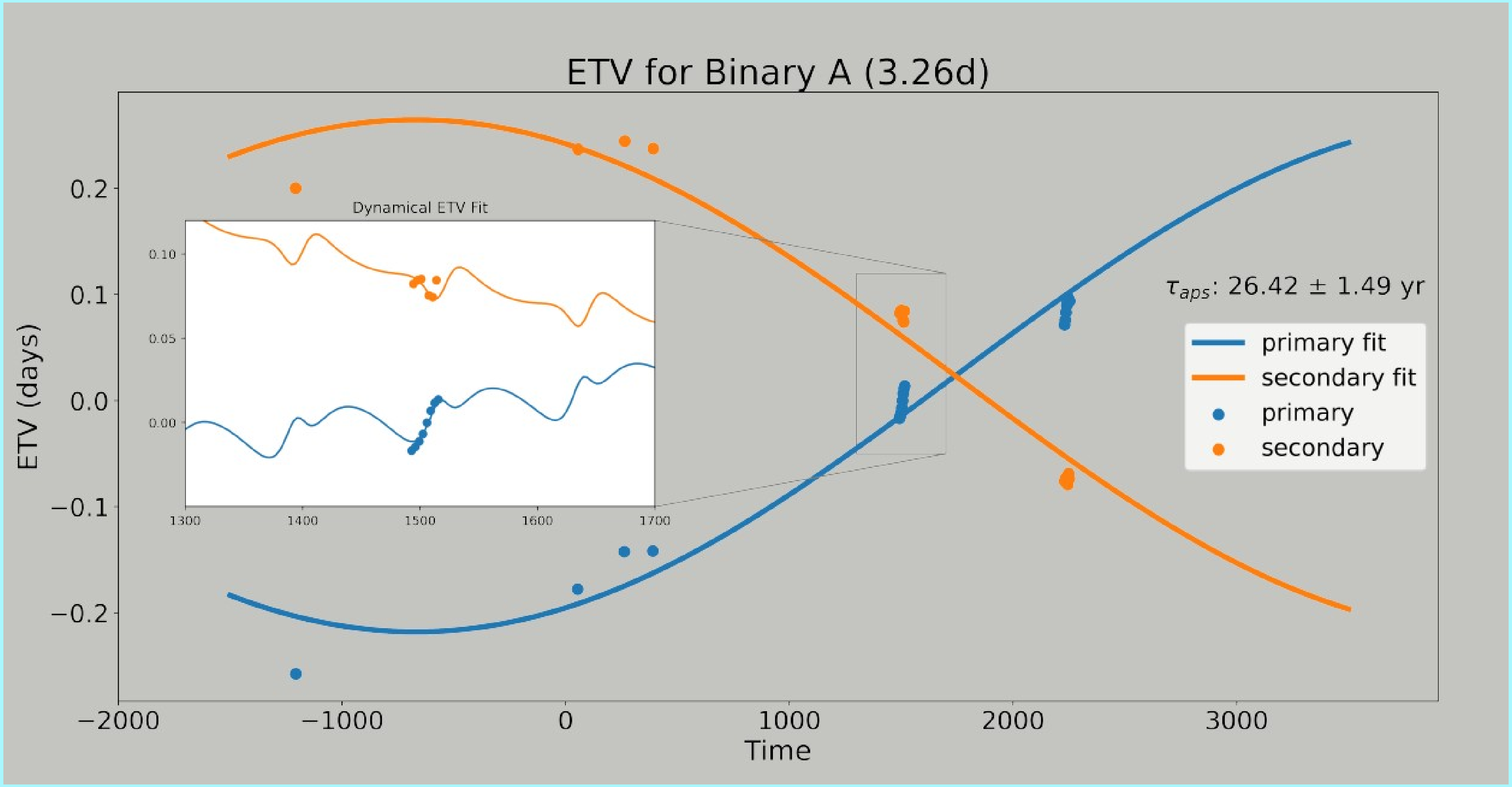
BU CMi

BU CMi: a multiply eclipsing quadruple

- ✶ Bright object with V_{max} = 6.42
- ✶ According to the GCVS it is an EA with P = 2.93 d and a displaced secondary minimum
- ✶ Volkov, Kravtsova & Chochol (2021, Astronomy Reports) discovered it is a doubly eclipsing quadruple system, with 2+2 hierarchy, P_{12} = 2.93 days, P_{34} = 3.26 days,
- ✶ The outer period estimated as P_{1234} = 6.6 years
- ✶ MUSICOS@SP 1.3m, MASCARA, TESS, 60cm of INASAN
- ✶ Gaia EDR3, π = 4.014(33) mas, astrometric over-noise as large as 73 σ



High-amplitude and fast timing variability of the A and B sub-systems interpreted by Volkov et al. (2021, Astronomy Reports) by nutation



Apsidal motion timescale of ∼ 25 yr (Jayraman et al., 2021, proc.)

Suspected „nutation“ ==> perturbations with P_{1234} timescale

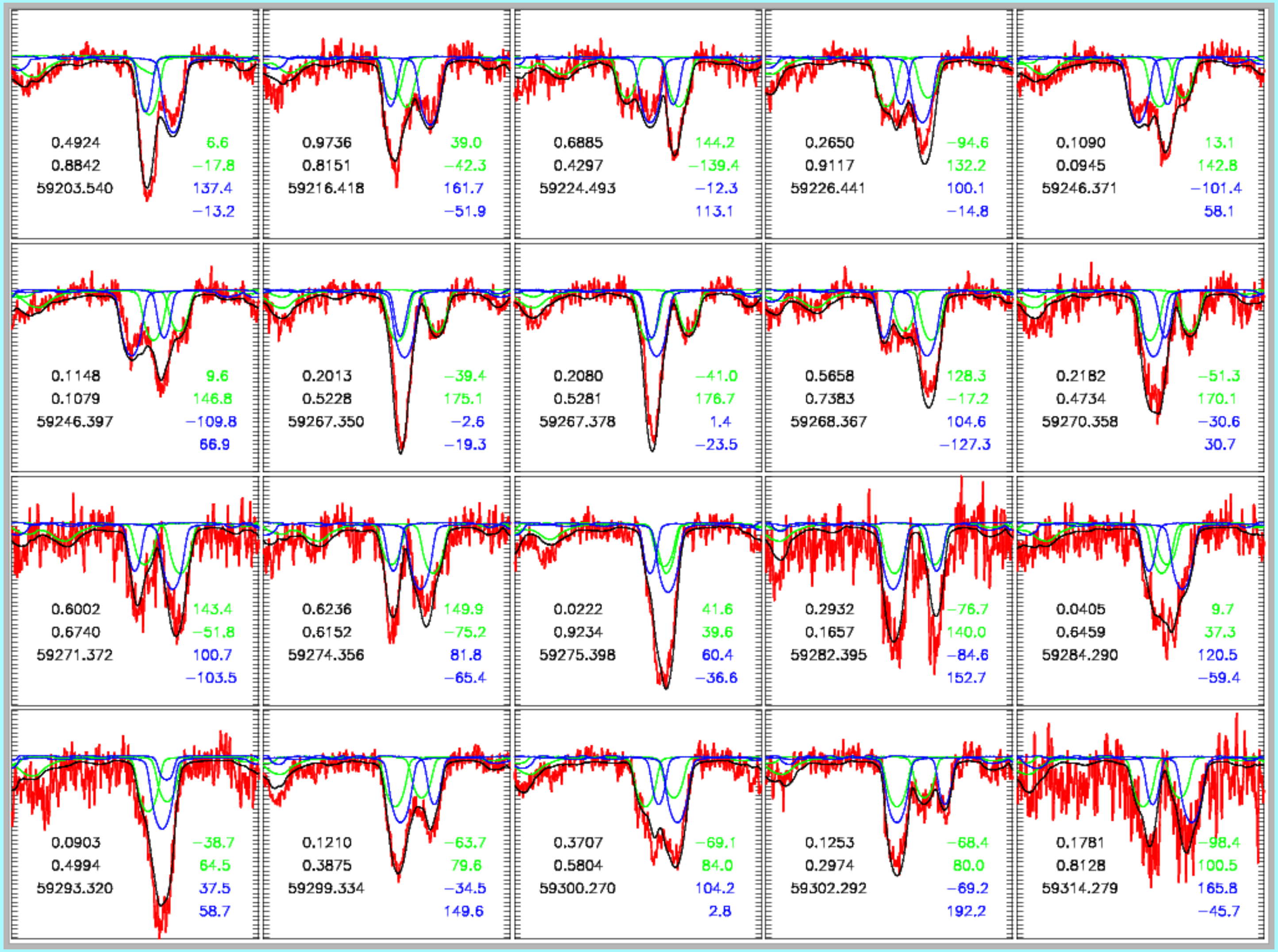
BU CMi: P_{1234} =100-150 days !

ETV: dynamical effects ~ LTTE !

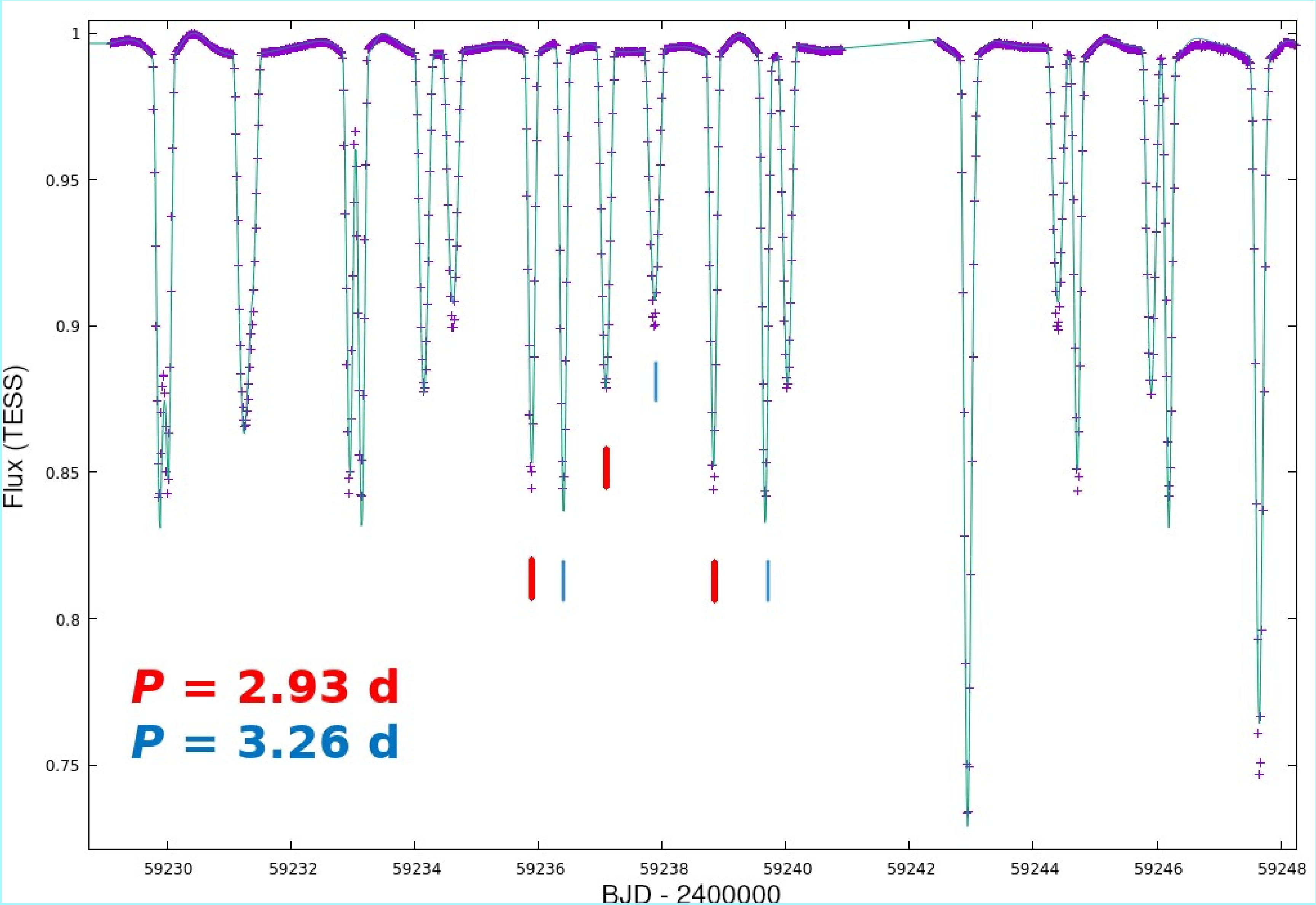
BU CMi (modeling)

- Quadruple spectrophotometric model, synthetic spectra + TESS light curves
- Fast component rotation: no RVs – line profiles strongly blended ==> direct modeling of the line profiles
- Up to 42 parameters to fit the spectra and the photometry (33 actually)
- Analytic proximity effects, LD, apsidal motion, Doppler beaming
- Optimum spectral templates searched (T_{eff}, log g)

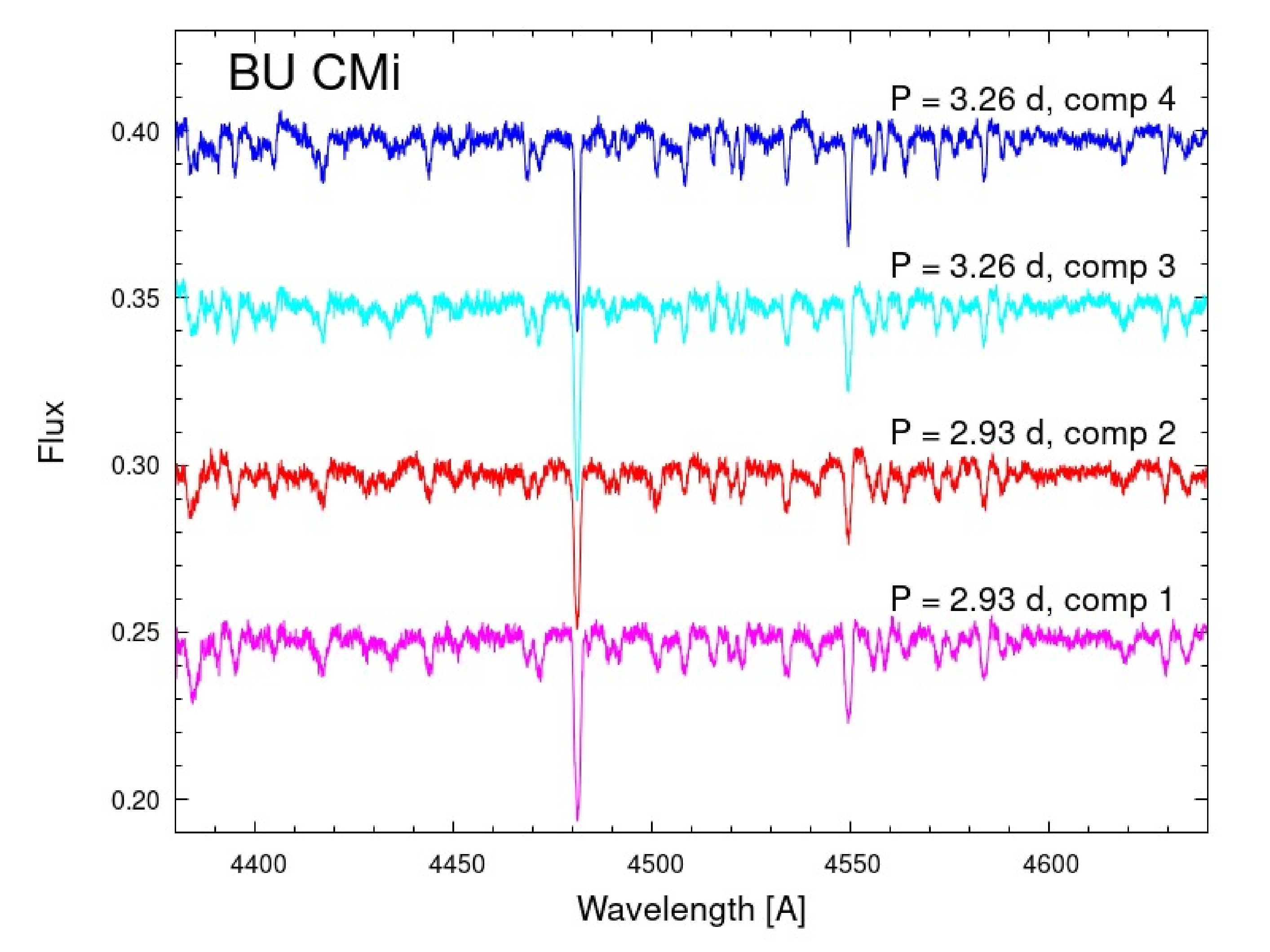
4470-4490Å



Multi-component global fit to 41 spectra from MUSICOS, spectrum around Mg II 4481 (20 profiles shown)



Corresponding fit the TESS photometry sector #34



iSpec

T_4 = 10040(350) K
log g_4 = 4.18(23)

T_3 = 10820(380) K
log g_3 = 4.63(26)

T_2 = 10180(430) K
log g_2 = 4.11(30)

T_1 = 10760(360) K
log g_1 = 4.23(29)

Tomographic disentangling of spectra assuming model RVs, iterative technique of Bagnuolo & Gies (1991, ApJ) used, correct disentangling depends on flux ratios

BU CMi (results: orbits)

- P_{1234} ~120 days: the tightest quadruple system known
- Previous record holder: VW LMi (Pribulla et al., 2008, 2020, MNRAS), $P_{12} = 0.47$ d, $P_{34} = 7.93$ d, $P_{1234} = 355$ d
- Dynamically driven apsidal motion: $U_{12} = 25.9$ yr, $U_{34} = 29.0$ yr
- The outer orbit inclination angle ($\sum M$ wrt. $M_{12} \sin^3 i_{1234}$ and $M_{34} \sin^3 i_{1234}$) is about 90° (=flat)
- Outer eclipses not detected yet

BU CMi (results: tidal evolution)

- Inner orbits are eccentric $e_{12} = 0.214$, $e_{34} = 0.243$, not circularized yet
- Pseudo-synchronous rate:

$$\frac{\Omega}{\omega} = \frac{2 + 27e^2}{2 + 15e^2}$$

- For BU CMi $\Omega_{12}/\omega_{12}=1.204$ and $\Omega_{34}/\omega_{34}=1.246$
- Observed rates are 1.31 to 1.55 times pseudo-synchronous rate
- Rotation not synchronized ==> very young ?

Conclusions

- Multiple systems show a plethora of dynamical effects on various time scales
- Satellite data: a treasure trove of new systems
- Strong perturbations and mutual eclipses: determination of parameters without spectroscopy
- Further development: perturbations, relativistic effects, multi-dataset approach (Gaia DR3 approaching)

Thank you !