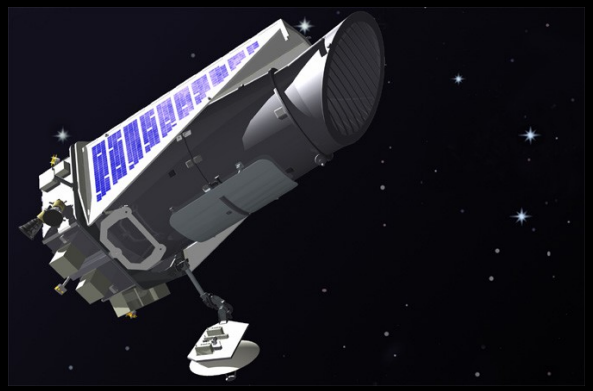
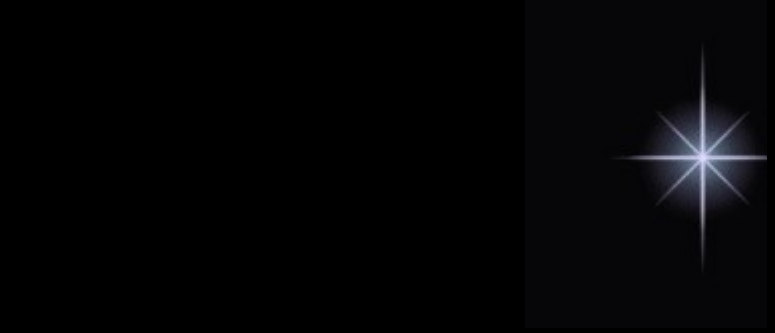
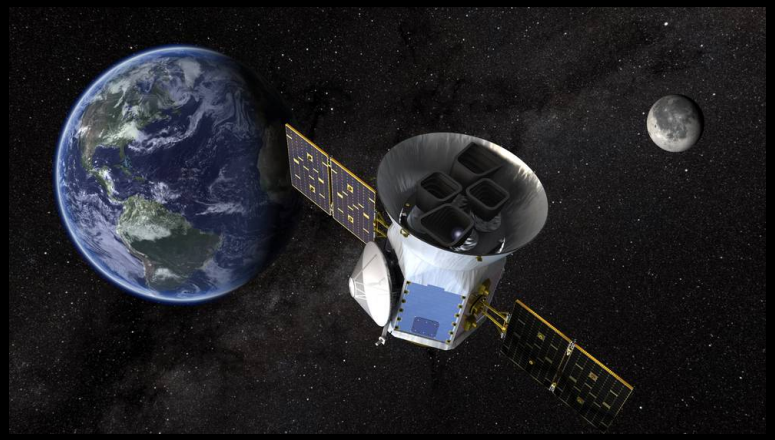


Tamás Borkovits
Baja Astronomical Observatory of Szeged University

(Not so) hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.





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(Not so) hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

T. Borkovits

(Not so) hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

Importance of hierachical triples (and multiples)

In the beginning...:

- Formation of close binaries (not only KCTF)
- Circumbinary planets
- Hot Jupiters?

...in the middle...:

- Sources of permanent perturbations (not only gravitational)
  - ***perfect sources of information***

... at the end:

- Exotic terminal states of stellar evolution (e.g. binary pulsars
- And, even for not so exotic ones
  - *E.g., what drives two white dwarfs to merge?*

Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

Third body perturbations in a hierachical triple system

Stellar three-body problem (Harrington, 1968, 1969)

Perturbations on three different time-scales

Classifications of periodic perturbations	Period	Relative amplitude
Short period perturbations	$\sim P_1$	$\sim (P_1/P_2)^2$
Long period perturbations	$\sim P_2$	$\sim P_1/P_2$
„Apse-node" terms	$\sim P_2^2/P_1$	1

Note: This is the classification introduced by Brown, 1936 for his Lunar-theory. Classification and nomenclature based on the planetary theory departs!

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Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

Third body perturbations in a hierachical triple system

Vast majority of the triple system studies concentrate on the apse-node, or secular effects. Their importance and significance is out-of question.

BUT what is the significance the shorter time-scale perturbations?

– theoretical: despite their low amplitude, they can substantially alter the secular dynamical evolutionary tracks of individual systems (Luo et al., 2016)

– practical (observational): it is, what we can observe and measure directly

(thanks primarily to *Kepler* in the past, and to *TESS* in these days)

Discovery of more CHT-s

Dynamical determination of masses & 3D configrations

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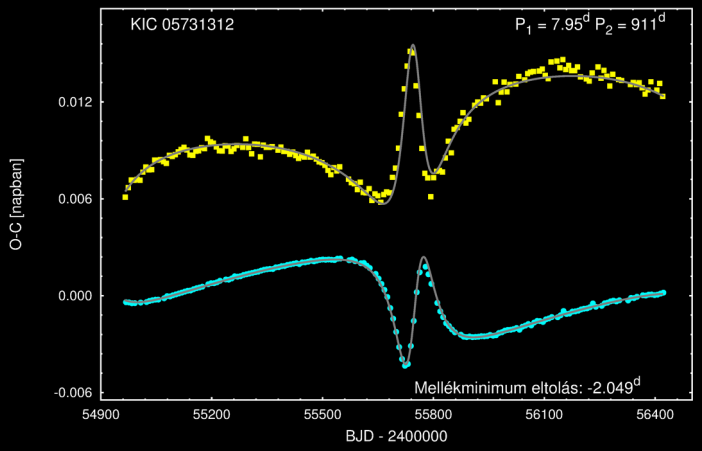
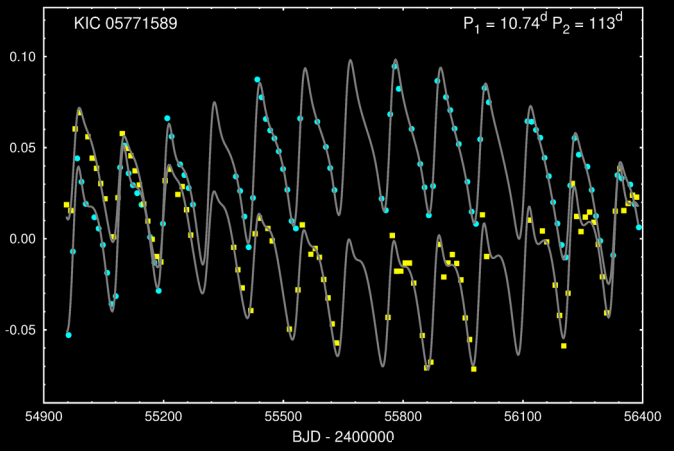
Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

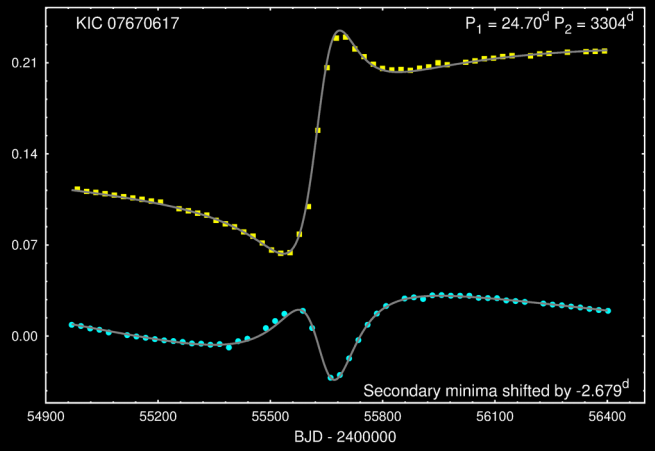
Eclipsing binaries in hierarchical triples – The *Kepler* revolution

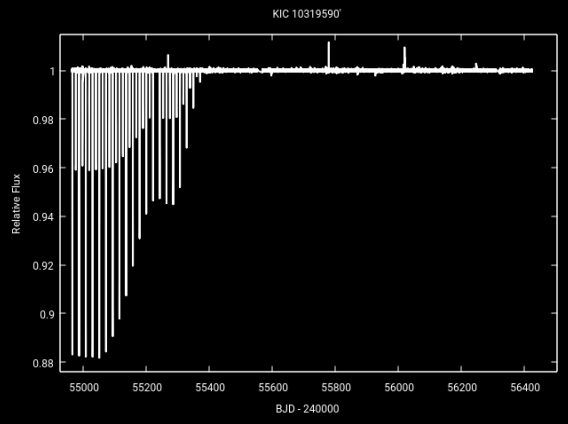
Two substantial giveaways –> an extended Royal Road

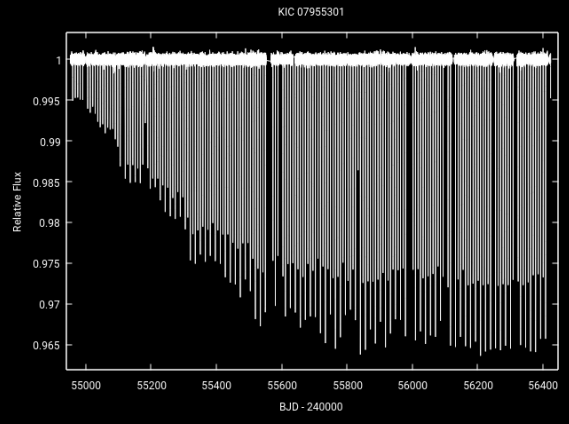
1. Well-observable, very short time-scale perturbations











T. Borkovits

Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

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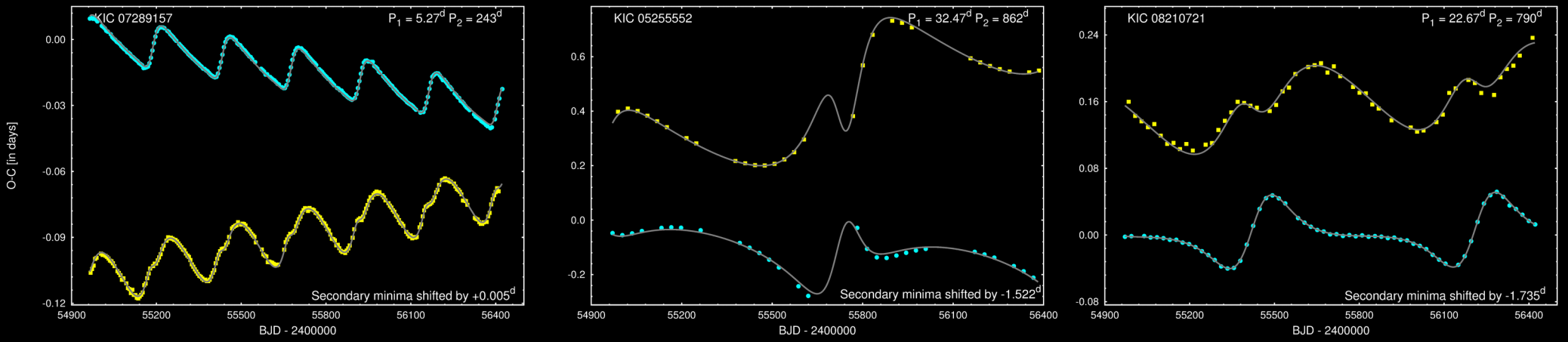


For further details see: **Borkovits et al. 2015, MNRAS, 448, 946** (analytic description)
Borkovits et al. 2016, MNRAS, 455, 4131 (application for *Kepler* triples)

Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

The Royal Road(s): 1) Eclipse Timing Variation Analysis

In conclusion: information in dynamical ETV

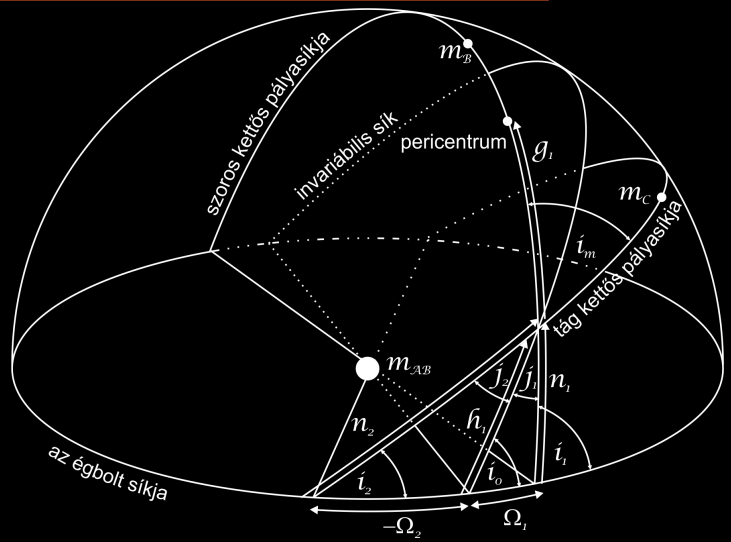
- LTTE + dynamical perturbations:

  – light-travel time: P_2, $a_{AB}\sin i_2$ [in km], e_2, ω_2, $f(m_C)$

  – third-body perturbations:

  – (P_2 time-scale): P_2, m_C/M, e_2, $(\Omega_1 - \Omega_2)$, i_{mut}, i_0 , g_2
  e_1, ω_1, g_1, h, j_1, j_2

  – (P_2^2/P_1 time-scale): e_1, ω_1, e_2, i_{mut}, g_1, g_2, h, m_C/M
  (apsidal motion, orbital plane precession)



The yellow quantities were *almost*, while the purple ones were *completely* unknown for compact triples before *Kepler*-era, although they are very important for dynamical evolution studies

T. Borkovits

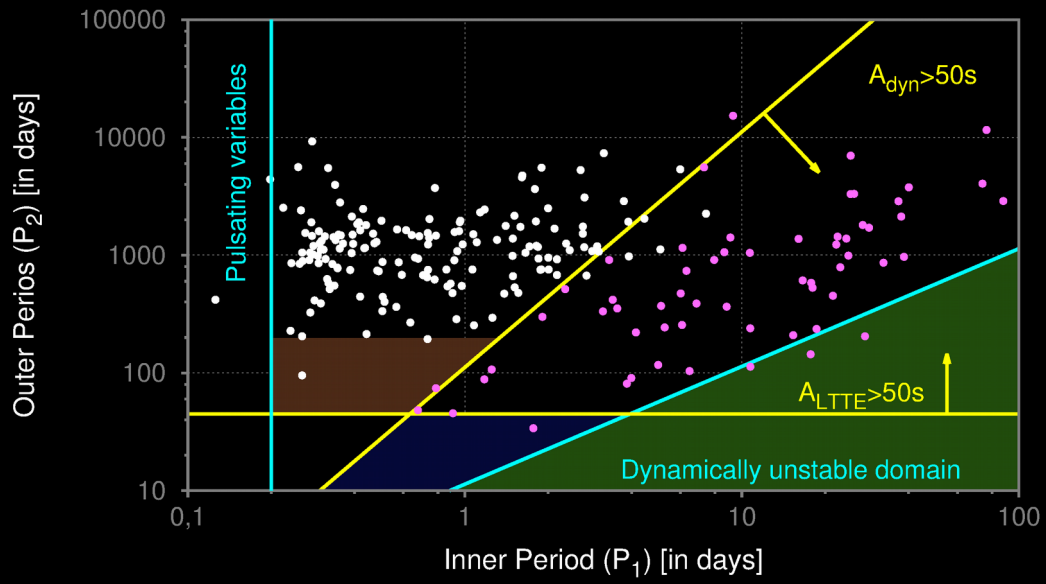
Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

The Royal Road(s): 1) Eclipse Timing Variation Analysis

Some statistics for 222 triples (including 160 pure LTTE systems, too)

- **Shortest outer period systems**
  - The tightest binaries (mostly overcontact systems) have no very close outer companion(s)? (The brown region is almost empty.)

Some implication for their formation mechanism?



Short time-scale perturbations and their modelling in compact hierarchical triple systems

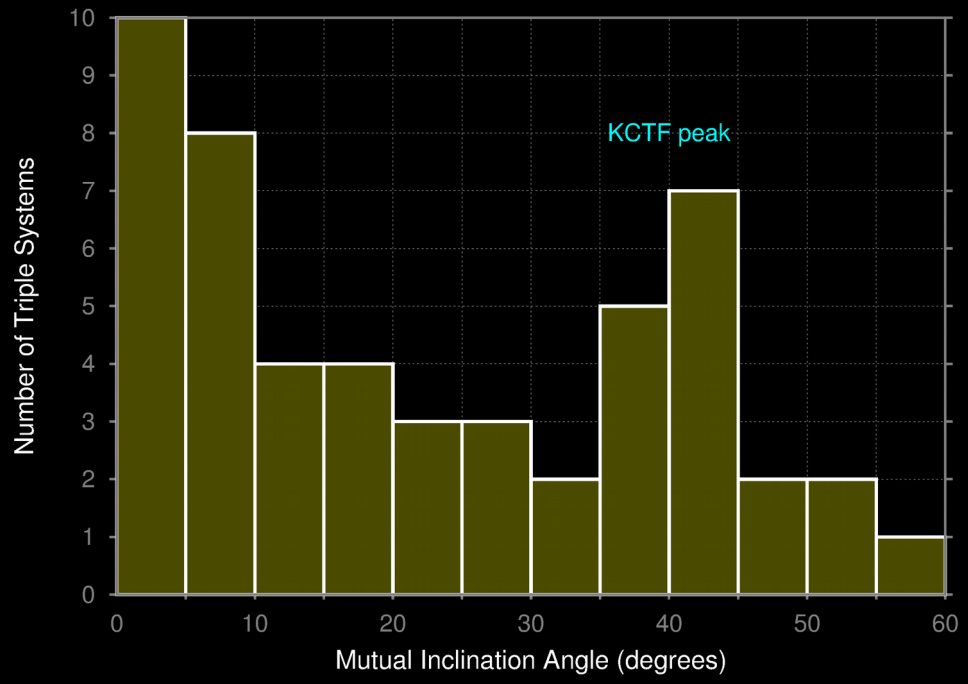
The Royal Road(s): 1) Eclipse Timing Variation Analysis

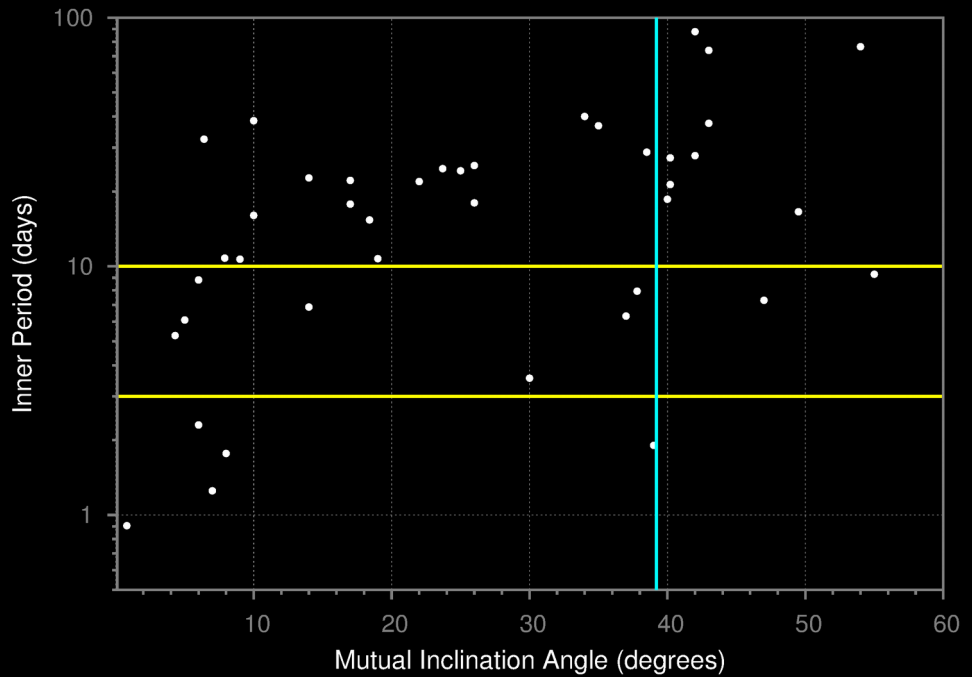
Some statistics for 62 triples

- **Mutual inclination:**

  (Only for systems with dynamical perturbations.)

  - (Second) peak at $i_m \sim 40^o$ (as Fabrycky & Tremaine, 2007 predicts), but the inner period distribution is inconsistent with their predictions





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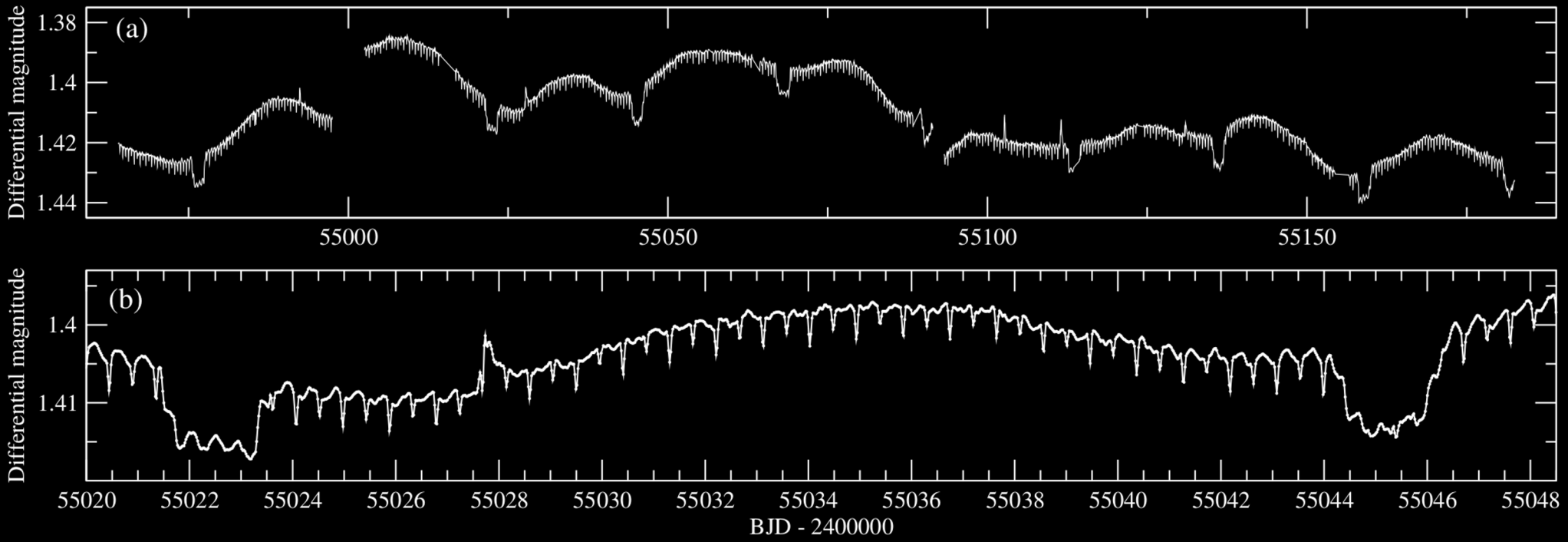
Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

Eclipsing binaries in hierarchical triples – The *Kepler* revolution

Two substantial giveaways –> an extended Royal Road

2. Extra eclipses – Trinity-like systems (HD 1810681)



For further details see: **Derekas et al. 2011, Science, 332, 216** (discovery paper)
Borkovits et al. 2013, MNRAS, 428, 1656 (lc+RV+ETV analysis)
Fuller et al. 2013, MNRAS, 429, 2425 (tidally forced oscillations)

T. Borkovits

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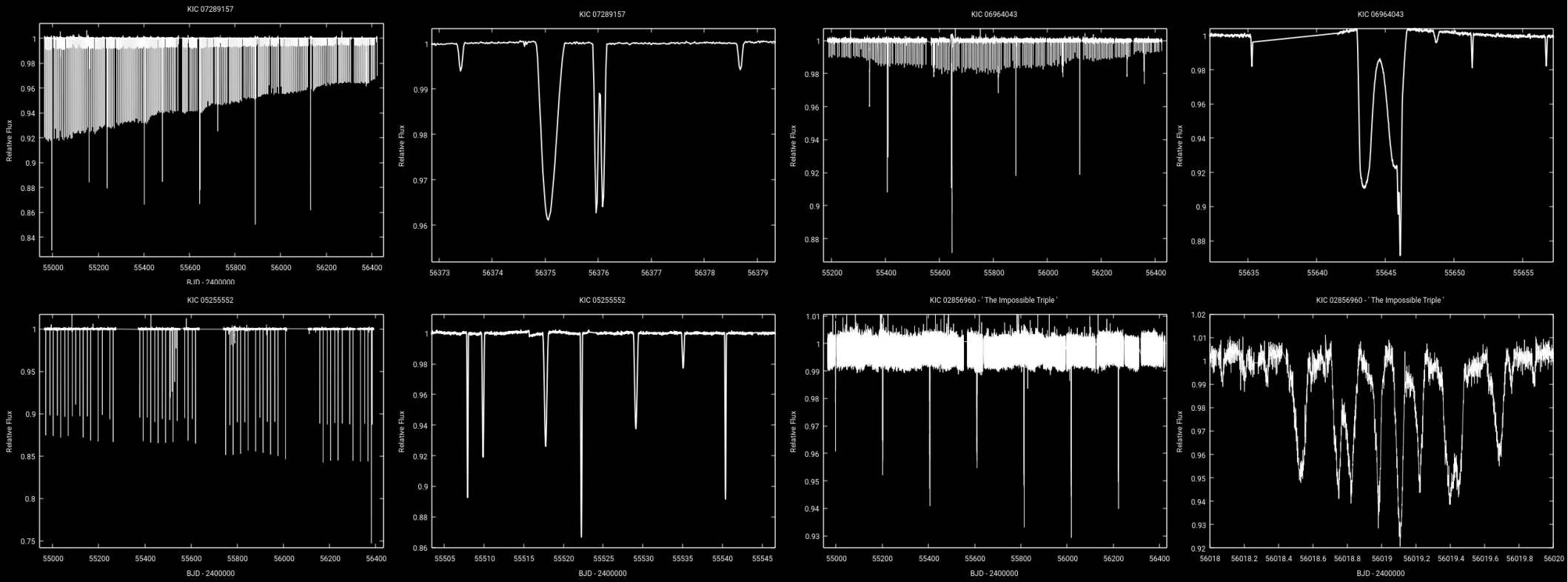

Eclipsing binaries in hierarchical triples – The *Kepler* revolution

Two substantial giveaways –> an extended Royal Road

2. Extra eclipses – Trinity-like systems

Extra Eclipser´s Hall of Fame*

11 – *Kepler* prime mission**
2 – CoRoT
2 – *K2*

* As of 15. October, 2018
** Not counting Kepler`s circumbinary planets

Eclipsing binaries in hierarchical triples – The *Kepler* revolution

Two substantial giveaways –> an extended Royal Road

2. Extra eclipses – Trinity-like systems

Extra Eclipser´s Hall of Fame*

11 – *Kepler* prime mission**
2 – CoRoT
2 – *K2*
1 – AAVSO observers

* ~~As of 15. October, 2018~~
** Not counting Kepler`s circumbinary planets

T. Borkovits

Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

The Royal Road(s): 2) (Spectro –) Photodynamical Analysis of ...

… (mostly, but not exclusively) multiply eclipsing multiple systems

Photo-dynamical:

Classical eclipsing binary lightcurve analysis:

– stellar motion purely Keplerian – and described mostly only in 2D!!! (fix orbital plane)
– only exception: apsidal motion → linear in time
(… khm… in the new versions of the WD code a Keplerian LTTE is also built in)
– presence of a third star can be accounted only with the use of an additive quantity of third light (wavelength-dependent)
– no outer eclipses

Eclipsing binaries in compact hierarchical multiples or, planetary systems:

– need a complete, 3D dynamical treatment of the motion,
i. e. numeric integration of the three, four, etc.-body motion, even including relativistic and/or tidal forces (and even integration of the stellar spin equations)
– handling of different kinds of extra eclipses, etc.

Some examples: Carter et al. 2011, Science, 331, 562 (KOI-126); Welsh et al. 2012, Nature, 481, 475 (K-34,-35); Dawson et al. 2014, ApJ 791, 89 (K-419);Orosz 2015, ASPC 496, 55 (KIC 07668648, 10319590), etc.

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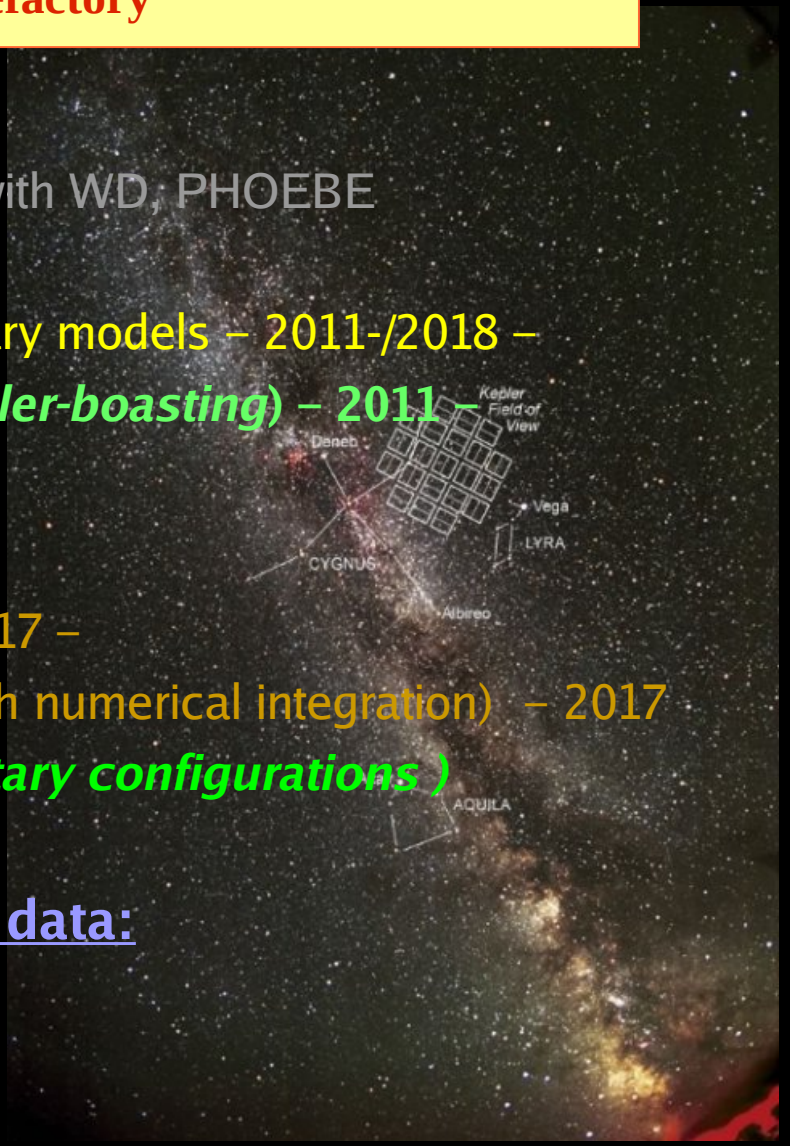
Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

The software package: Lightcurvefactory



More precise physical models:

Radiative and atmospheric models – identical with W.D, PHOEBE

→ to be extended in the near future

Inclusion of oscillations, tidal effects – preliminary models – 2011-/2018 –

Inclusion of some relativistic effects **(e.g. *Doppler-boasting*) – 2011 –**

Extended geometry and dynamics...

Three-, and even four-body eclipses – 2011/2017 –

Inclusion of three- and four-body dynamics (with numerical integration) – 2017

(inclusion of further hierarchic, and planetary configurations)

Simultaneous analysis of different kinds of data:

Multi-band photometry – 2014 –

RV- and ETV-curves – 2017 –

SED+isochrones – last week

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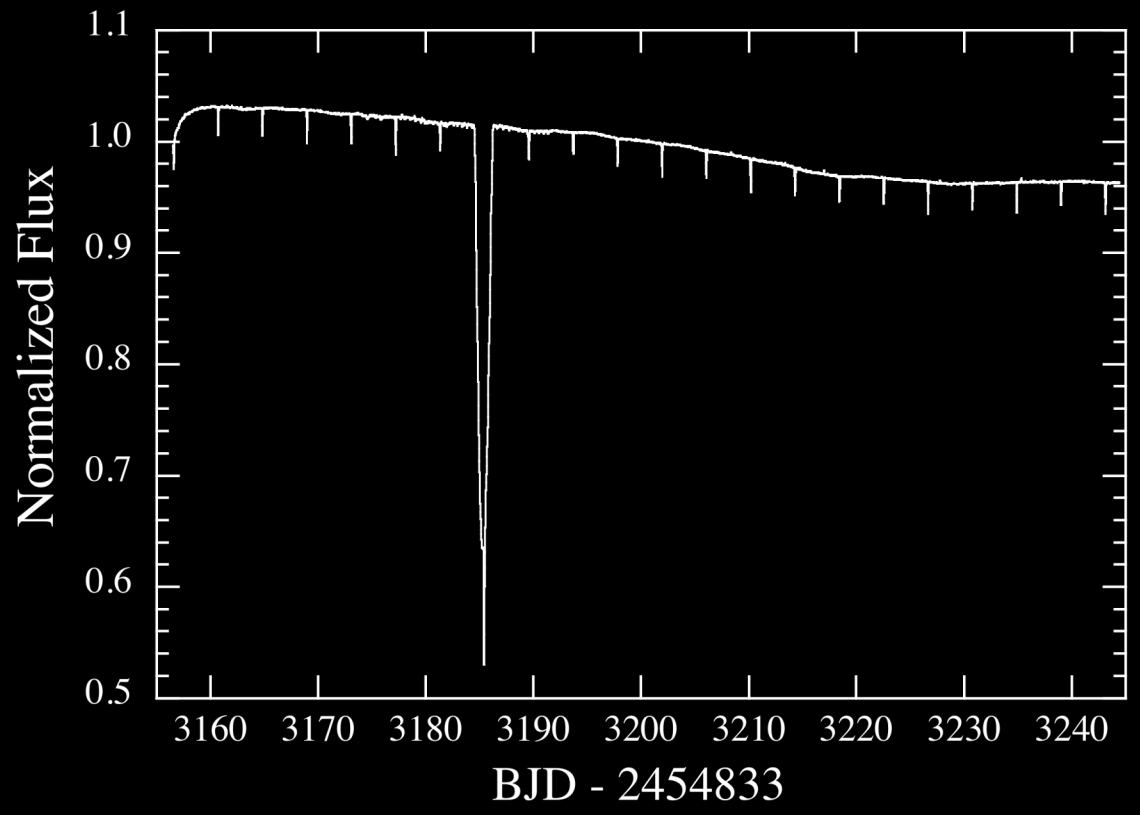
Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

The Royal Road(s): 2) Photodynamical Analysis of Triply Eclipsing Systems...

A recent example: EPIC 249432662



A ~15-mag star in Scorpius, observed during Campaign 15 of the K2 mission

~3% deep eclipses reveal a slightly eccentric ~8.2-day period EB

An almost 50% deep, more than 2-day-long, extra fading with complex structure

ETV analysis reveals rapid period variations

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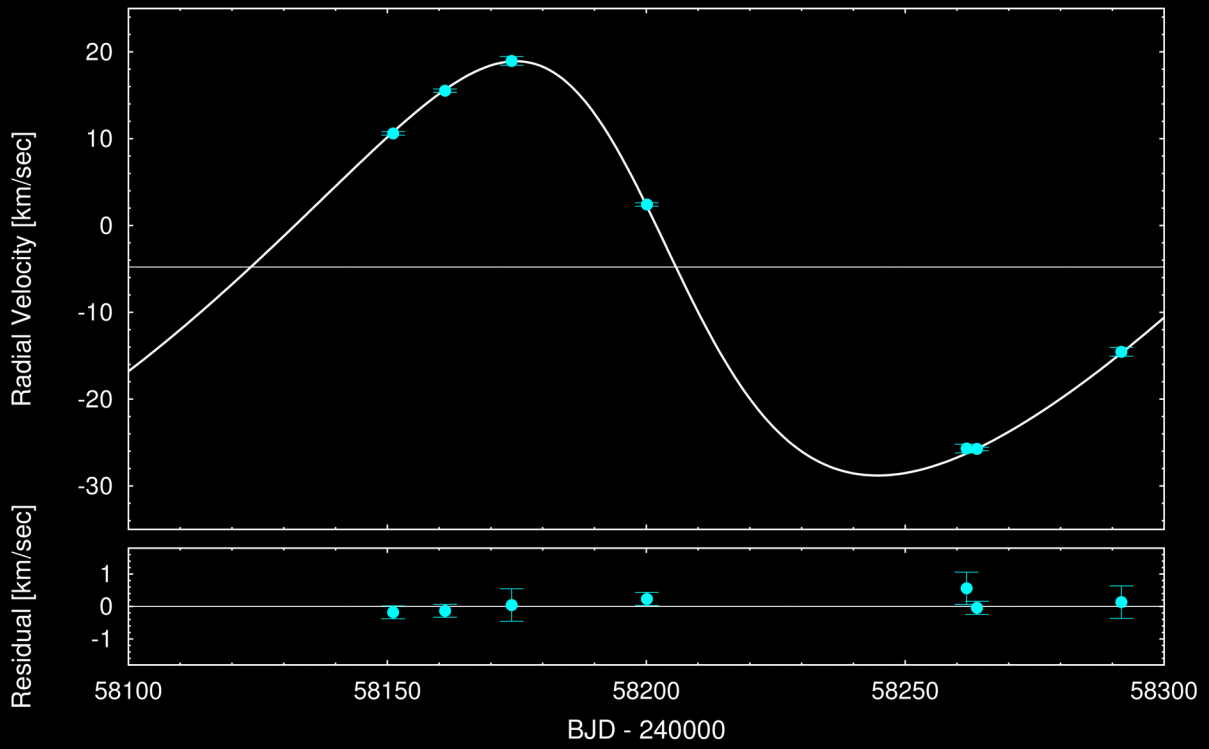
Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

The Royal Road(s): 2) Photodynamical Analysis of Triply Eclipsing Systems...

Spectroscopic follow-up (KECK I HIRES + McDonald Observatory)



Only one, probably MS K star is seen in the spectra

Joint photodynamical analysis of K2 lightcurve + ETV curve + RV data:

The fourth RV point obtained at 22 March 2018 allowed us to constrain the outer period with ~2-3-day accuracy.

T. Borkovits

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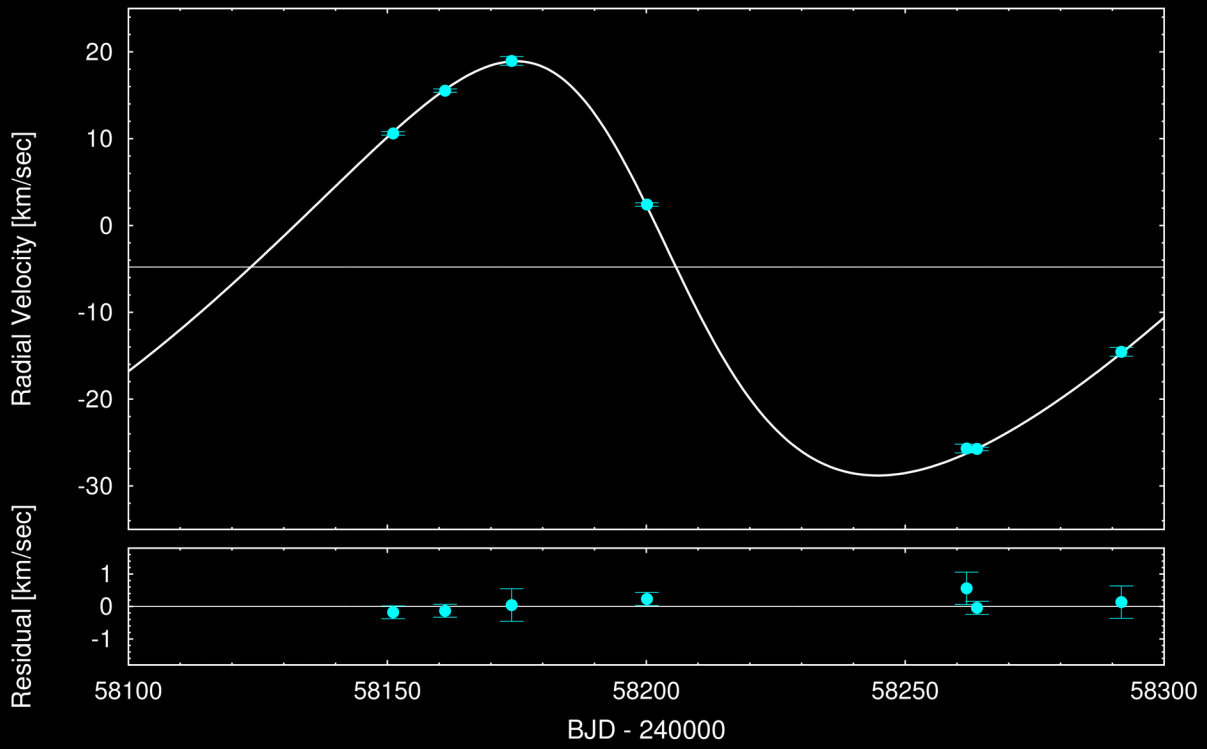

Only one, probably MS K star is seen in the spectra

Joint photodynamical analysis of K2 lightcurve + ETV curve + RV data:

The fourth RV point obtained at 22 March 2018 allowed us to constrain the outer period with ~2-3-day accuracy.

The forthcoming outer eclipses should be occurring within 5 – 10 days of that time!

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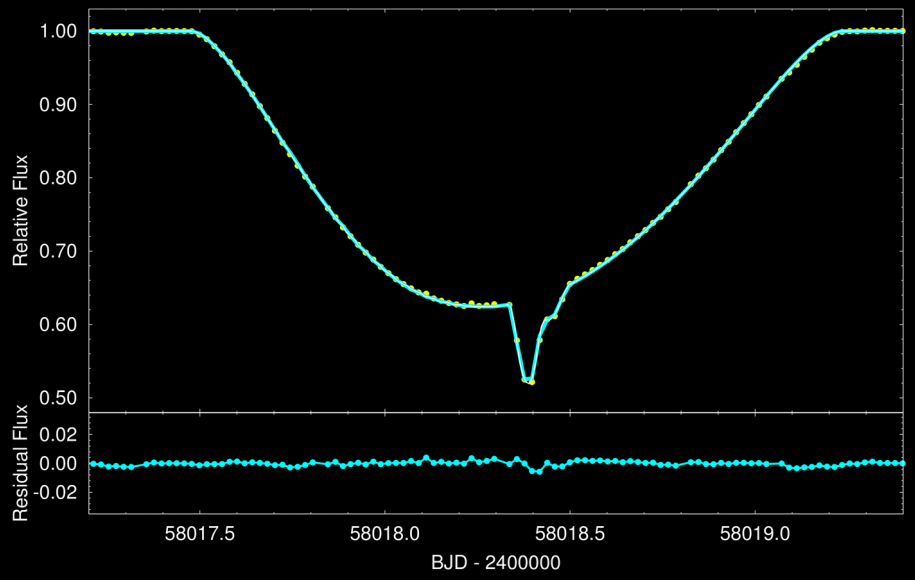

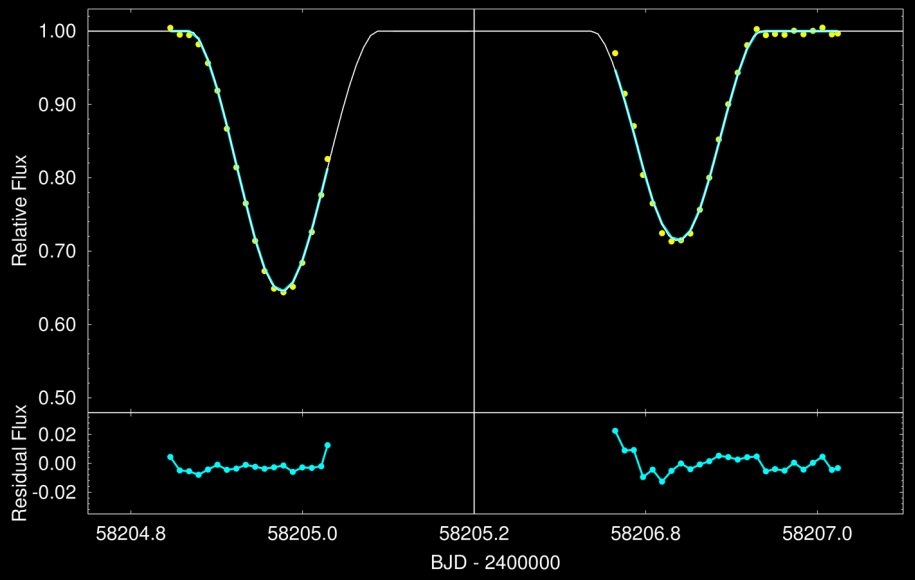

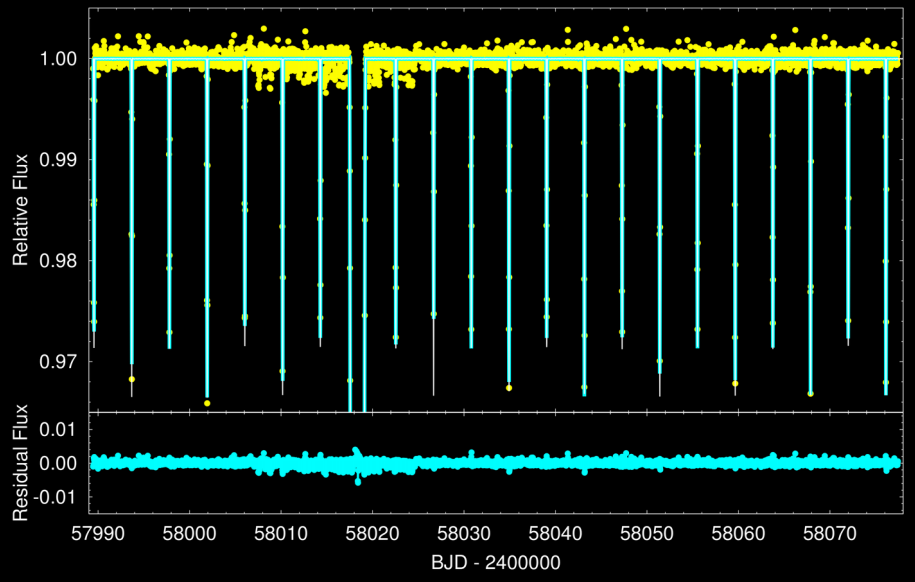

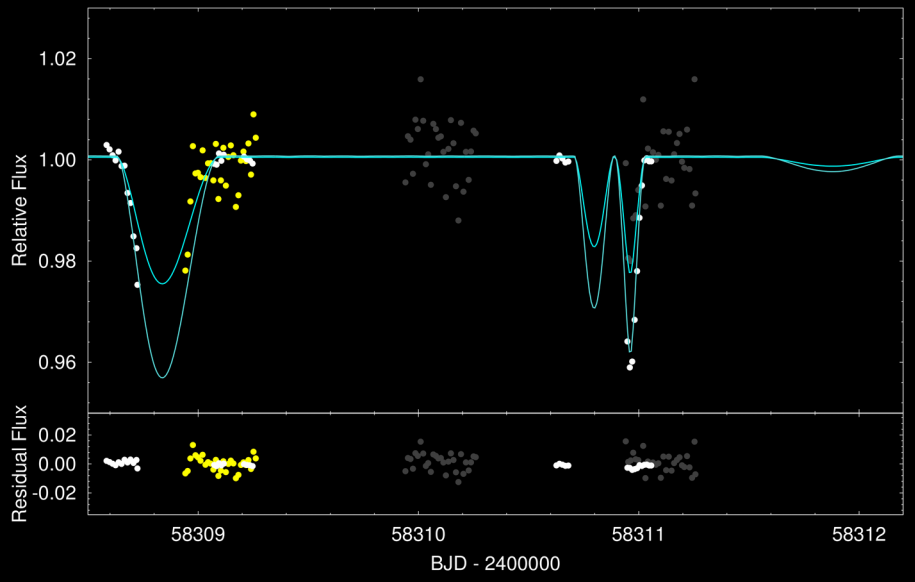

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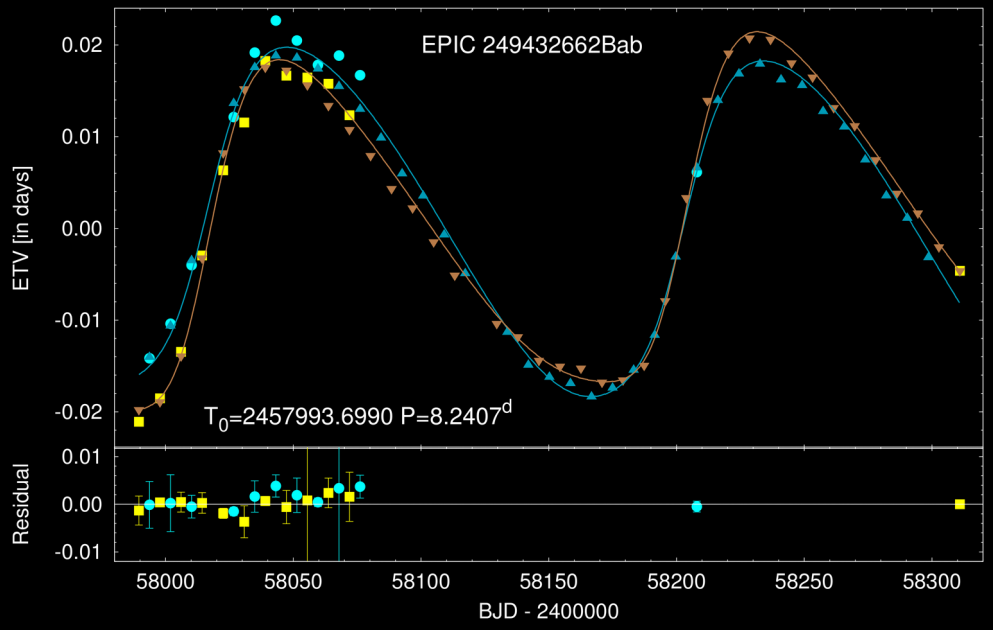

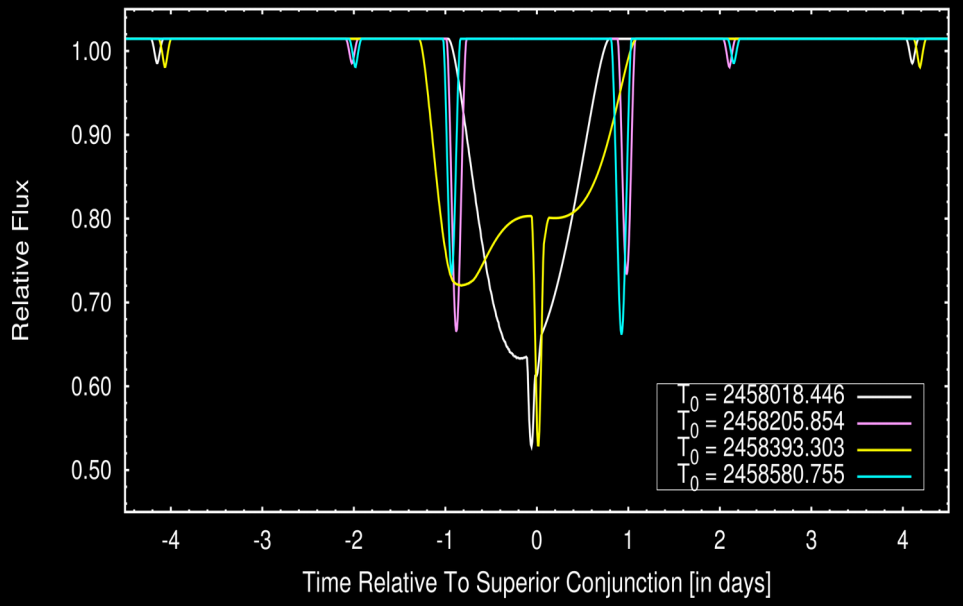

Most interesting results: – extremely flat system: $i_{mut} = 0.189^o \pm 0.124^o$

– similar mass-ratios: $q_{in} = 0.876 \pm 0.012$; $q_{out} = 0.877 \pm 0.044$

Further details in Borkovits, Rappaport, Kaye et al., 2019, MNRAS 483, 1934

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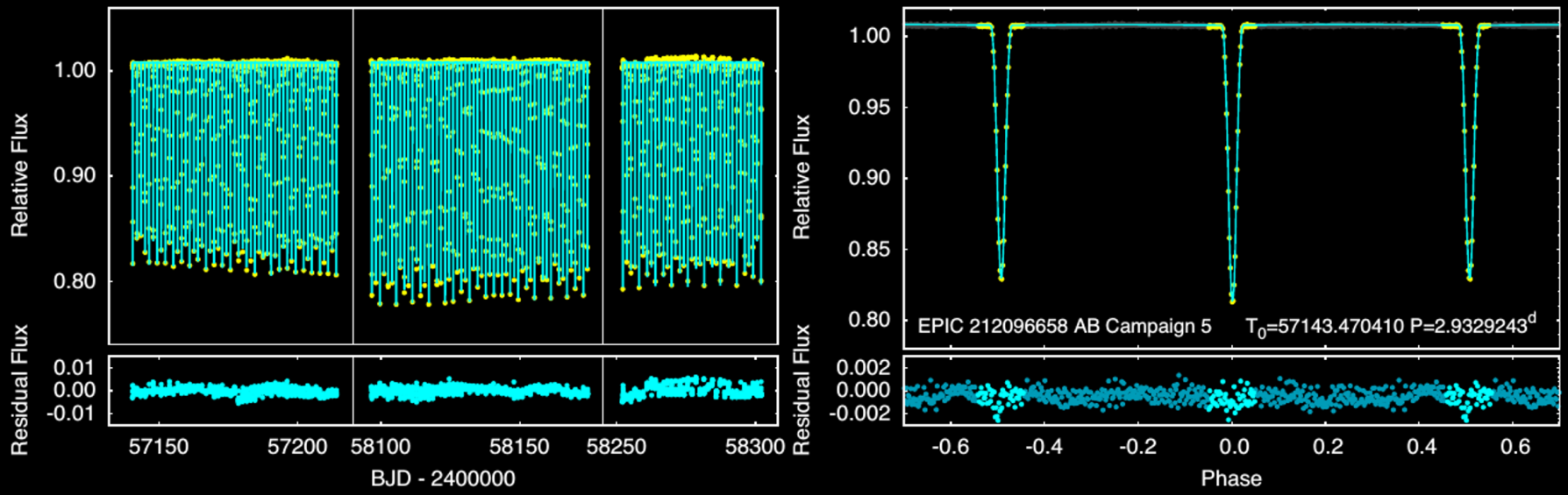
Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

The Royal Road(s): 2) … and quadruple system (both 2+1+1 & 2+2)

An example for the usefulness of the desk drawer observations : EPIC 210966582



A relatively bright (V ~ 10.84), red dwarf in the solar neighbourhood, located in the auspicious region of Cancer which was observed in three K2 campaigns (C05,16,18). K2 observations show cyclic ETV with a period of ~59^{d}. Slight eclipse depth variations are also visible...

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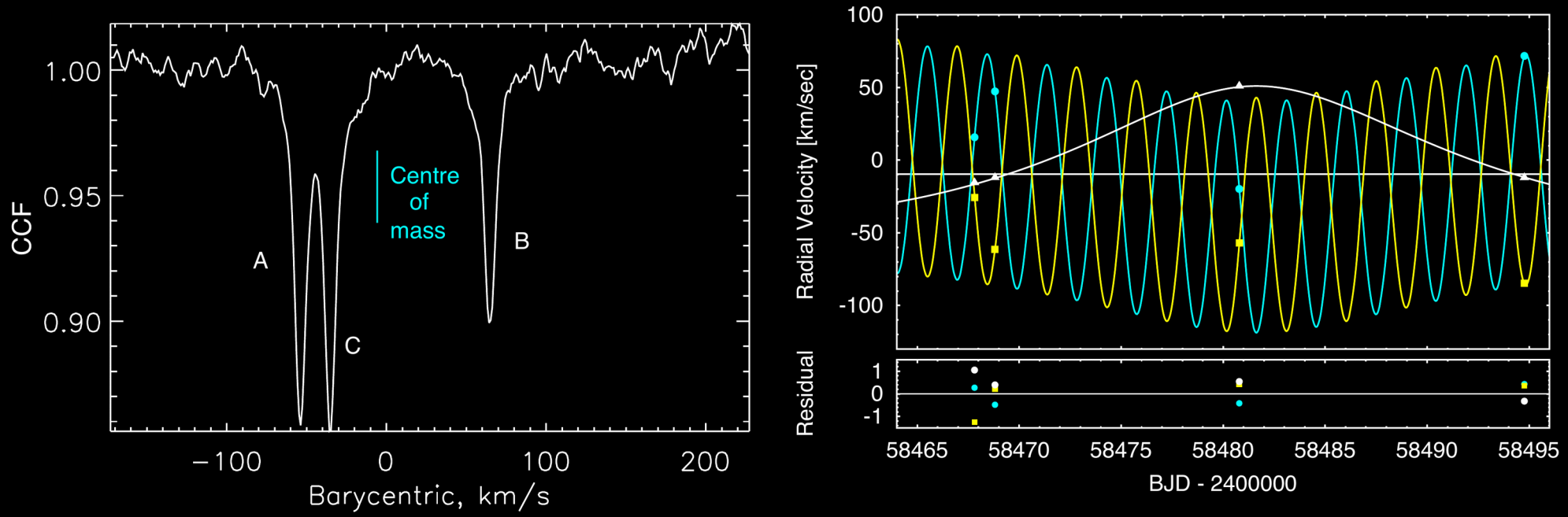

Independent spectroscopic observations by Julius Sperauskas & Andrei Tokovinin, with different instruments (mainly VUES & CHIRON):

an SB 3 system formed by three very similar stars

T. Borkovits

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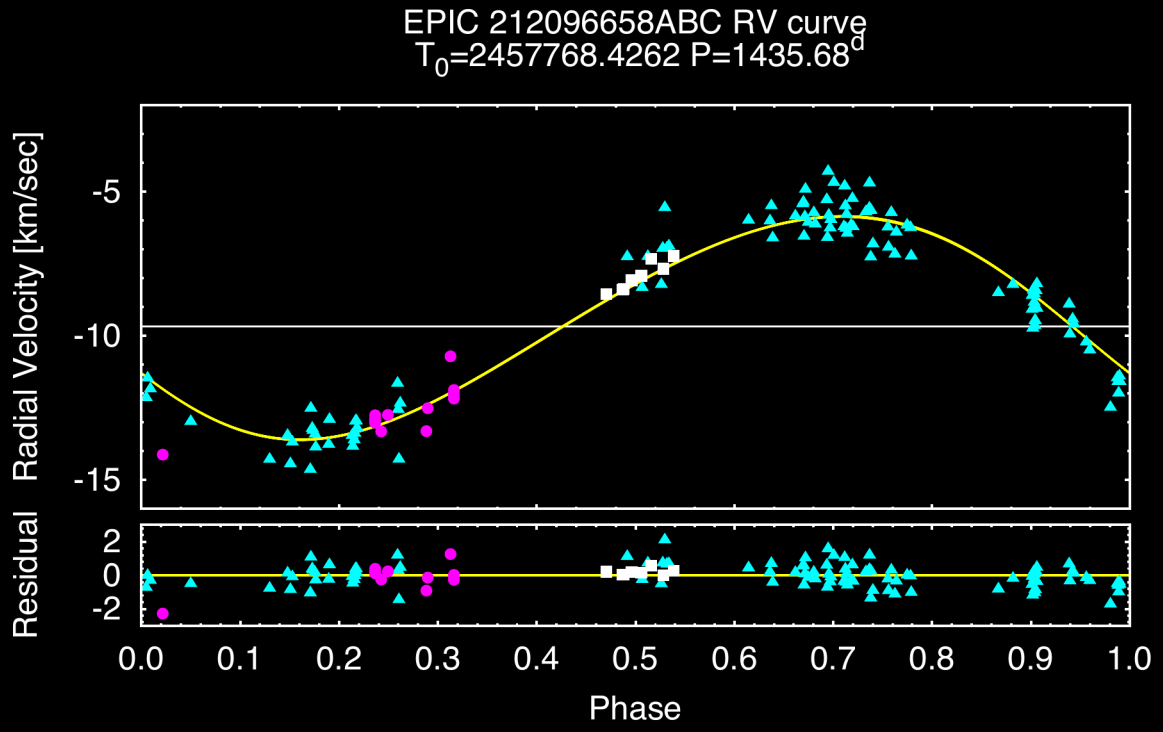

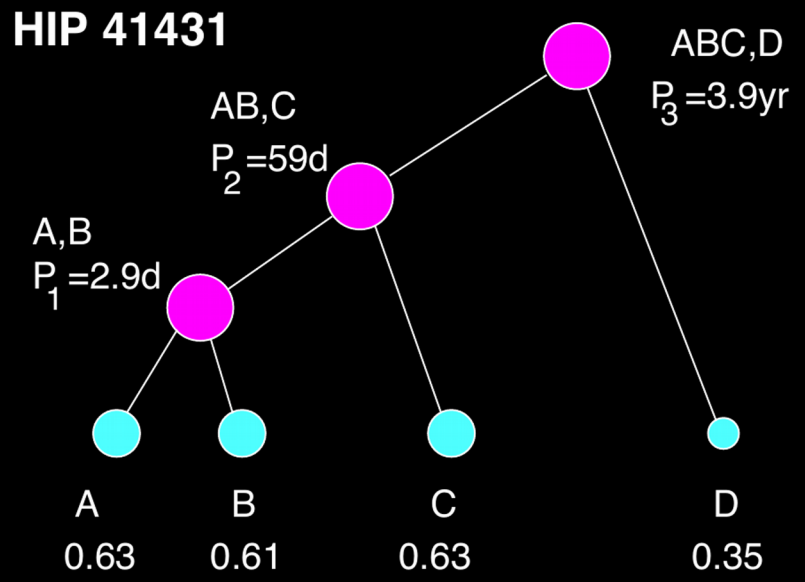

Andrei was looking for former RV measurements, and he realized that Dave Latham at CfA had been observed this system continuously for two decades!

– According to these old RV data, this system is indeed a 2+1+1 quadruple system, with an outmost period of ~ P_3=1436^d.

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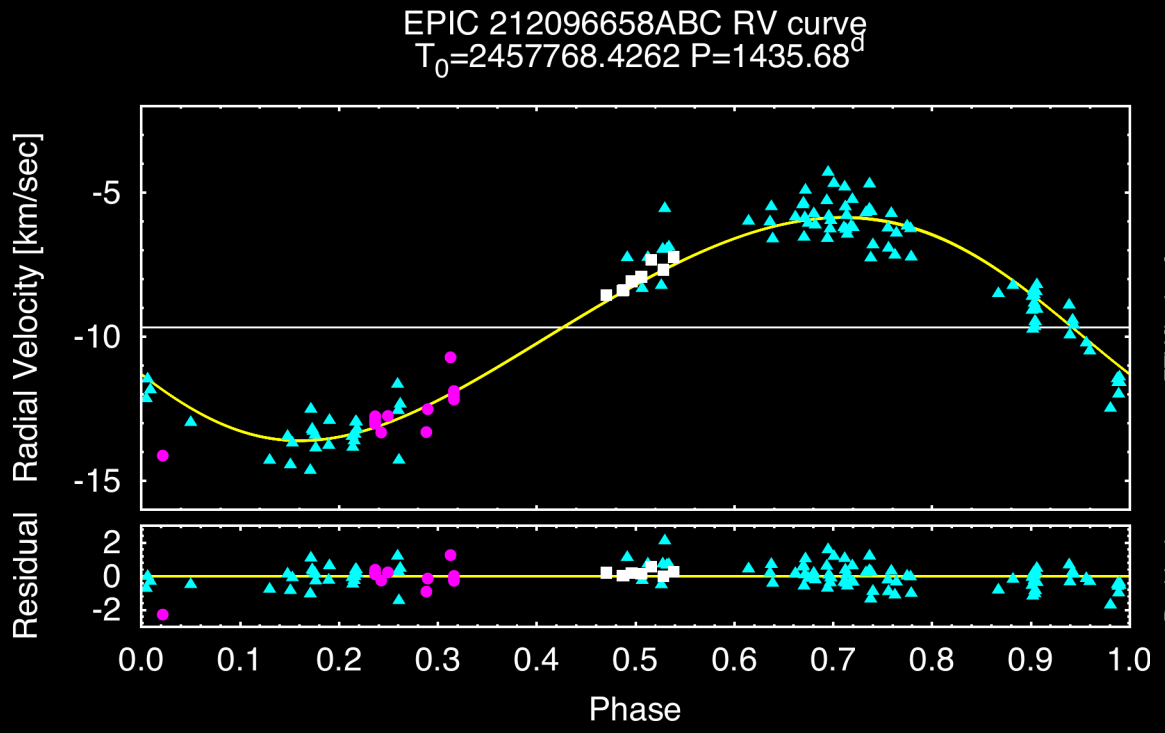

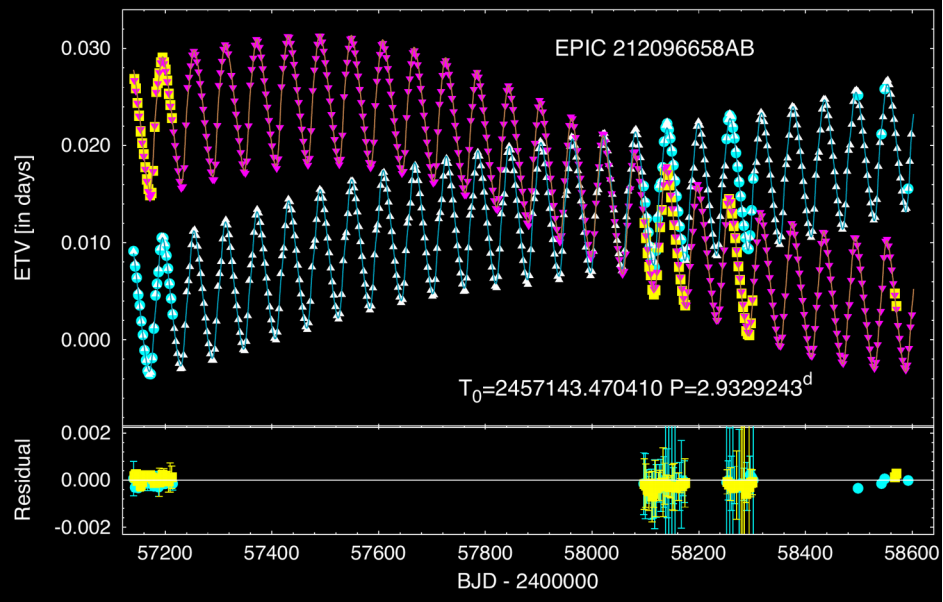

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– It explains also the systematic residual of the ETV in the three-body photodynamical fit.

T. Borkovits

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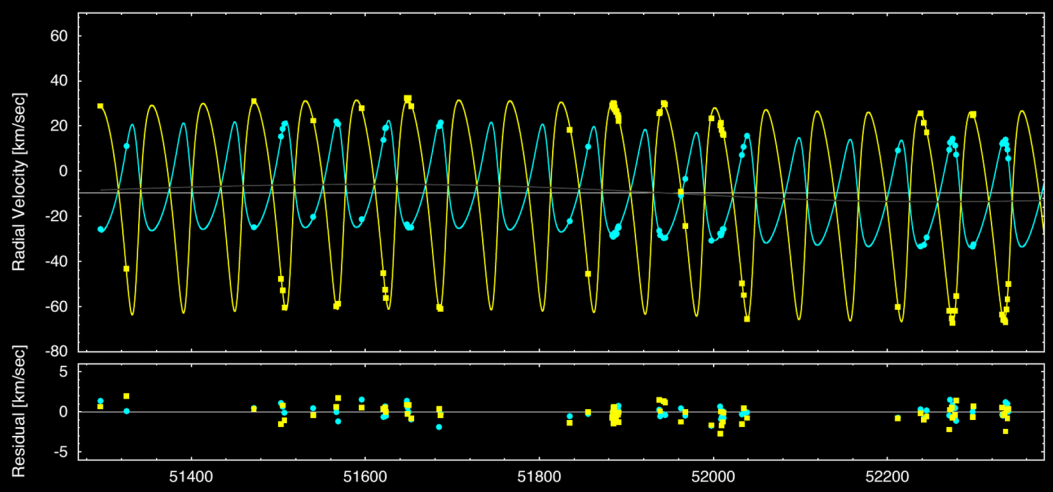

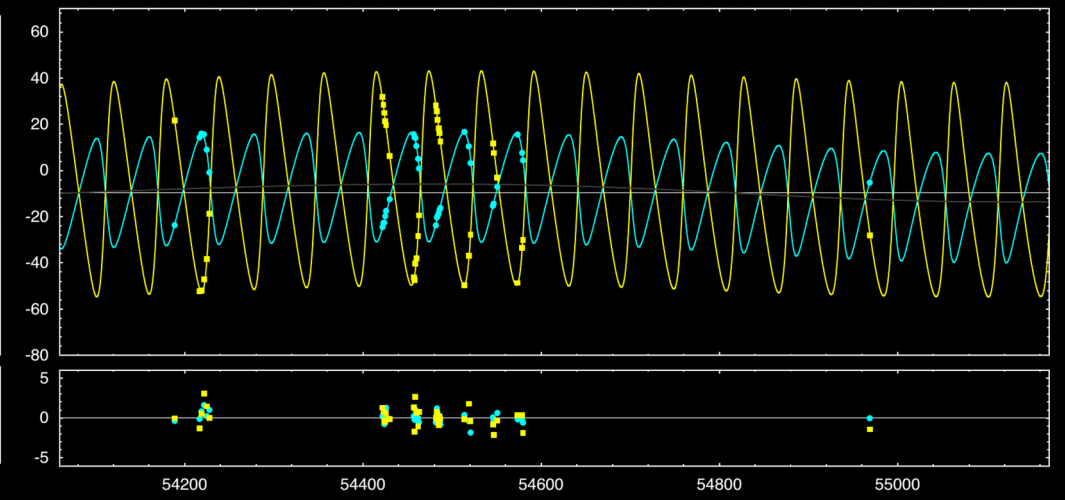

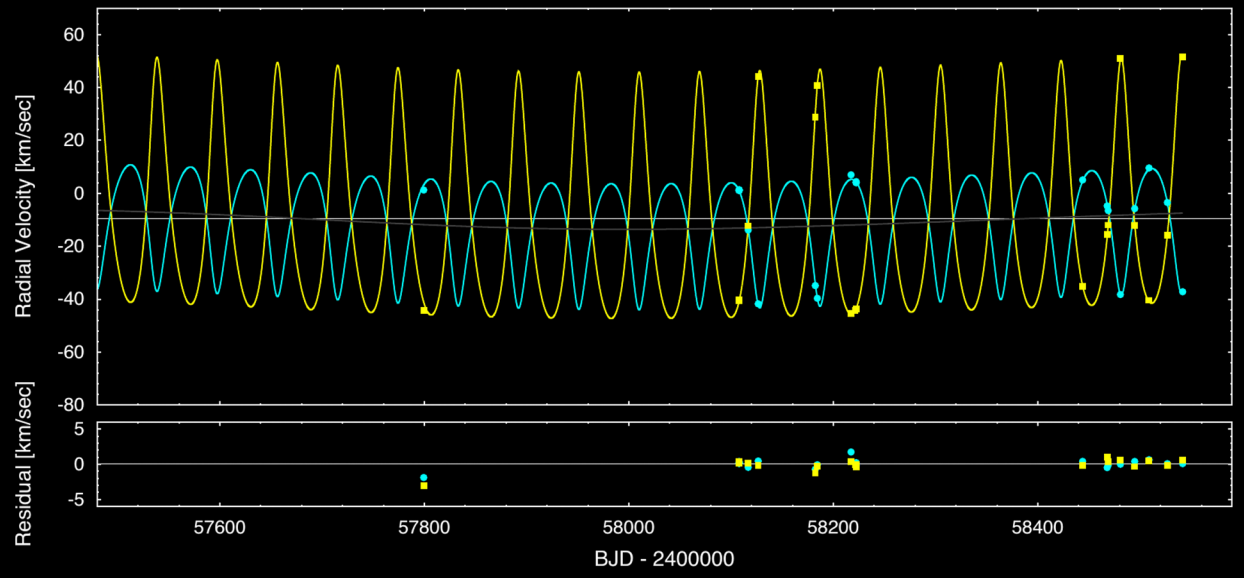

T. Borkovits

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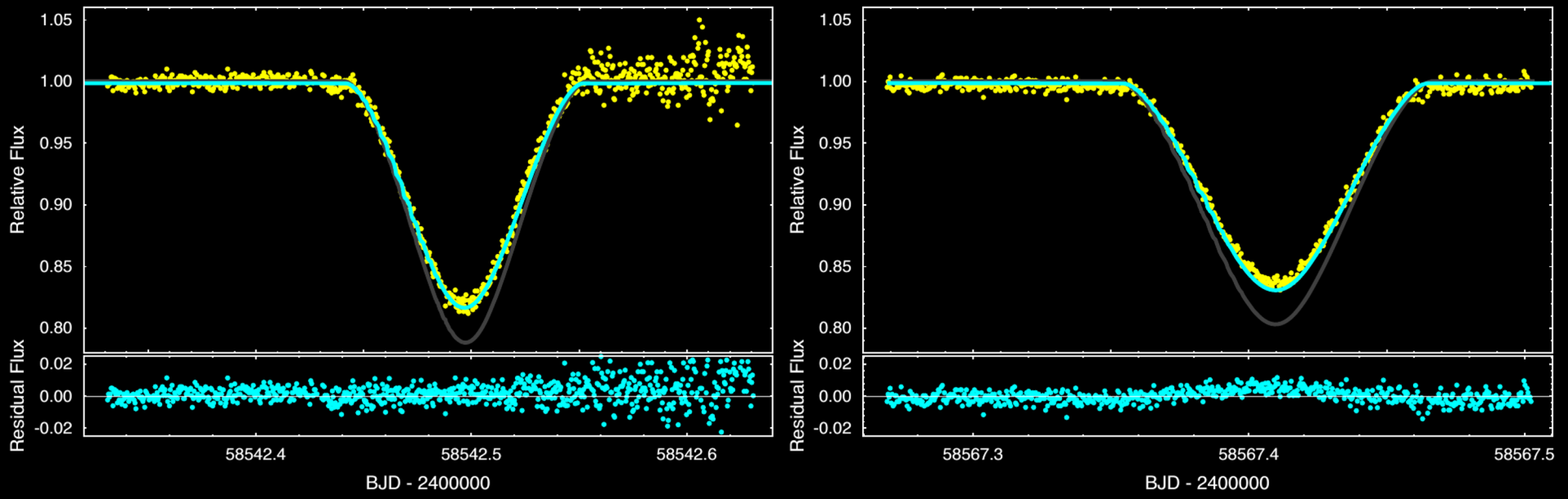
The Royal Road(s): 2) … and quadruple system (both 2+1+1 & 2+2)

An example for the usefulness of the desk drawer observations : EPIC 212096658



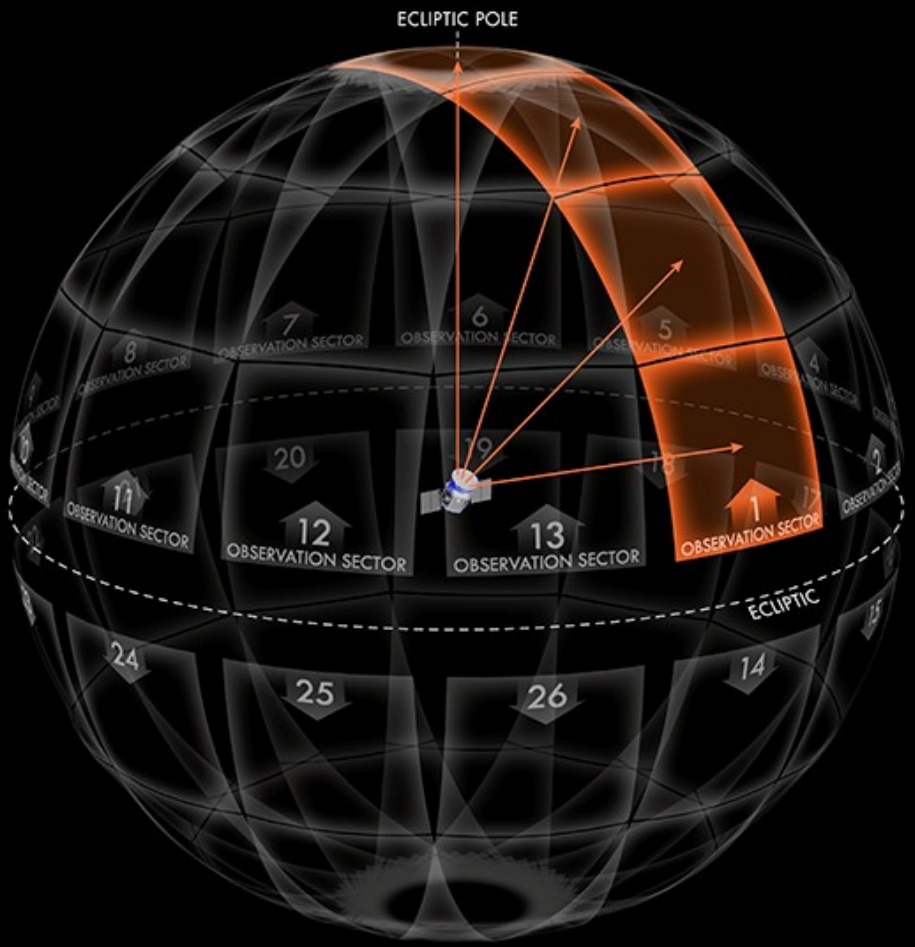
Primary (left) and secondary eclipses (right) observed this year with the 50-cm RC telescope of Baja Astronomical Observatory: eclipse depth variations are evident, and in nice accordance with the predictions of the 2+1+1 spectro-photodynamical model.

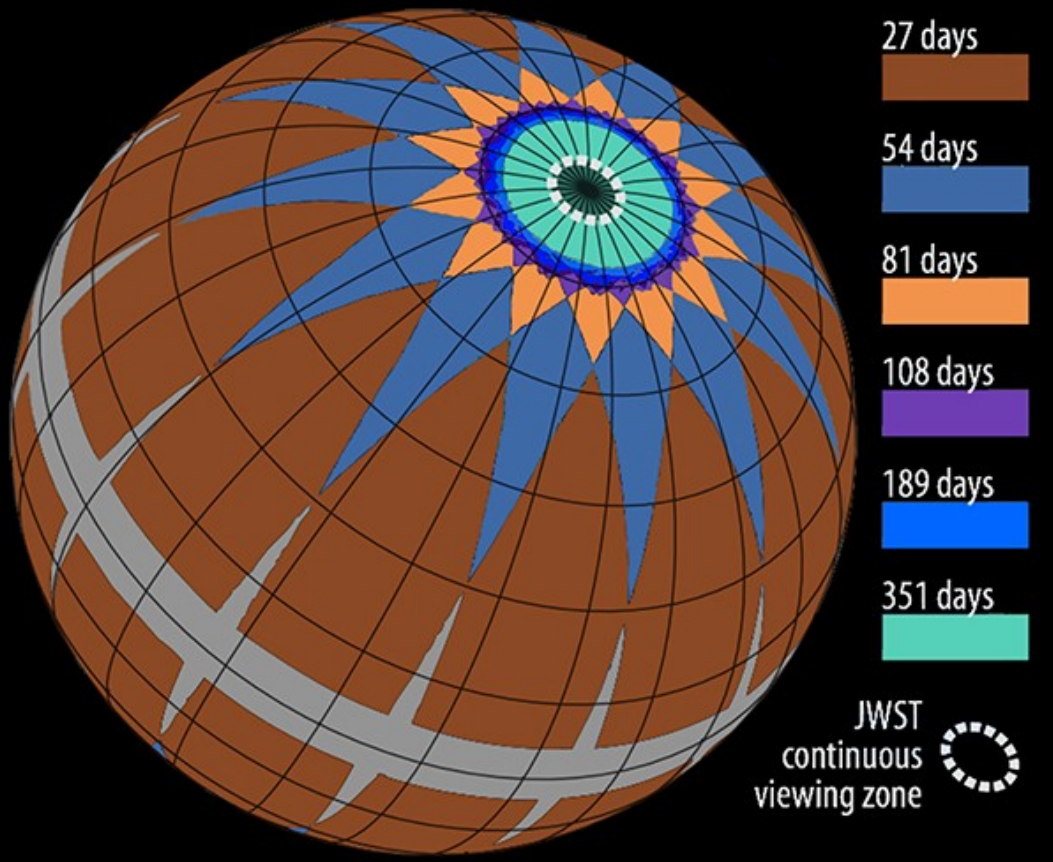
Further details in Borkovits, Sperauskas, Tokovinin et al., 2019, MNRAS 487, 4631

T. Borkovits

Not so hierarchical stellar multiples with the eyes of *Kepler*, *TESS* et al.

The future is in progress...





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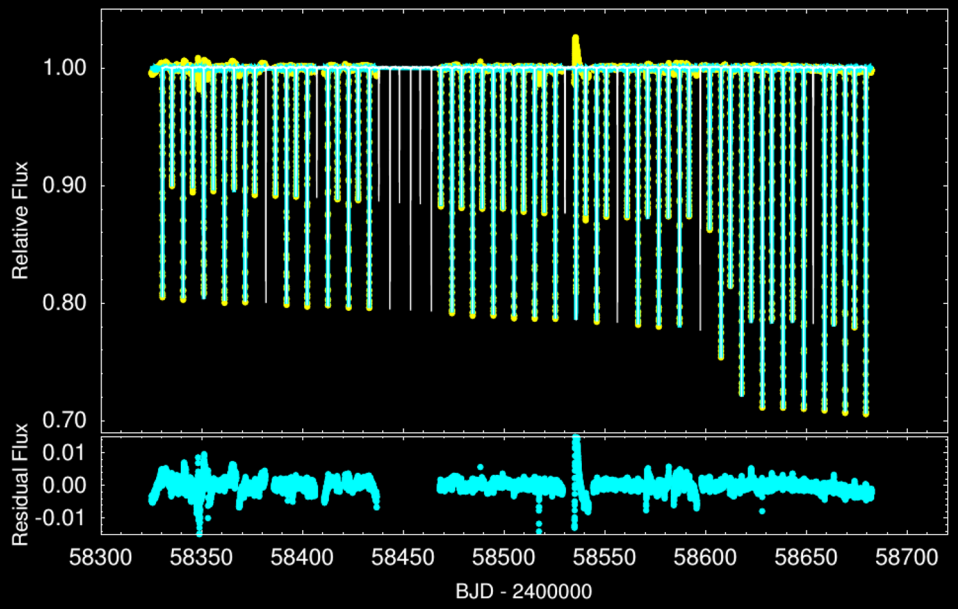

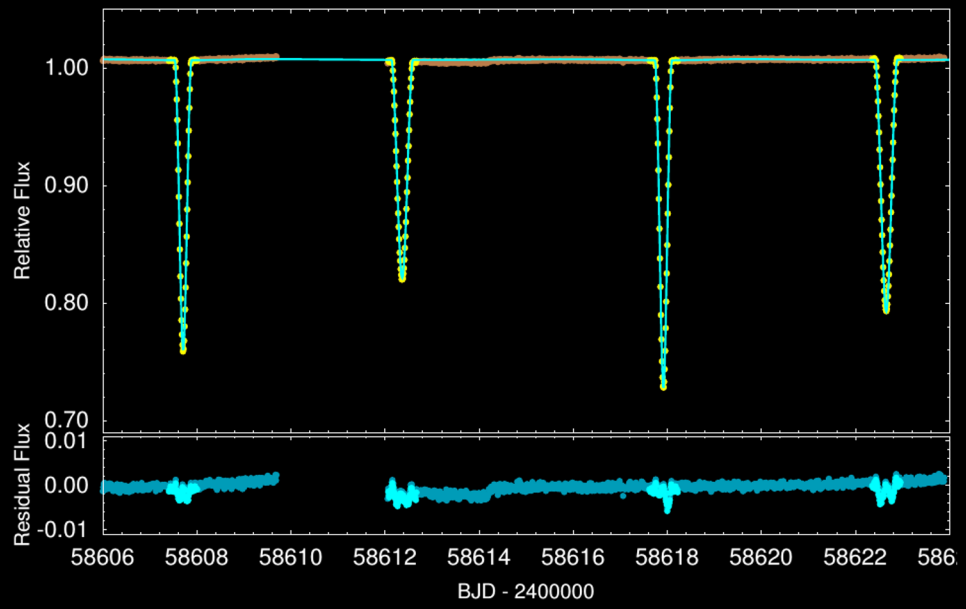

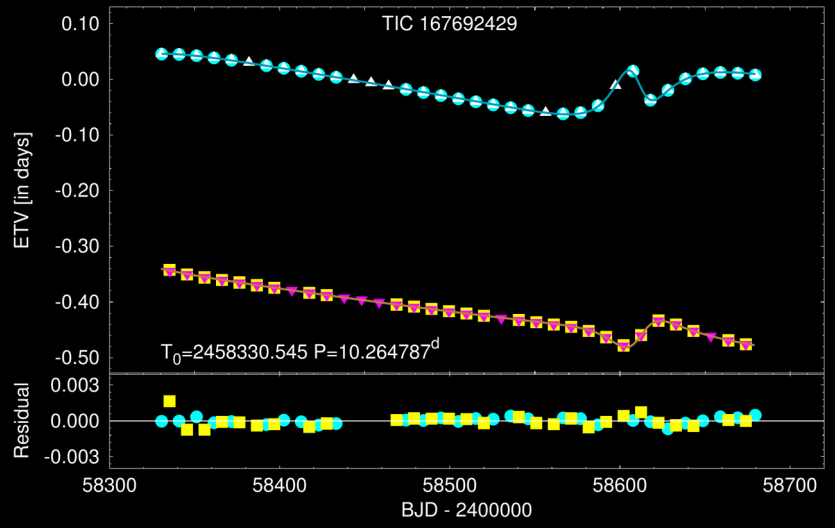

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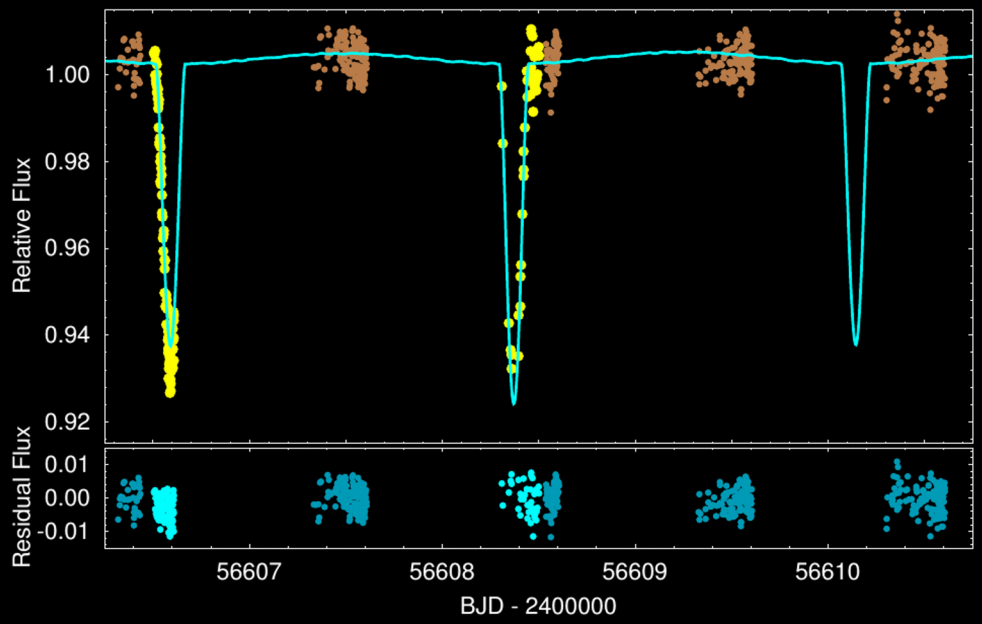

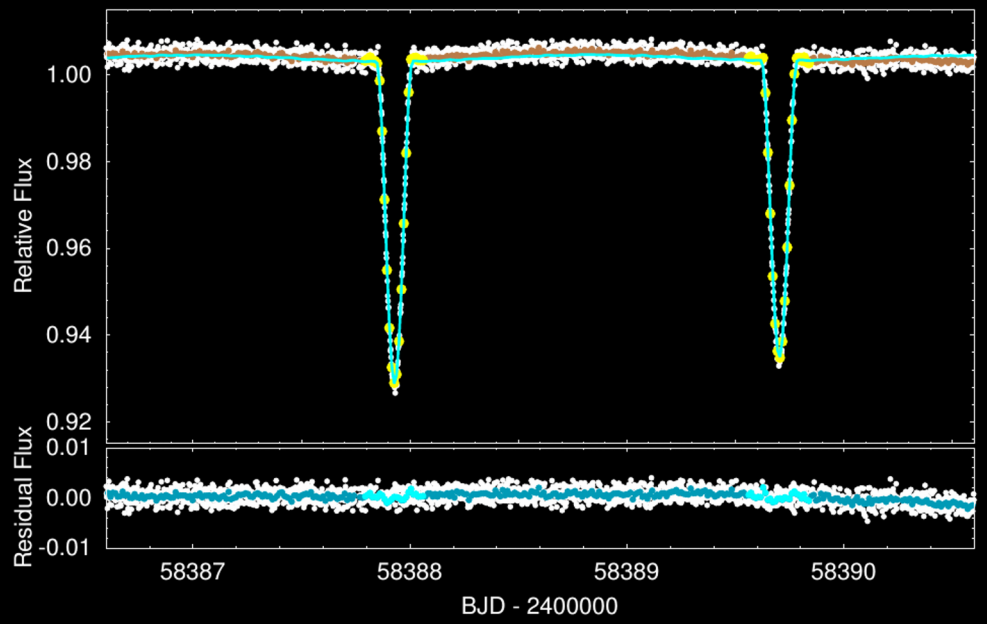

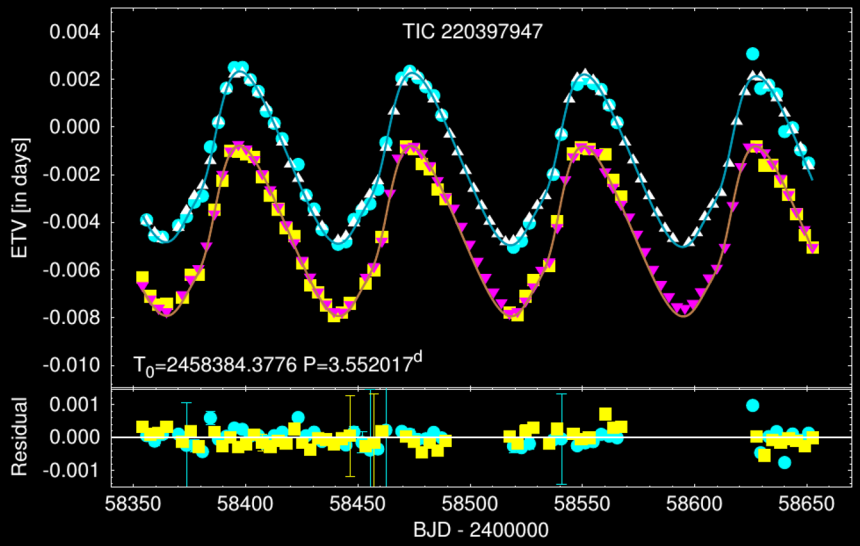

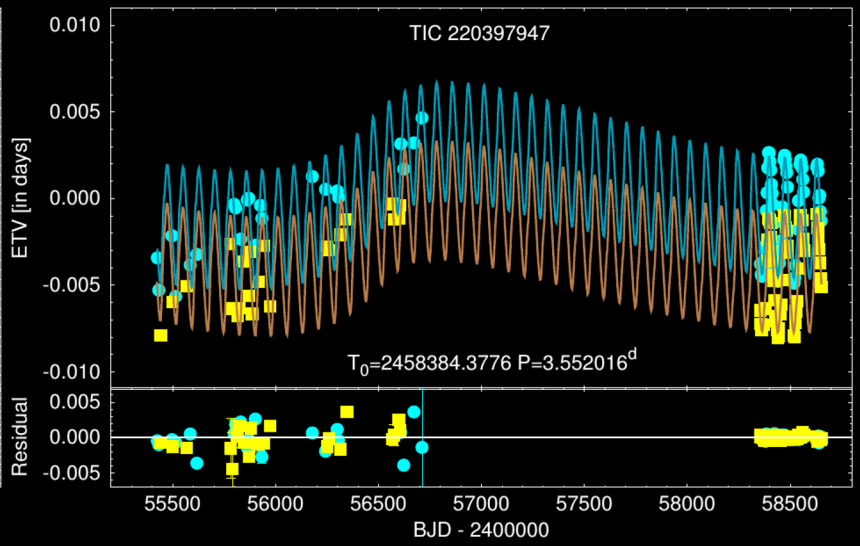

Thank you for the attention!