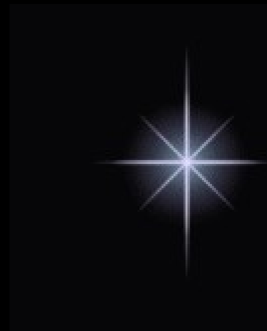

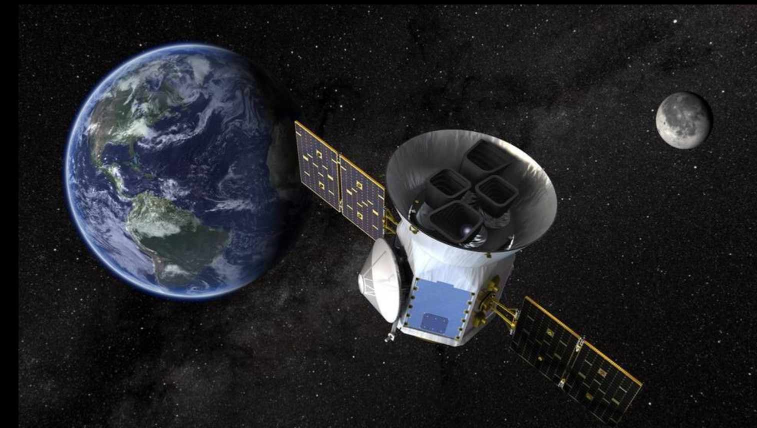

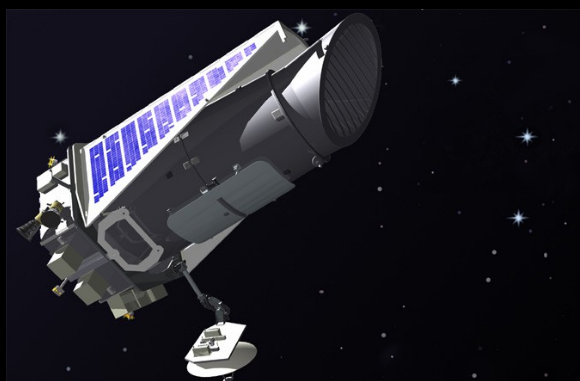

Borkovits Tamás
Astronomical Observatory of Szeged University

Then and now:
A new look on the ETVs of hierarchical triple candidates in the primordial Kepler-field revisited by TESS

Collaborators: S. Rappaport (M.I.T. Kavli Institute), E. Forgács-Dajka,
T. Mitnyan, I.B. Bíró, I. Csányi (Baja), A. Pál (Konkoly),
T. Hajdu, J. Sztakovics (ELTE, Astron. Dept.) et al.

Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

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THEN

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **448,** 946–993 (2015) doi:10.1093/mnras/stv015

Eclipse timing variation analyses of eccentric binaries with close tertiaries in the *Kepler* field

T. Borkovits,[1,2★] S. Rappaport,[3] T. Hajdu[4] and J. Sztakovics[4]
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[3] *M.I.T. Department of Physics and Kavli Institute for Astrophysics and Space Research, 70 Vassar St, Cambridge, MA 02139, USA*
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Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **455,** 4136–4165 (2016) doi:10.1093/mnras/stv2530

A comprehensive study of the *Kepler* triples via eclipse timing

T. Borkovits,[1,2★] T. Hajdu,[3] J. Sztakovics,[3] S. Rappaport,[4★] A. Levine,[5] I. B. Bíró[1] and P. Klagyivik[6,7]
[1] *Baja Astronomical Observatory of Szeged University, H-6500 Baja, Szegedi út, Kt. 766, Hungary*
[2] *ELTE Gothard-Lendület Research Group, H-9700 Szombathely, Szent Imre herceg út 112, Hungary*
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[6] *Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain*
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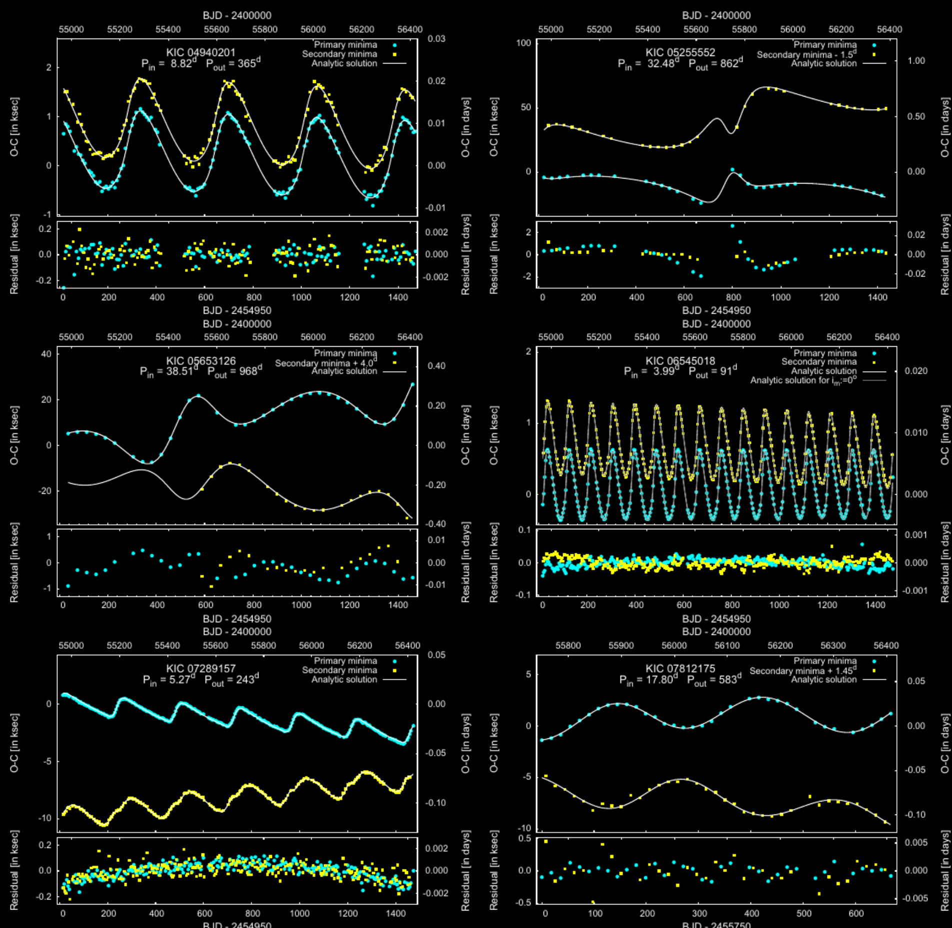
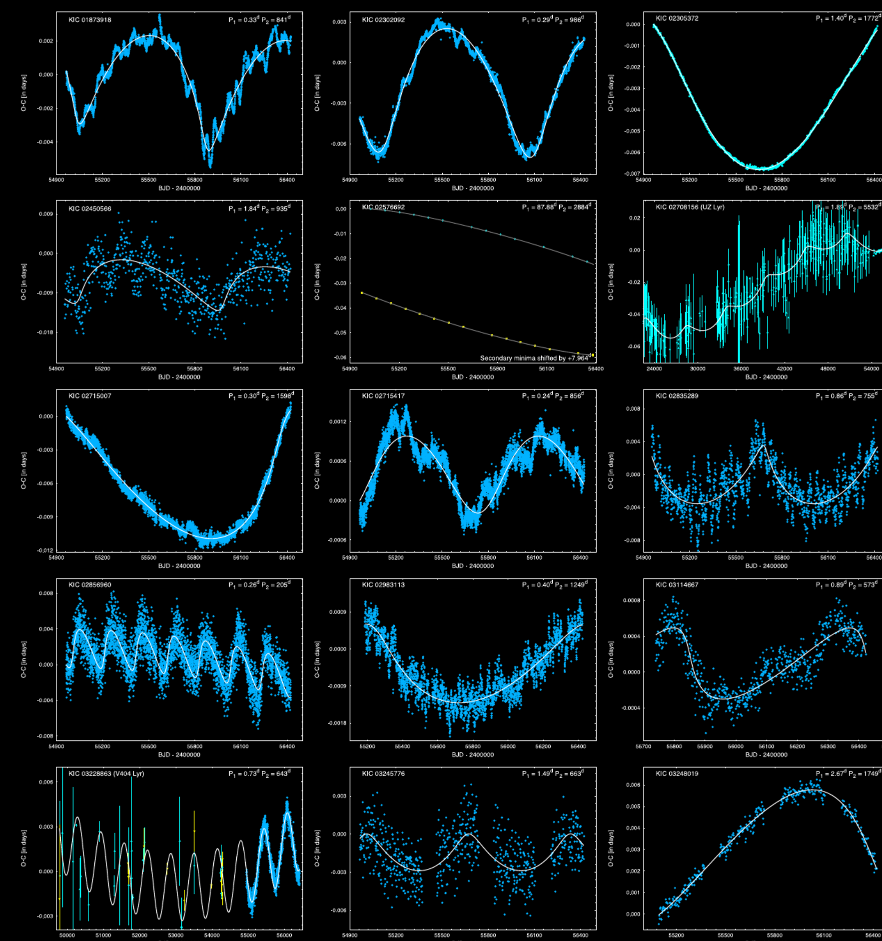
Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

THEN





26 : 221

Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

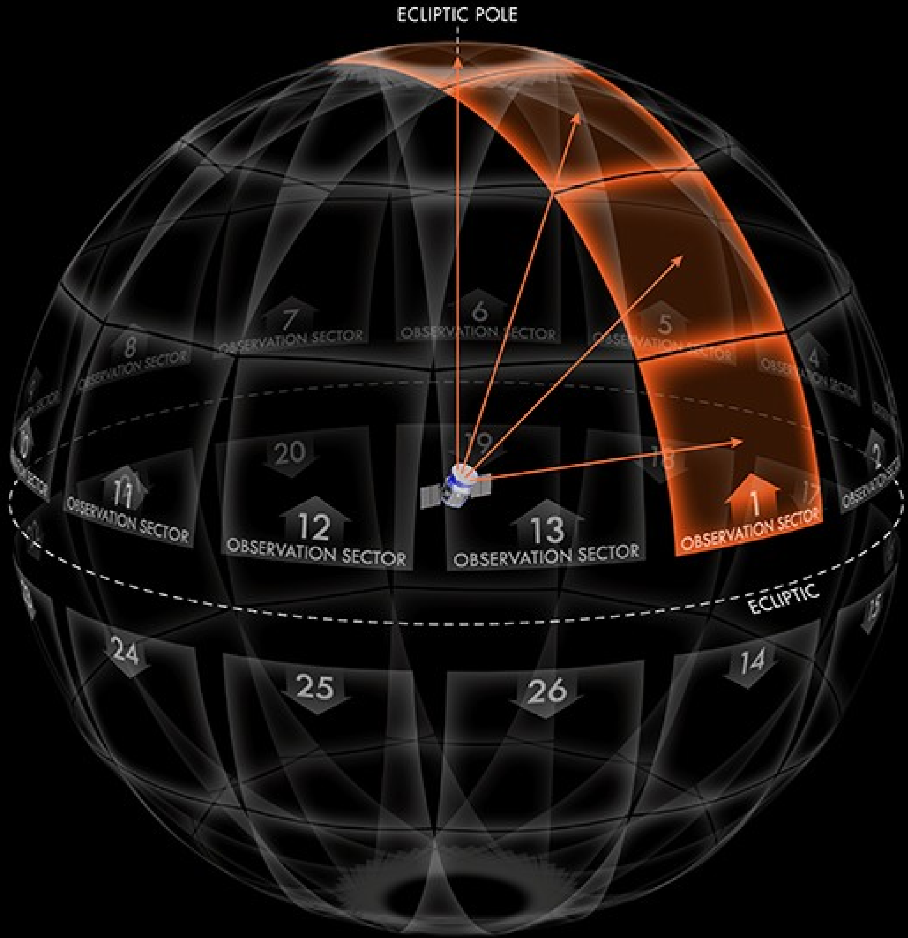
Since then ...

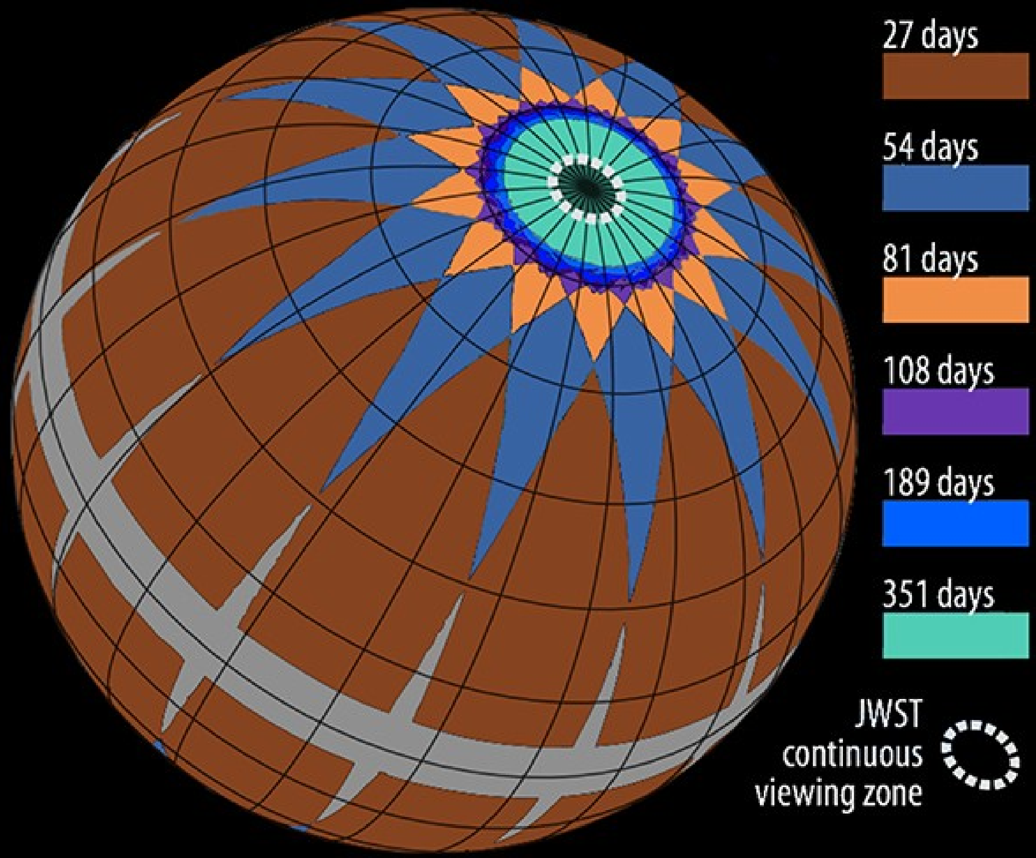
Kepler has gone

Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

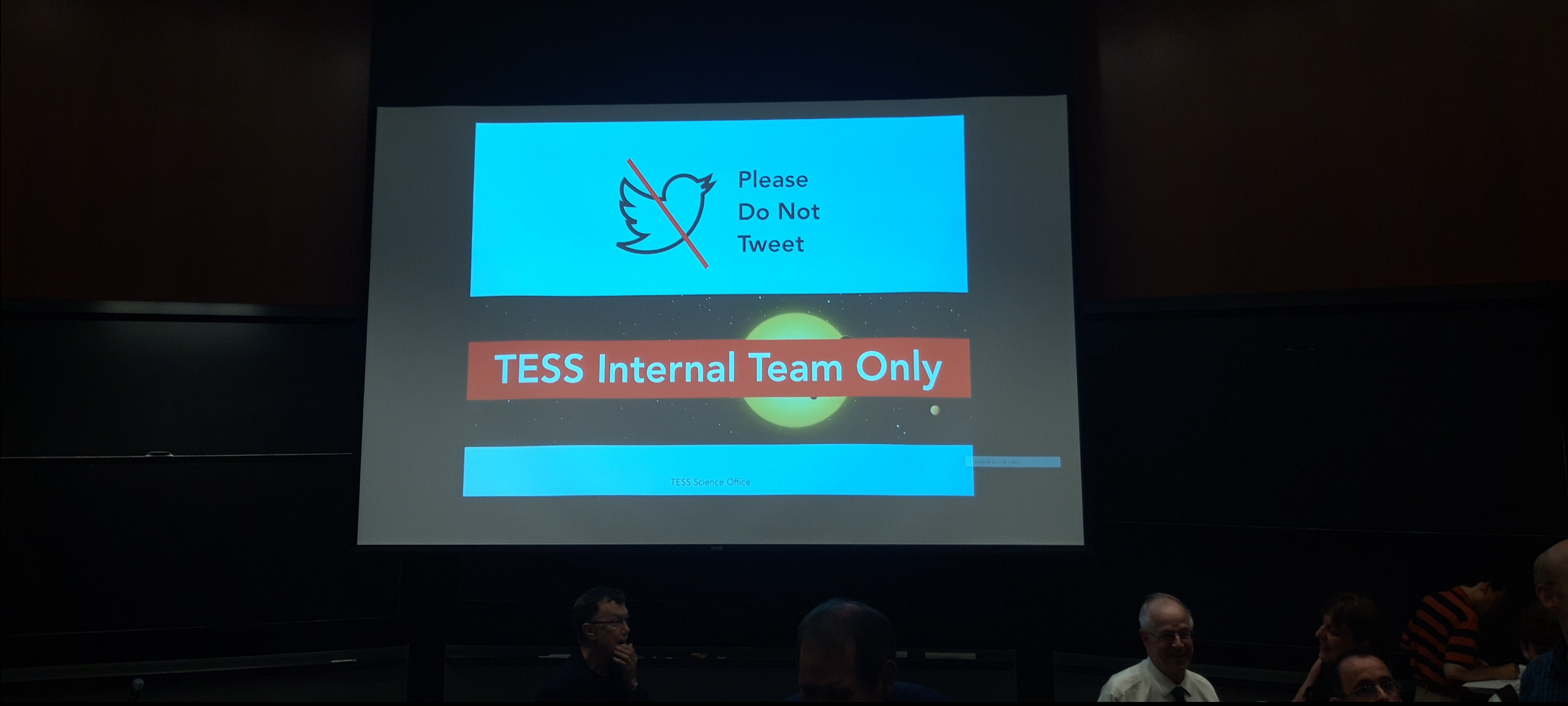
Since then ...





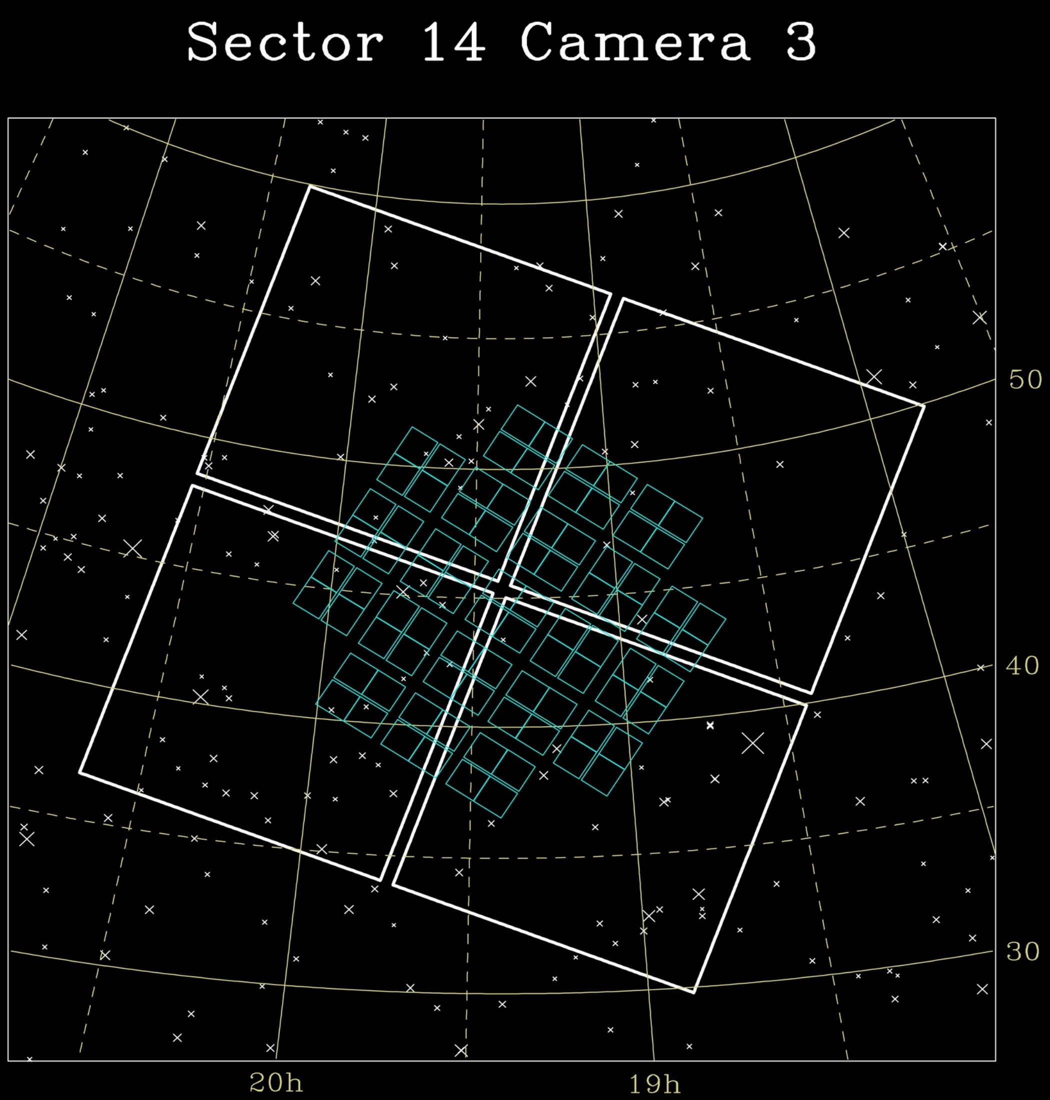
TESS has arrived

Since then ...



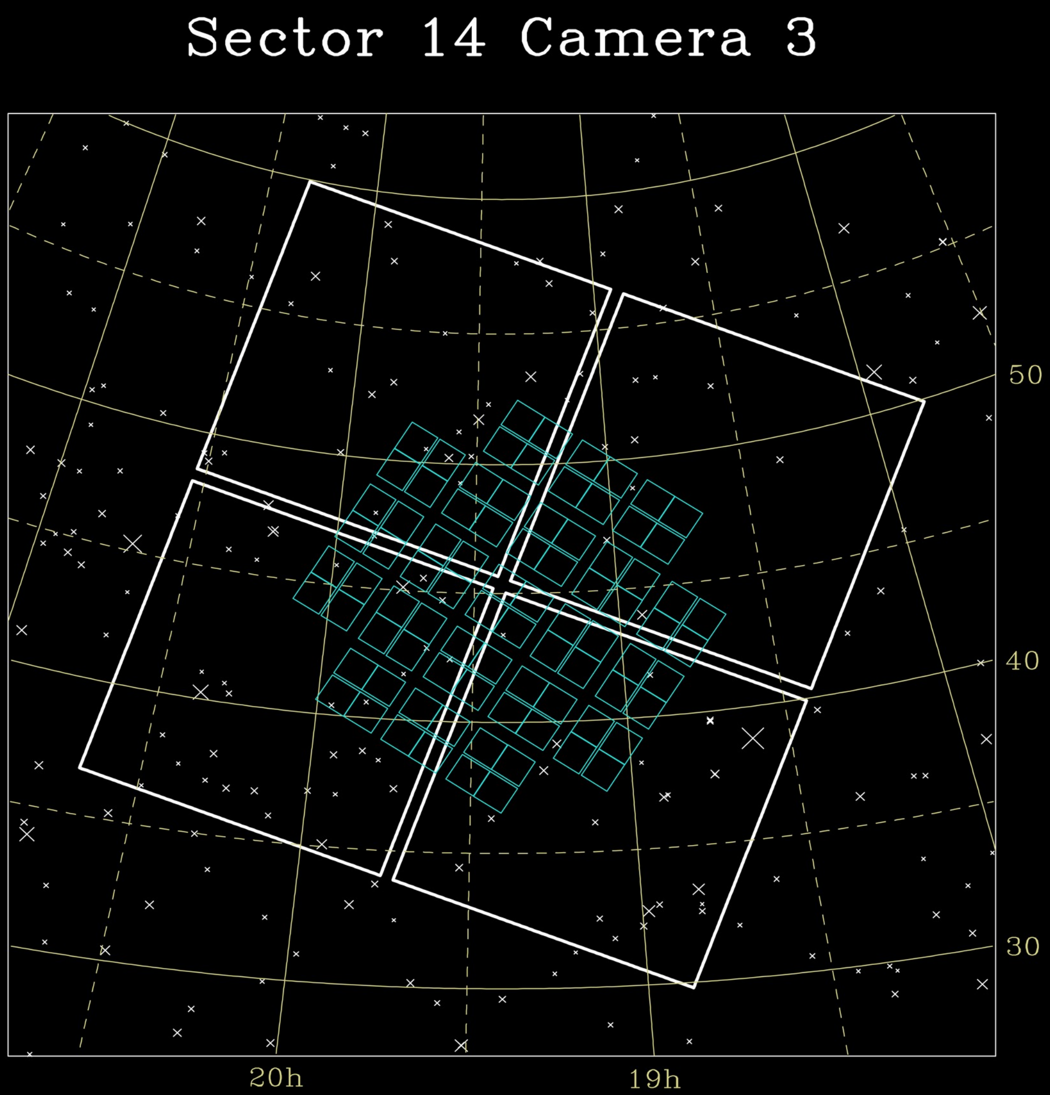
M.I.T. – 2018. 08. 06. 9:53

Since then ...



One more year ...

Since then ...



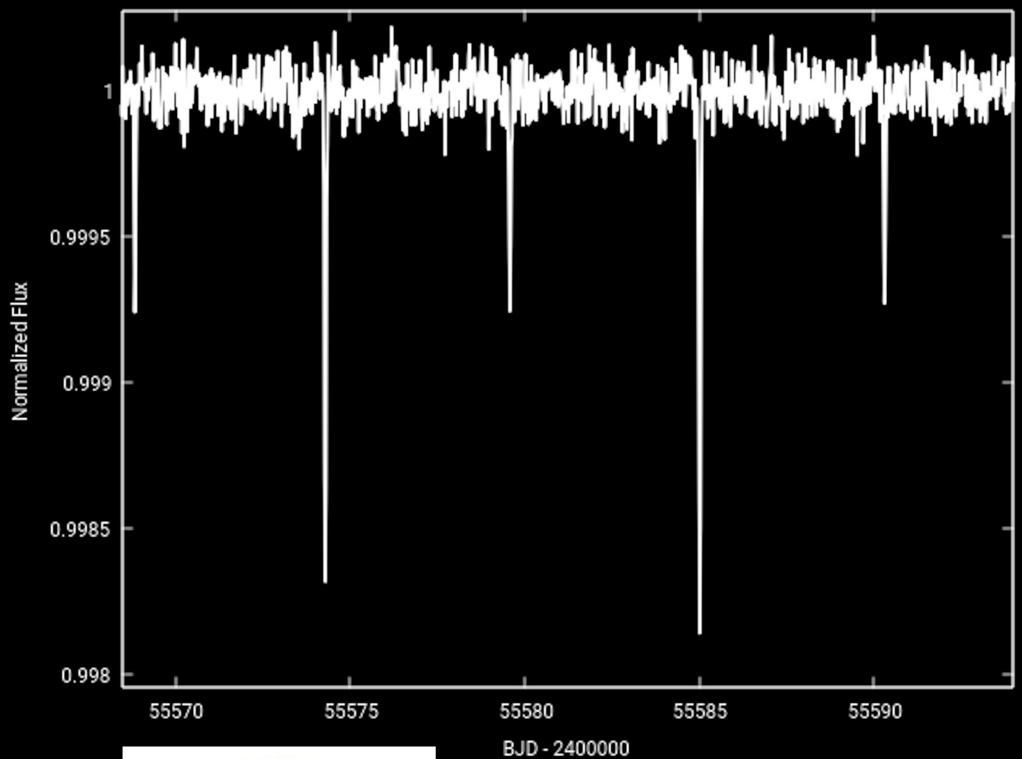
One more year ...

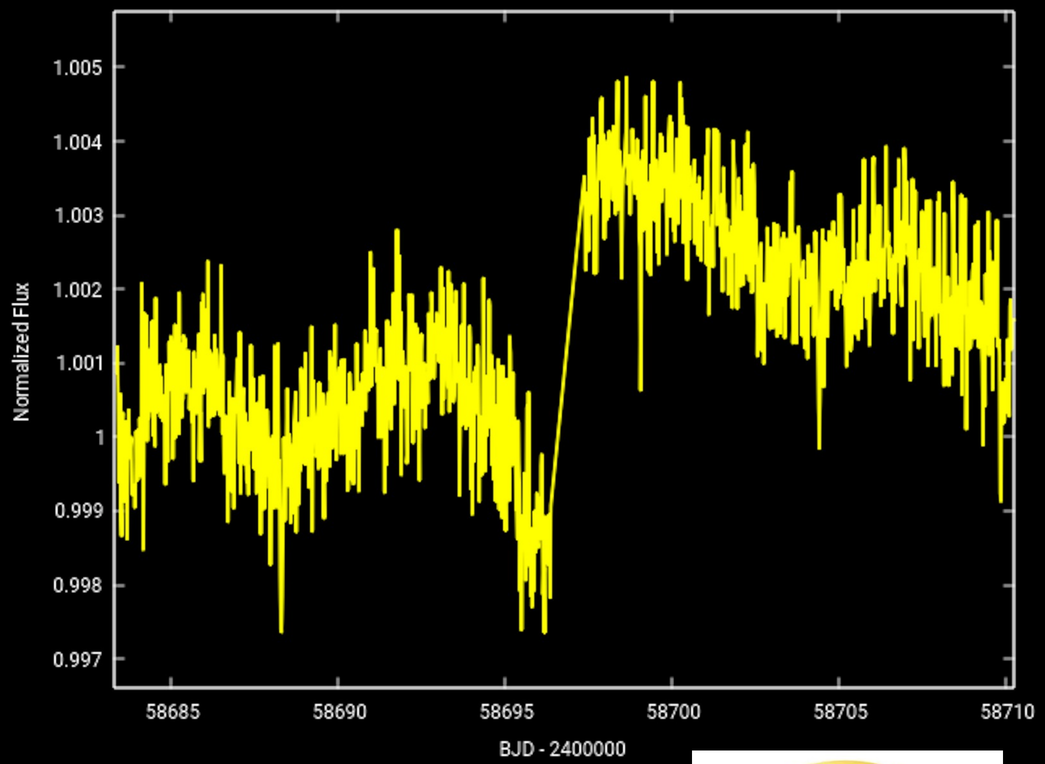
… and, summer
(of 2019) is coming!

Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

Since then ...





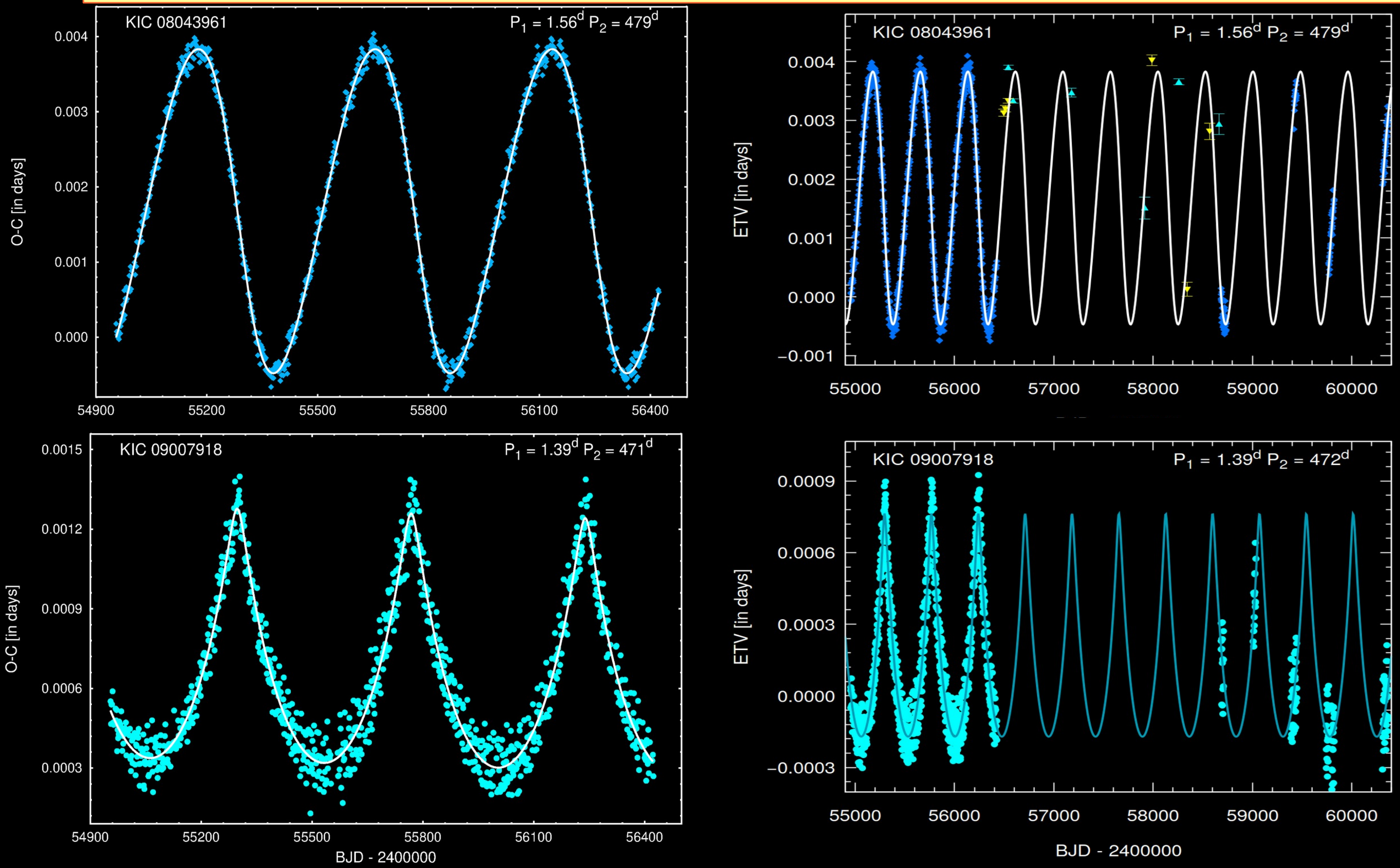
Then ...

... Now

Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

LTTE systems periods shorter than half of the prime Kepler mission



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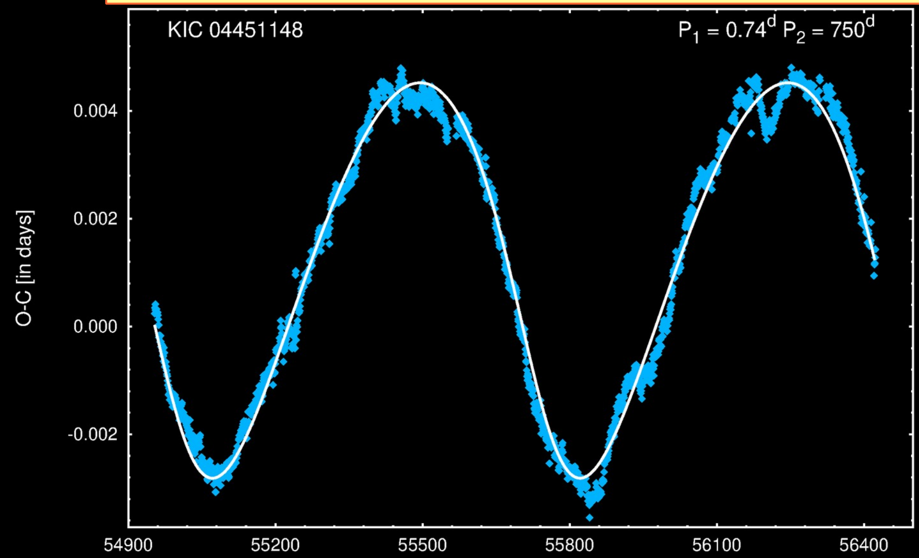
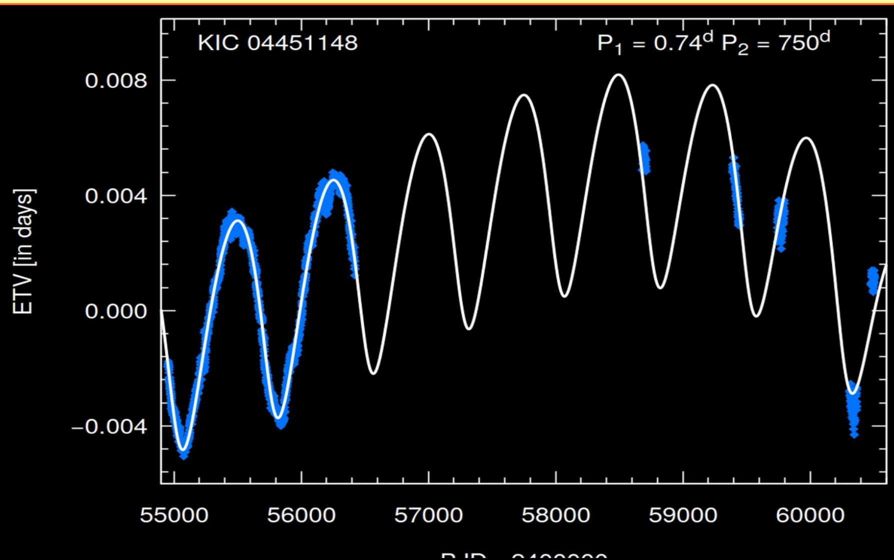
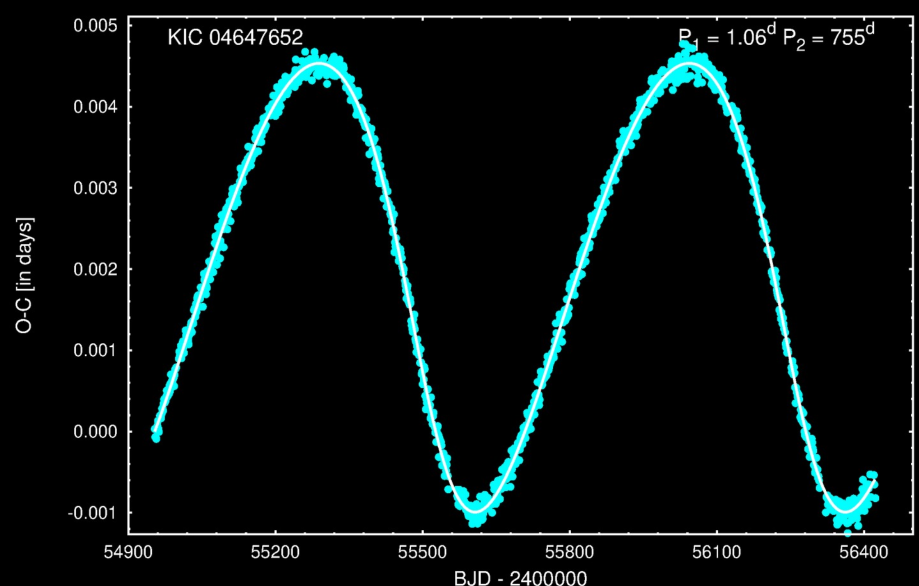
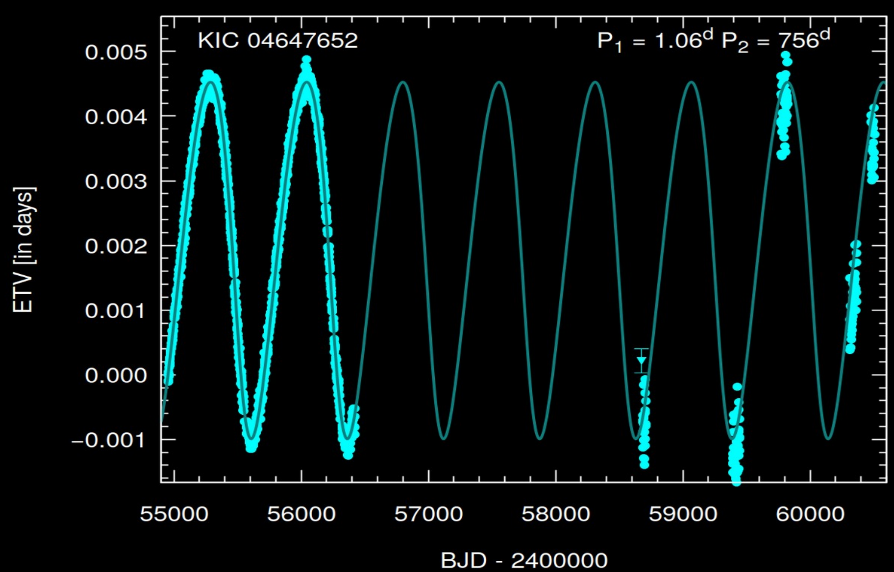
LTTE systems periods longer than half of the prime Kepler mission





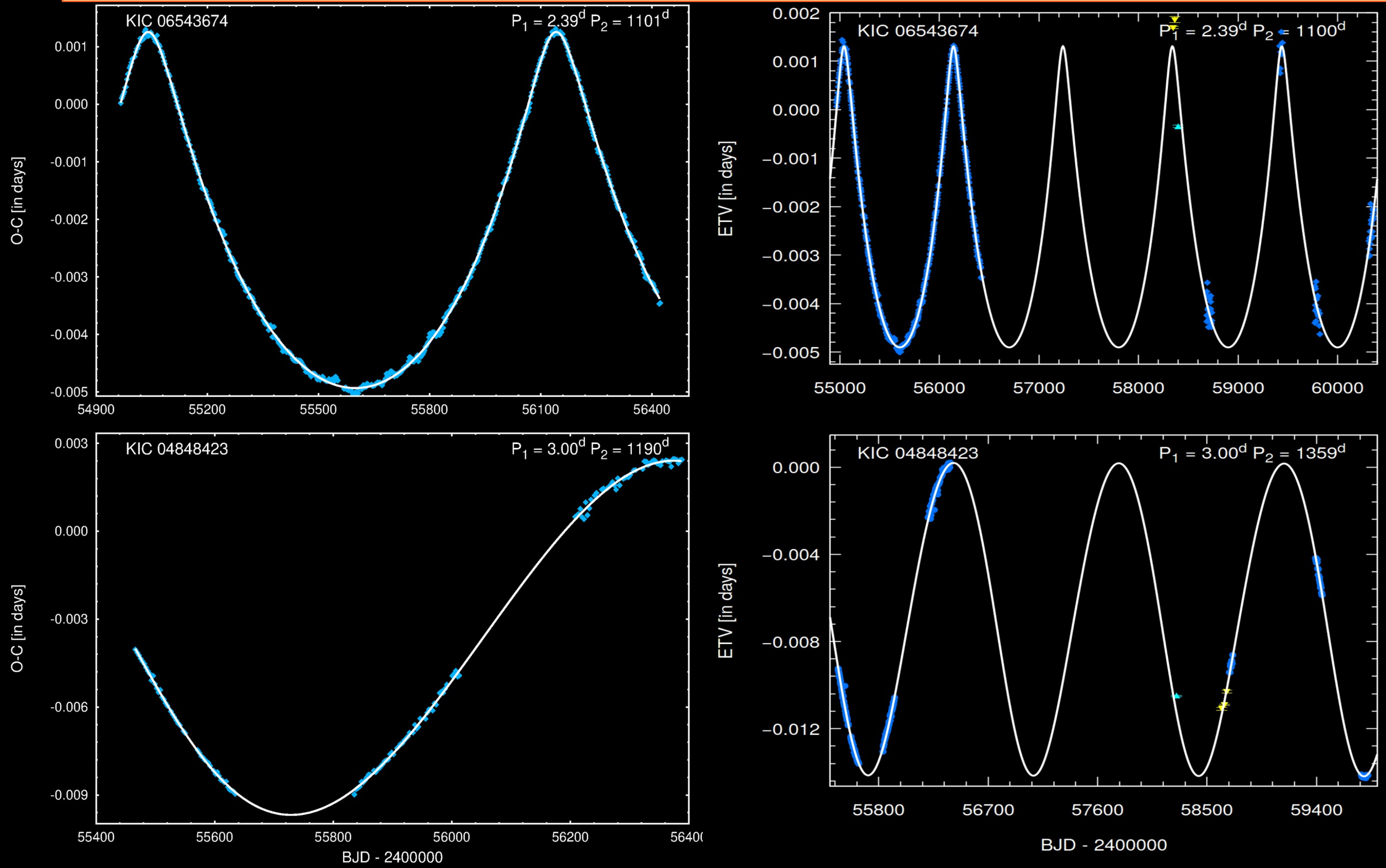




Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

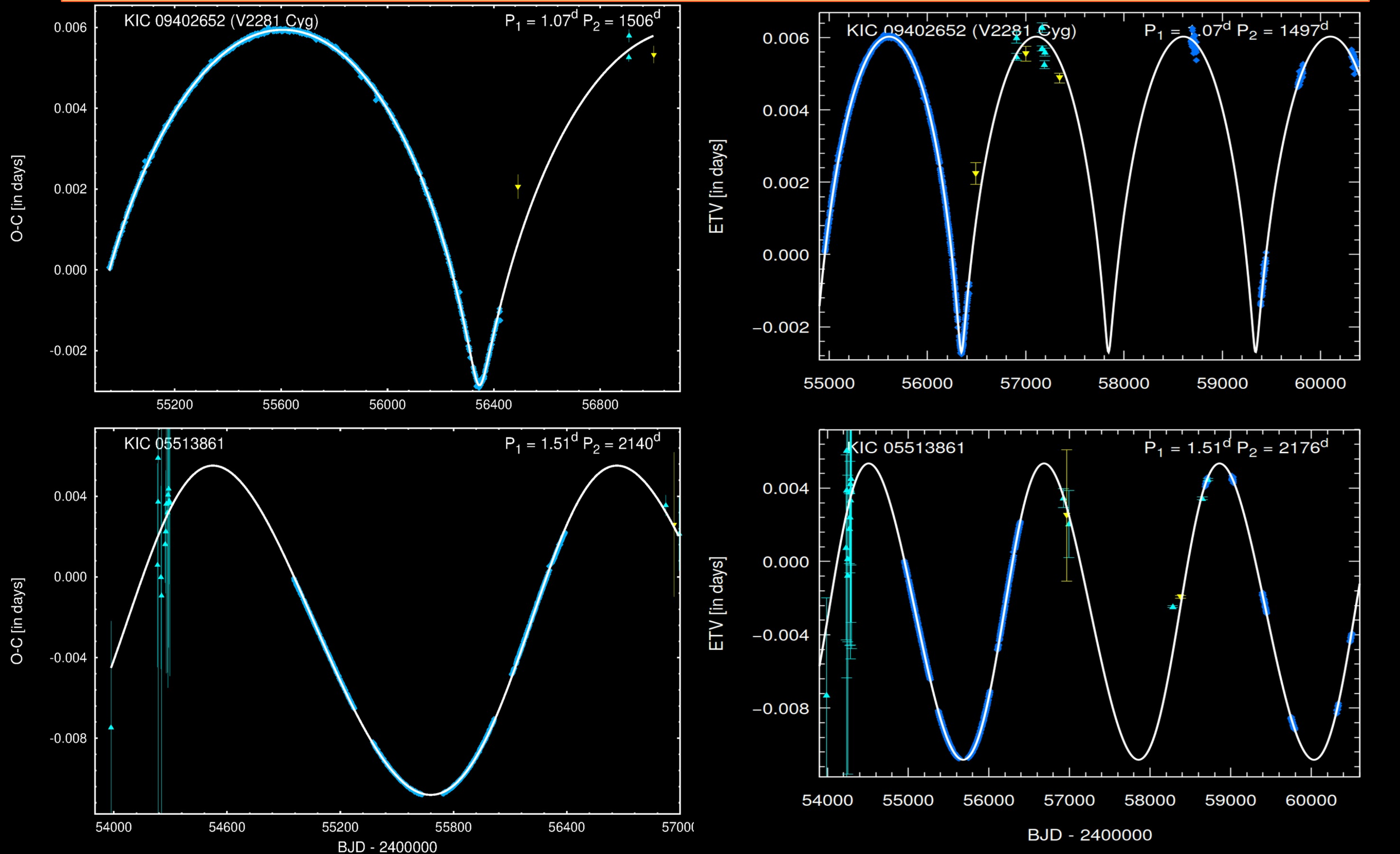
LTTE systems periods close to the length of the prime Kepler mission



Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

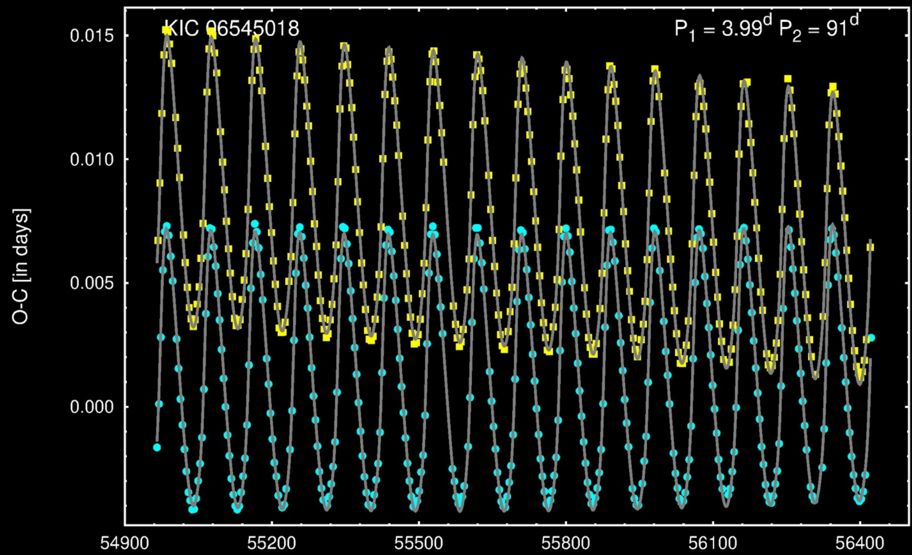
LTTE systems periods longer than the length of the prime Kepler mission

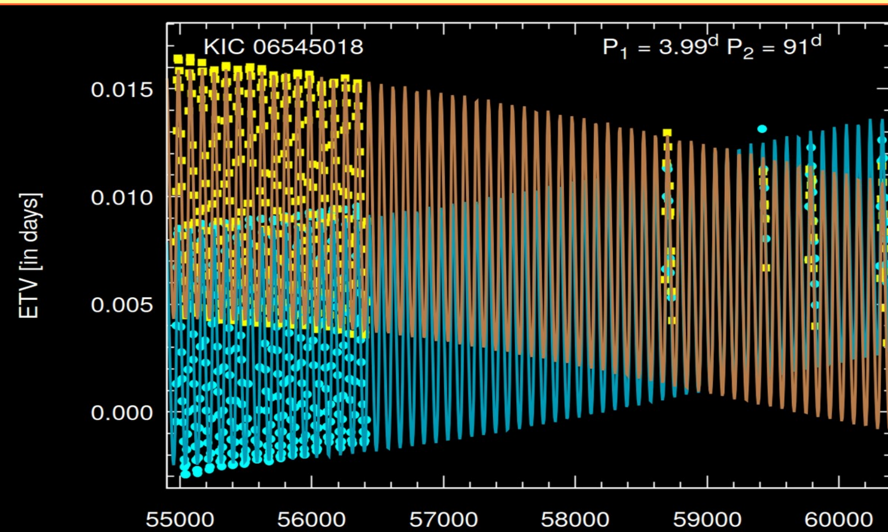


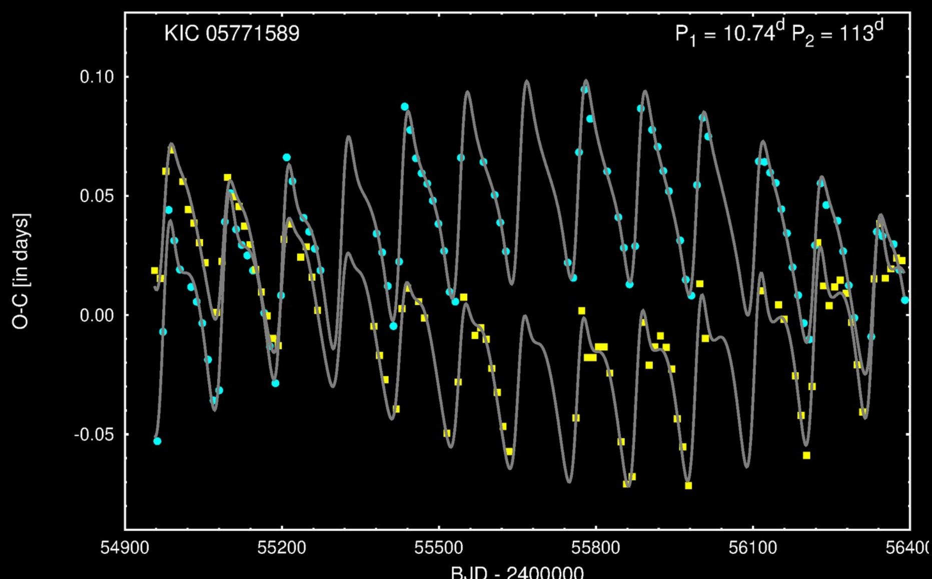
Tamás Borkovits – Then and now:

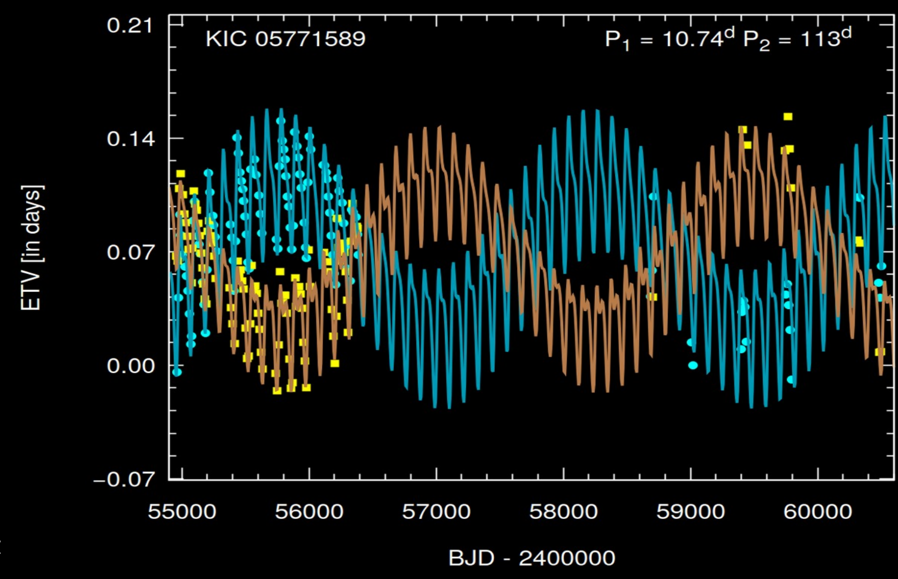
Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

Extreme tight and compact systems – HARDCORE triples





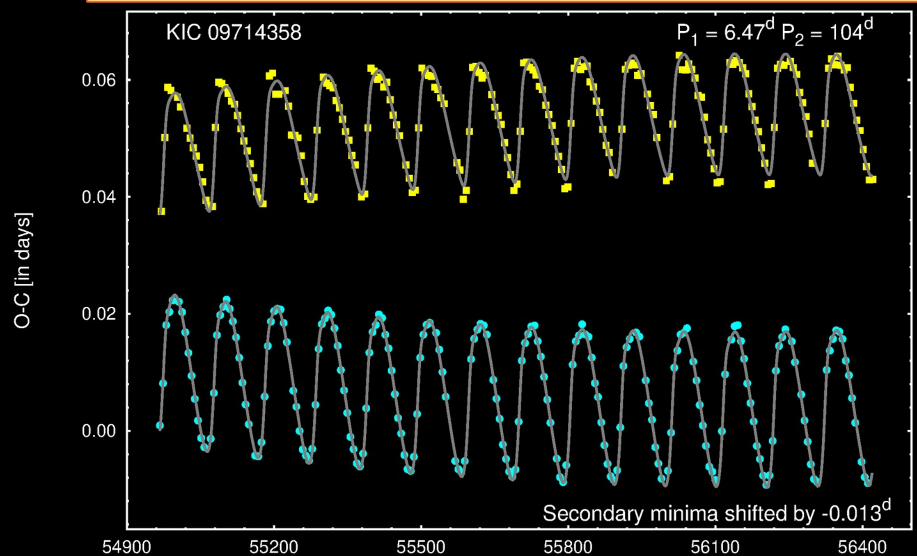


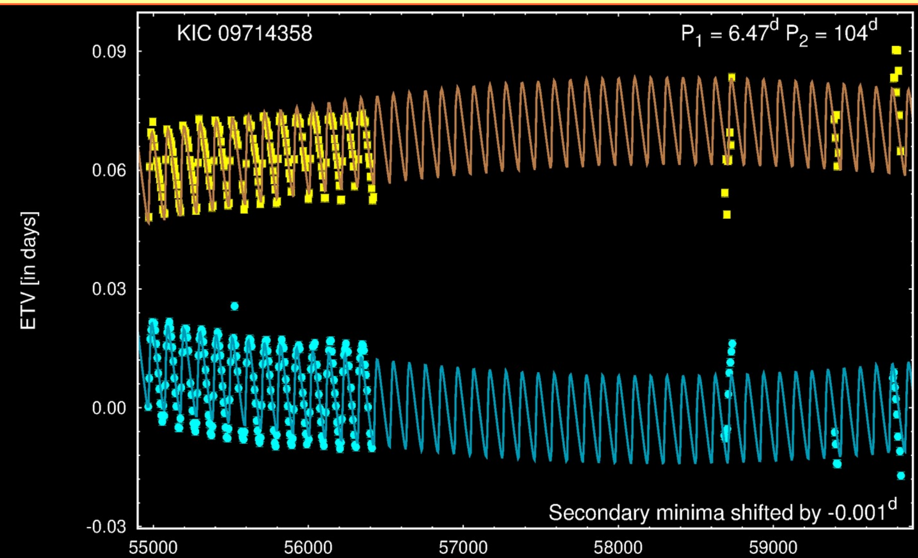


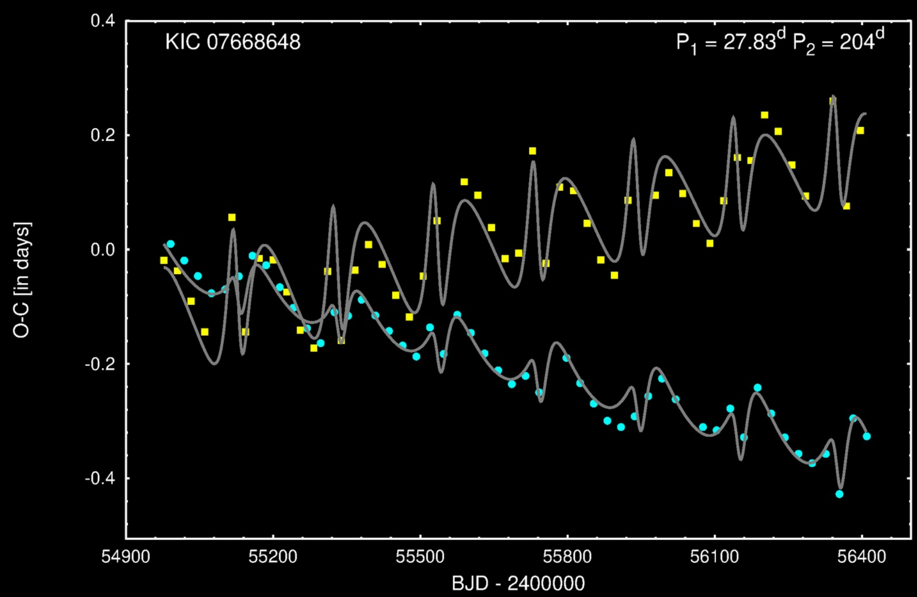
Tamás Borkovits – Then and now:

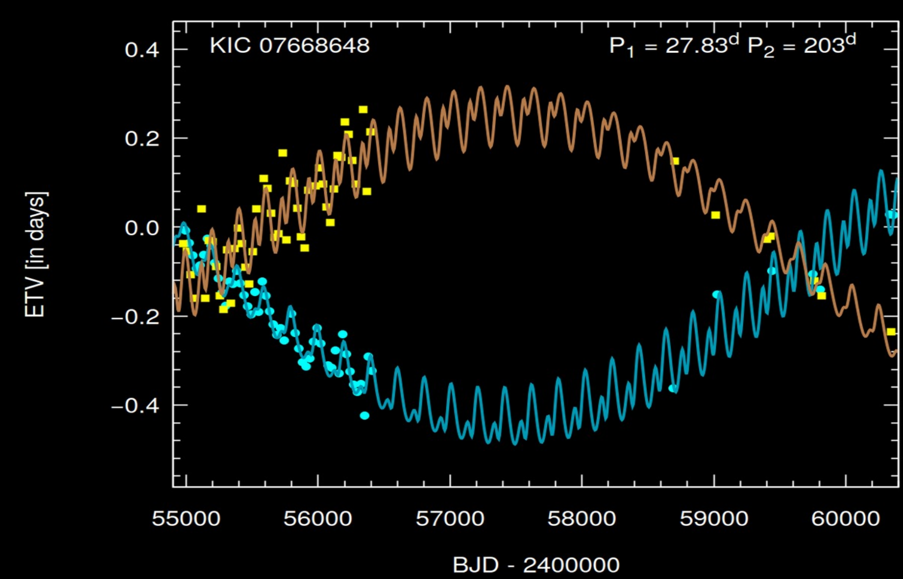
Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

Extreme tight and compact systems – HARDCORE triples





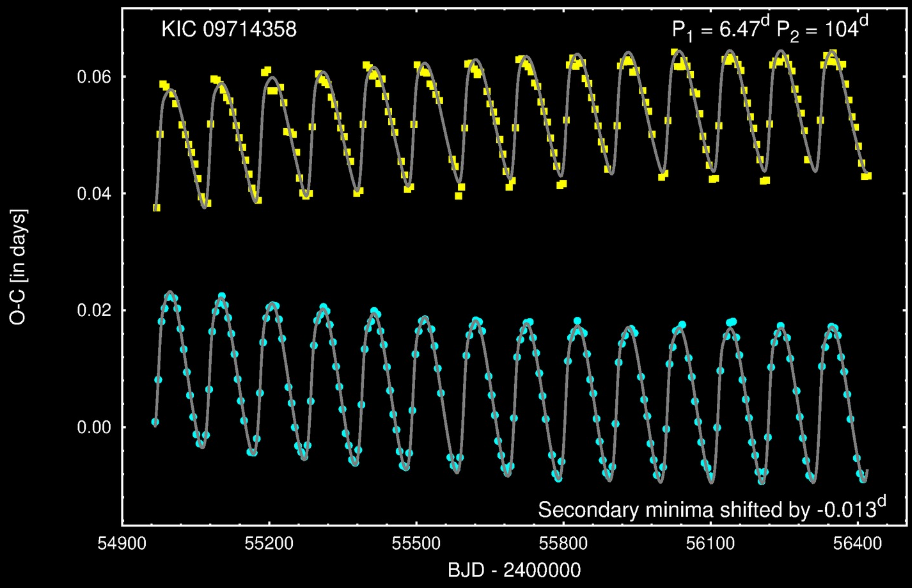


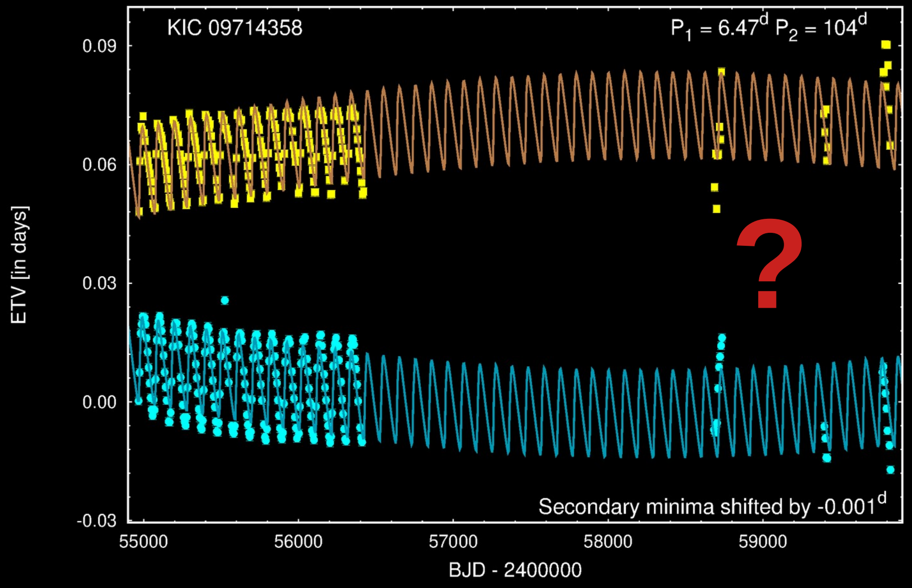


Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

Extreme tight and compact systems – HARDCORE triples

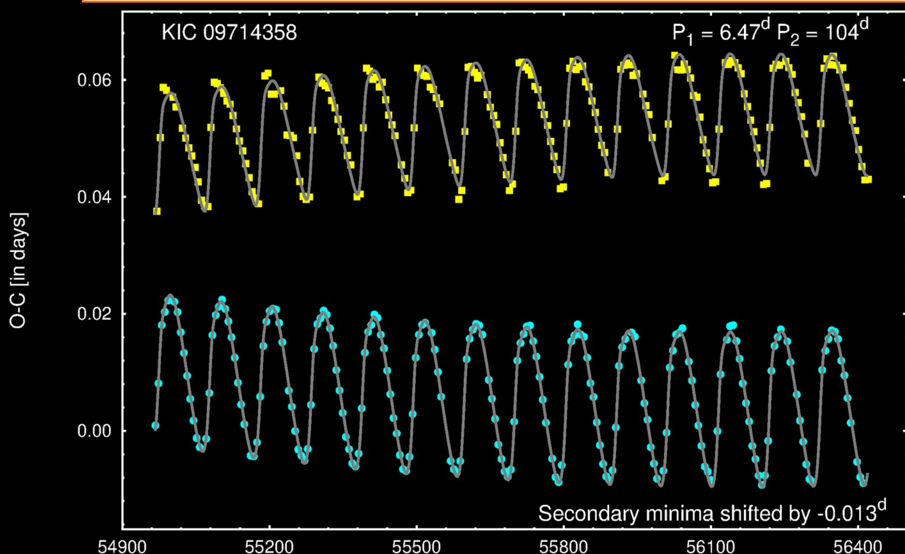


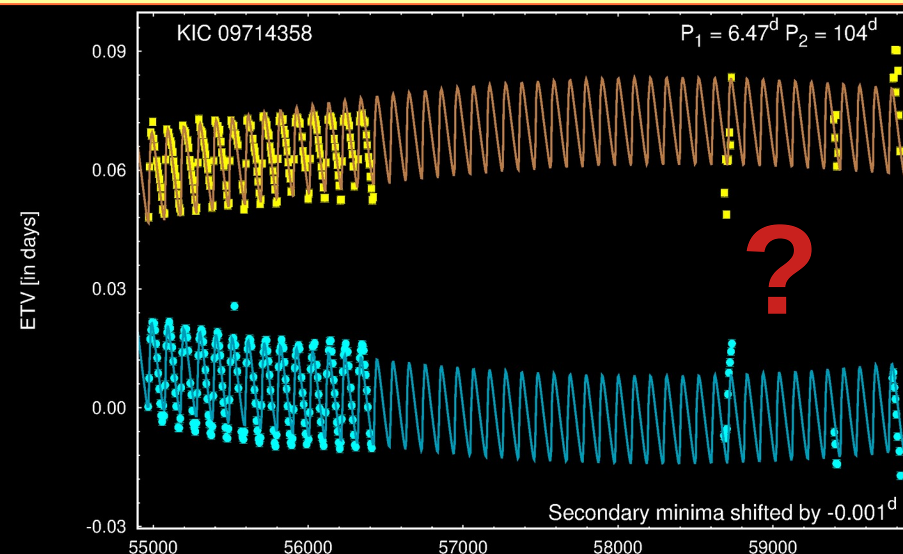


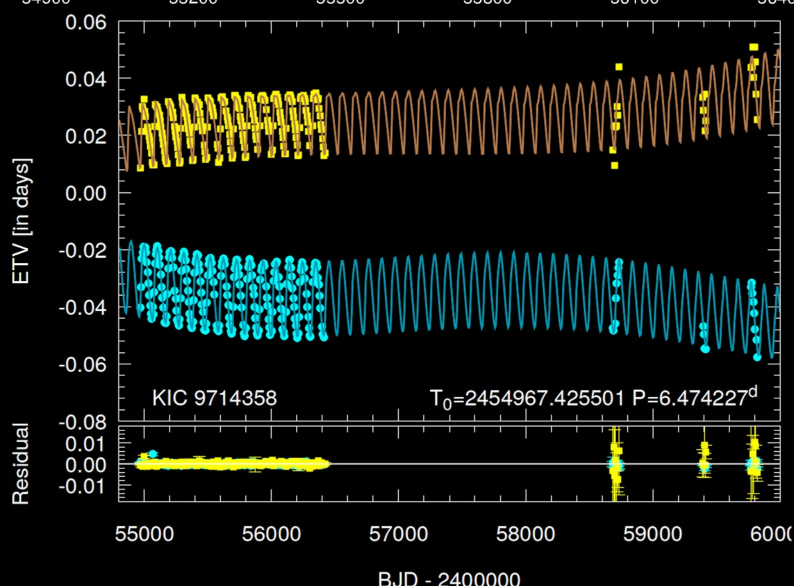
Tamás Borkovits – Then and now:

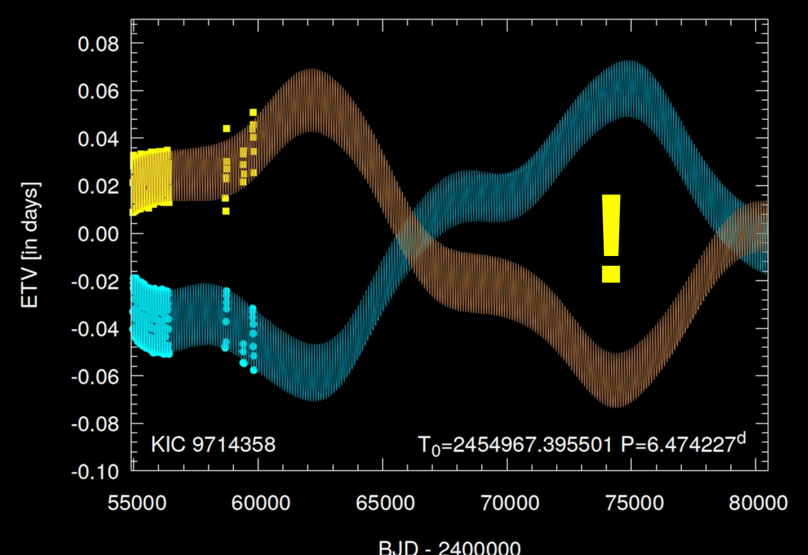
Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

Extreme tight and compact systems – HARDCORE triples

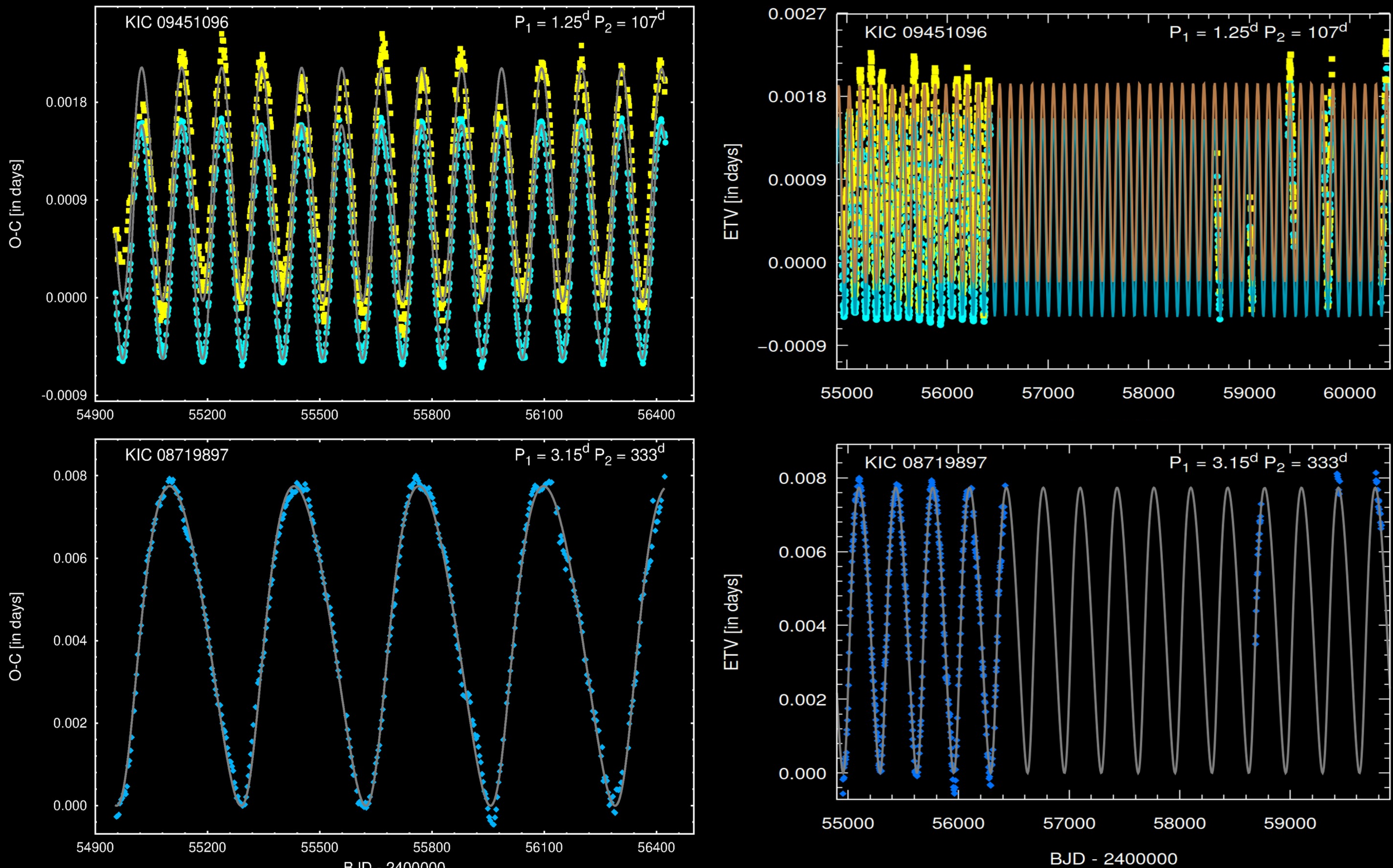








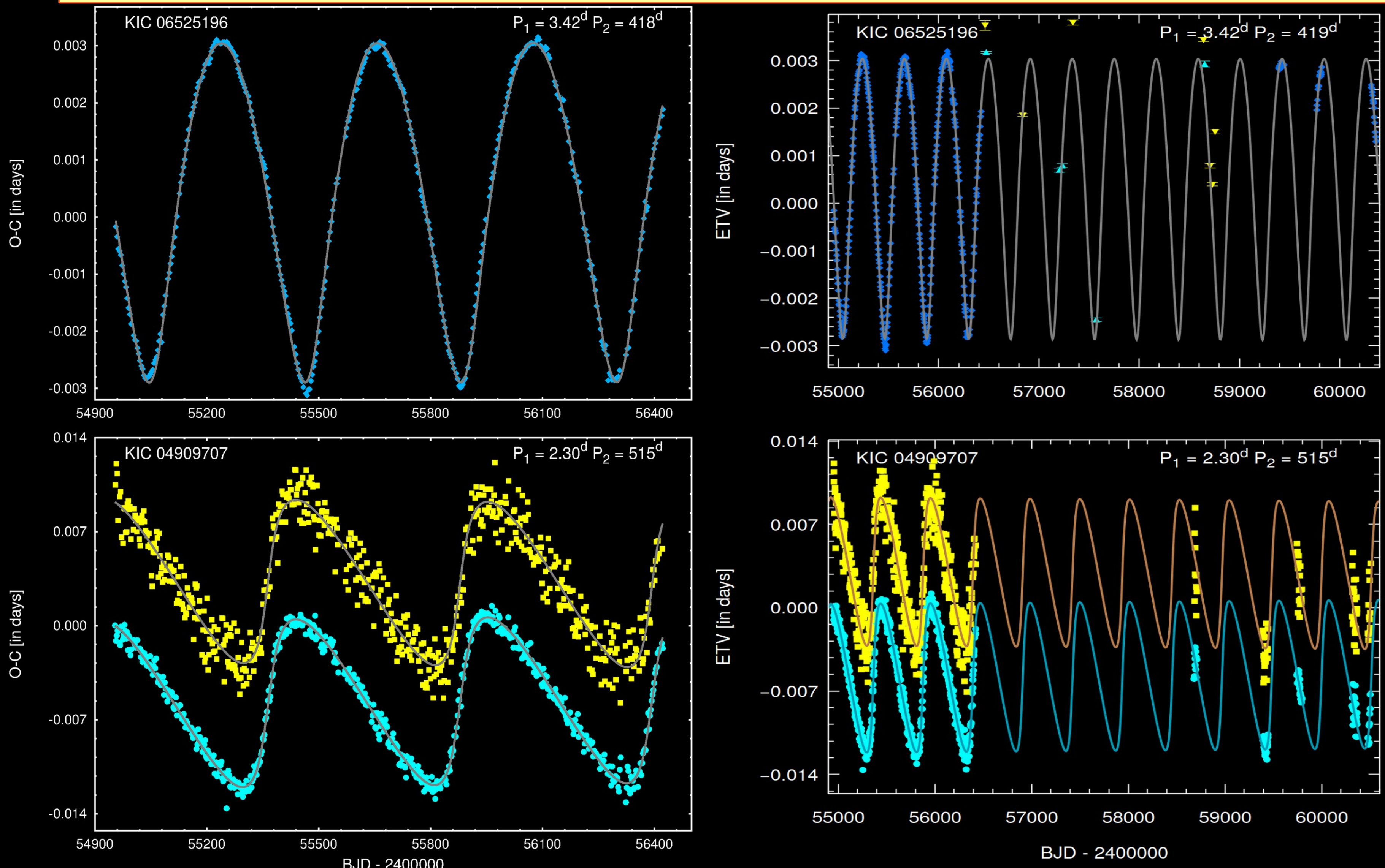
Not so tight, but compact systems



Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

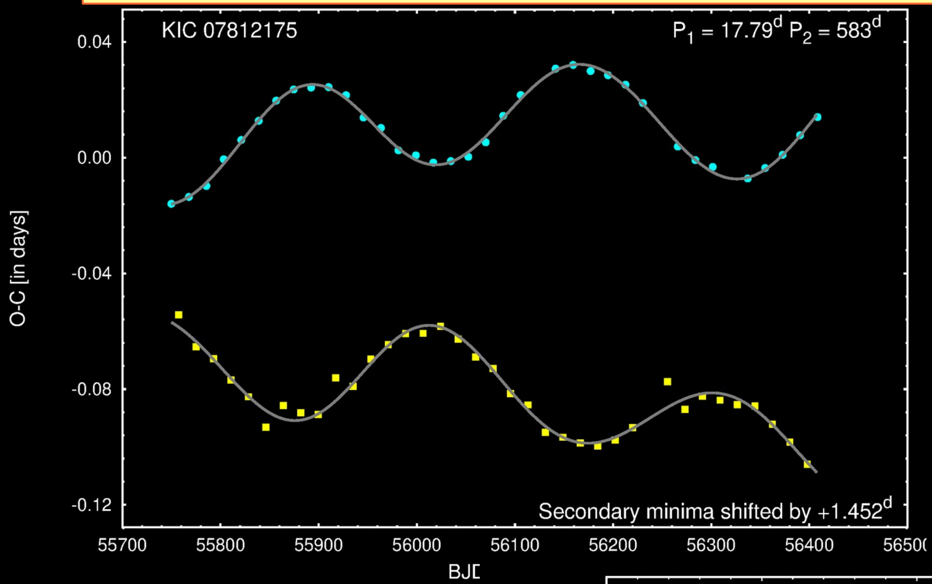
Further short-period triples with 3-rd body perturbations

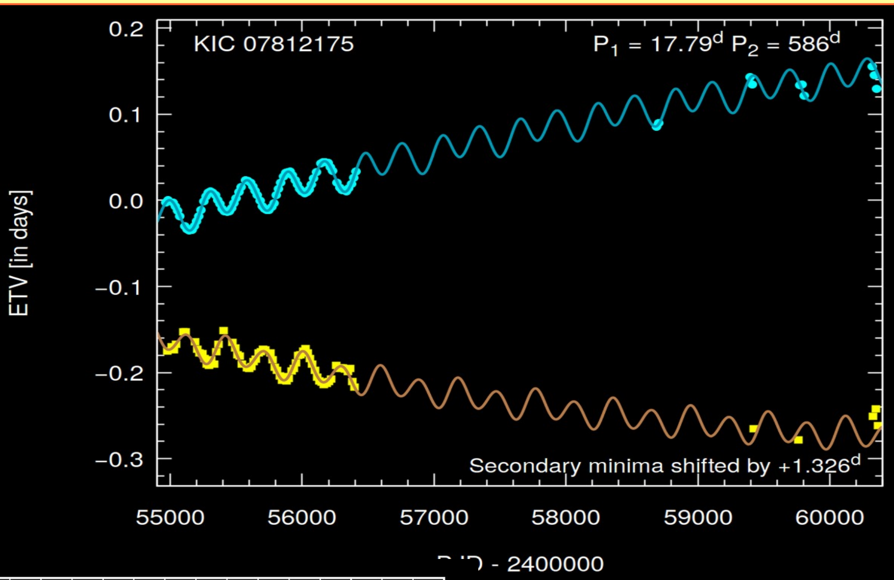


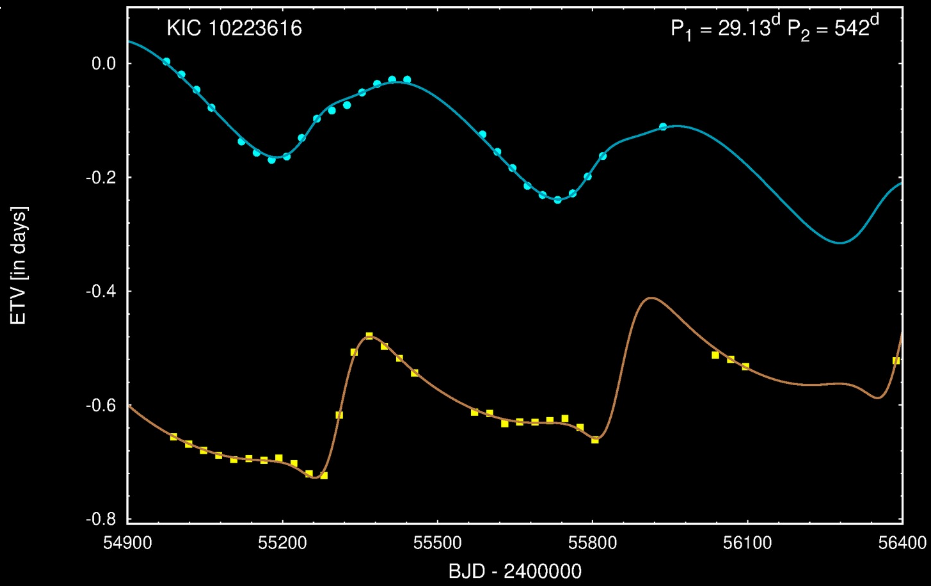
Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

Further shorter period triples with 3-rd body perturbations







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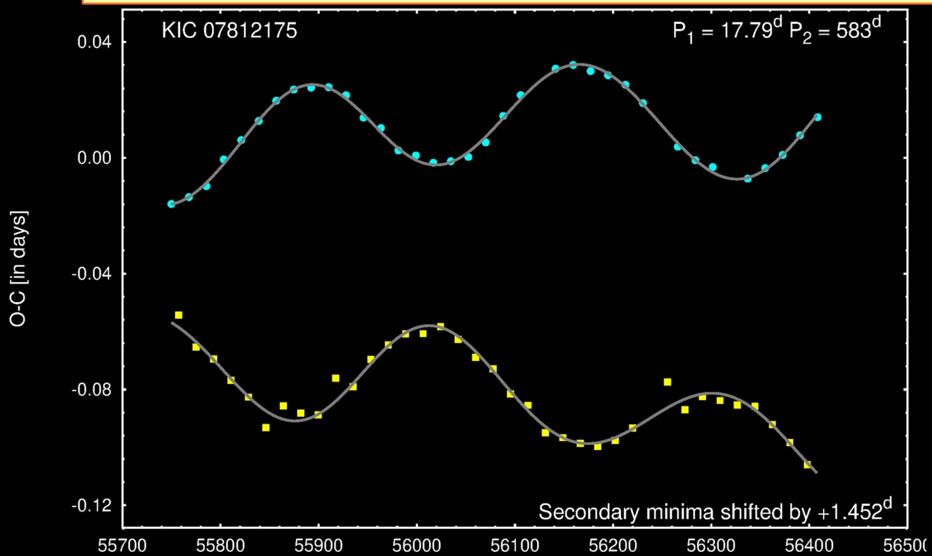
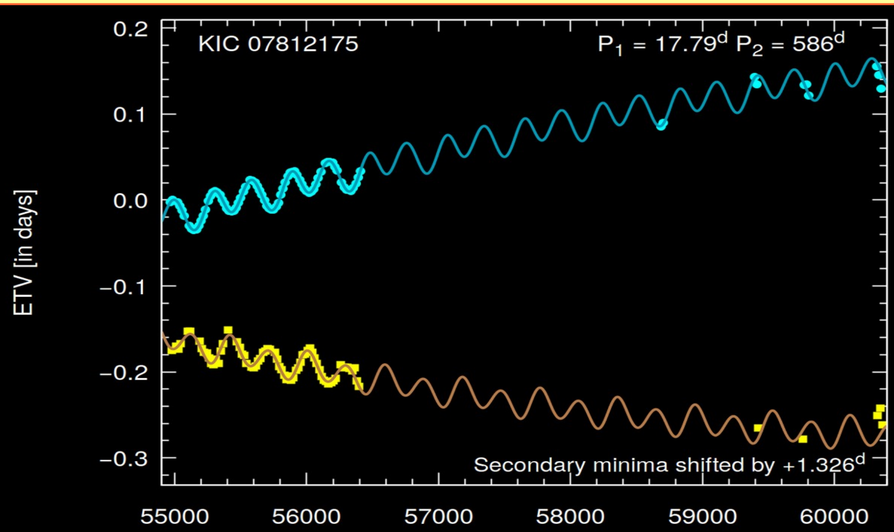
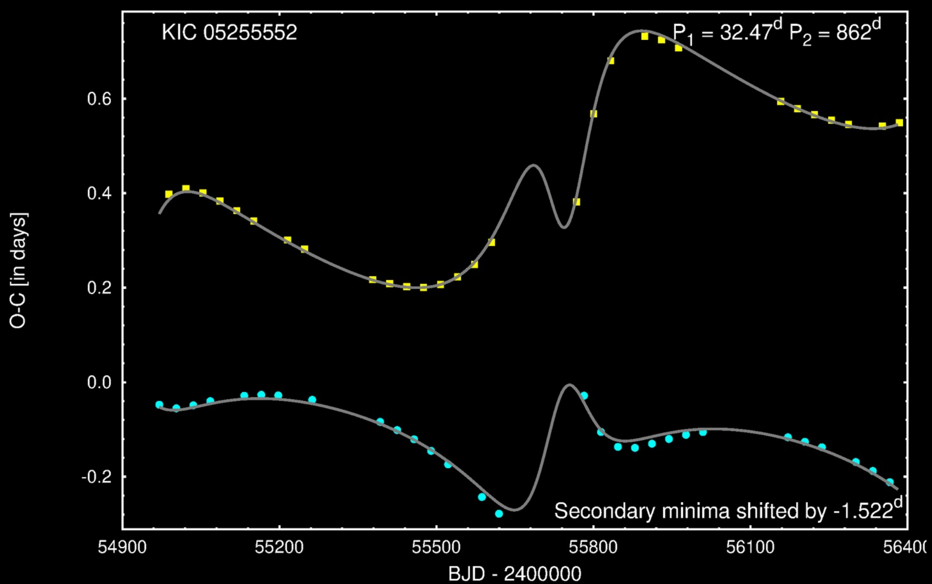
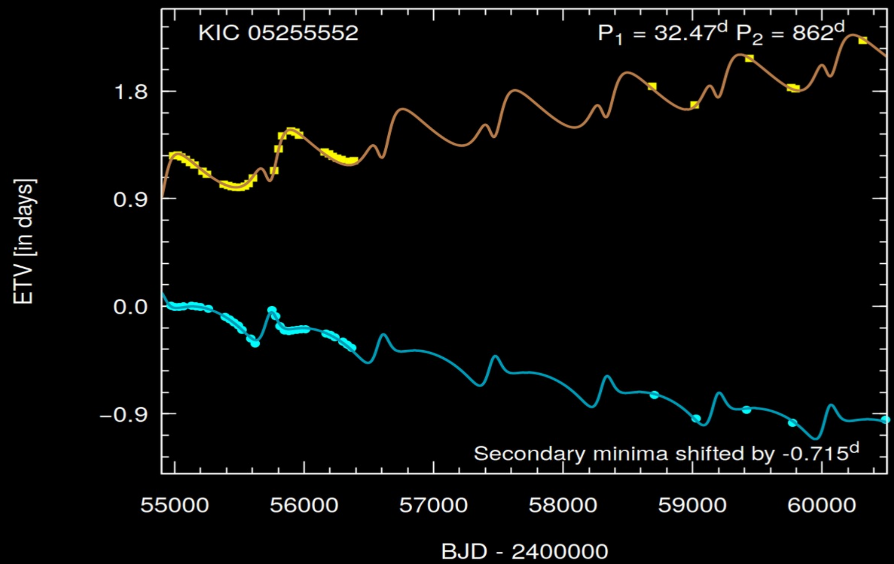
Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

Further shorter period triples with 3-rd body perturbations





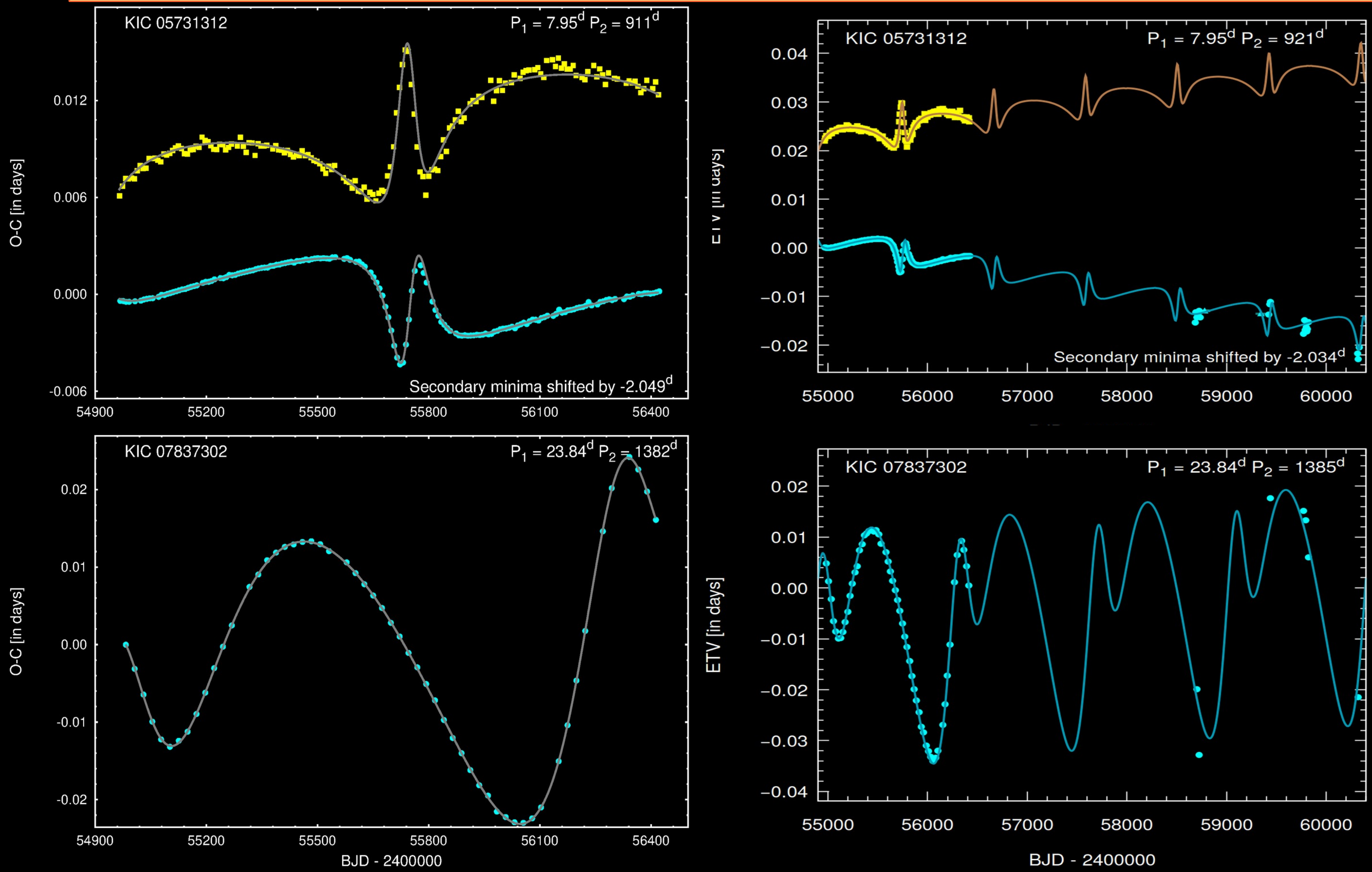




Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

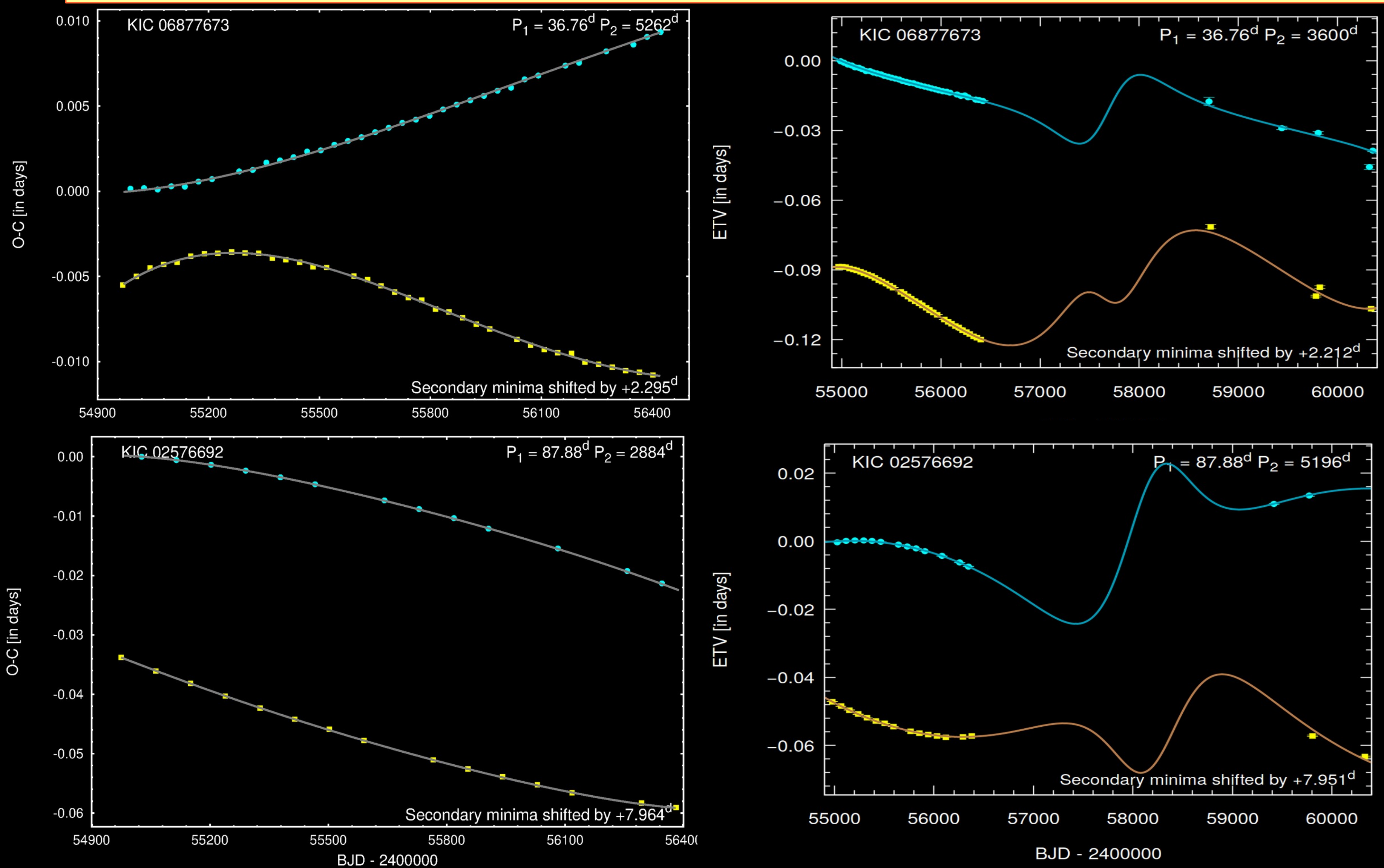
Longer period triples with 3-rd body perturbations



Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

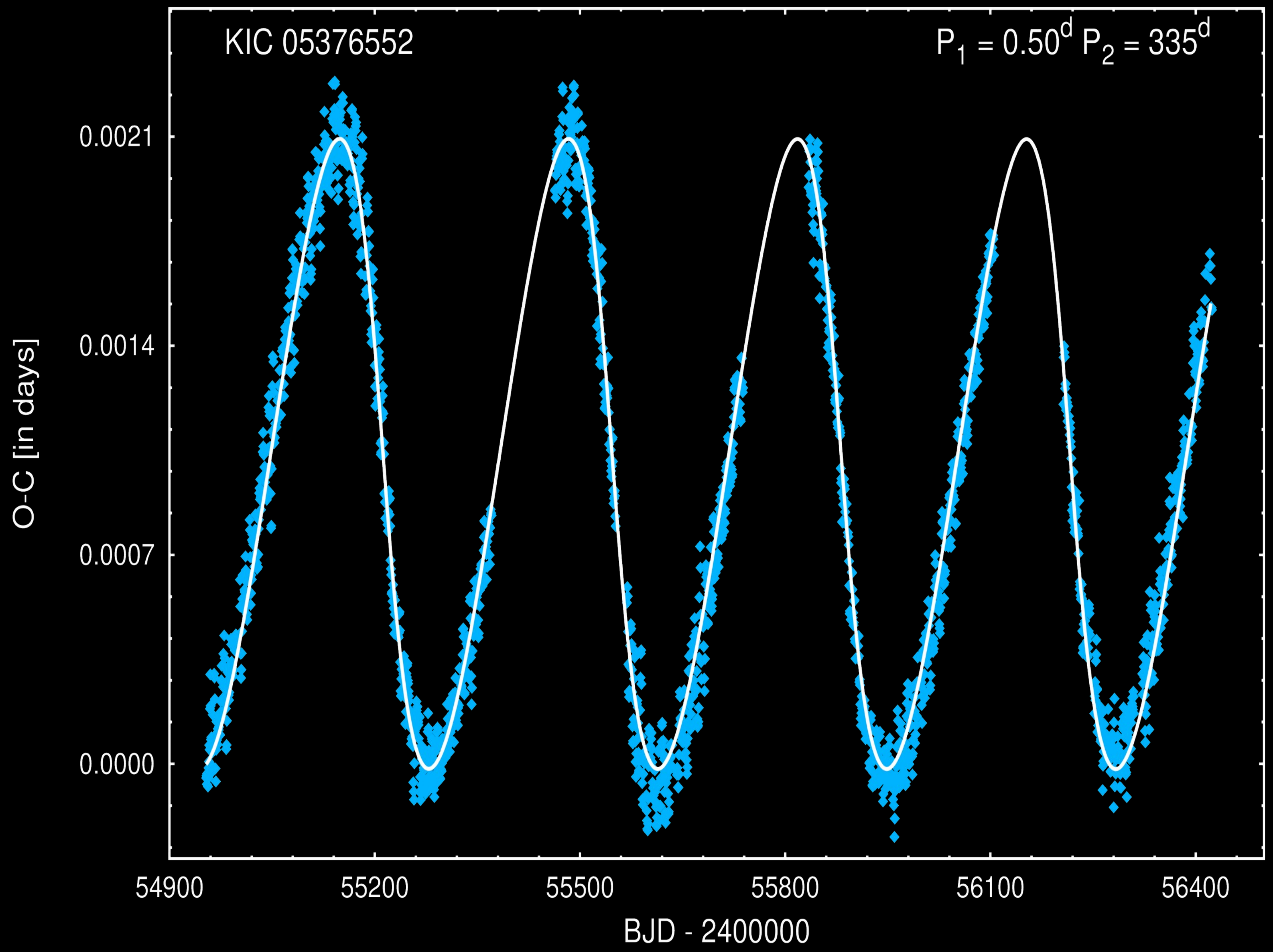
Longer period triples with 3-rd body perturbations (category: JOKE)



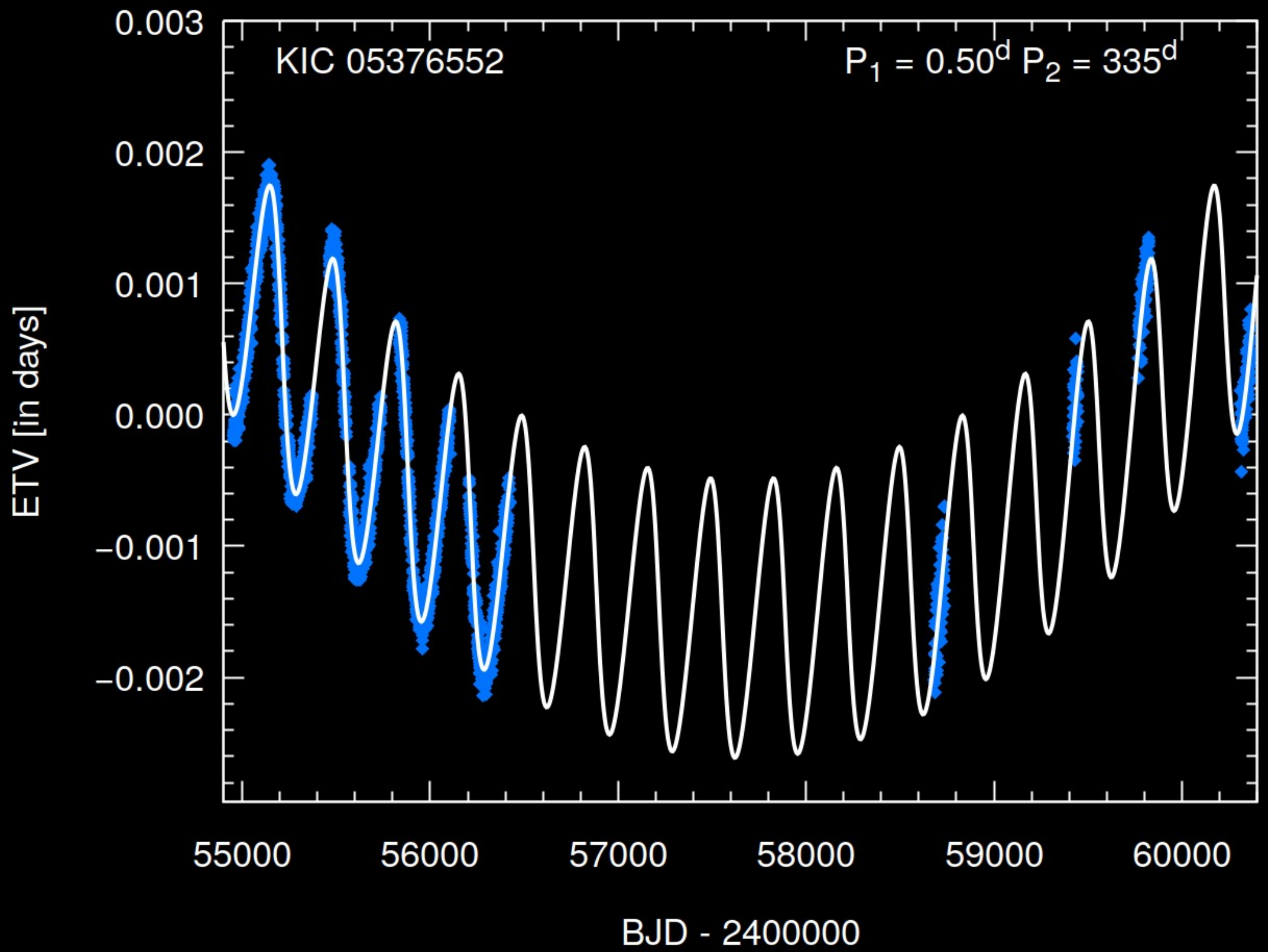
Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

Other funny ETVs



Other funny ETVs



Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

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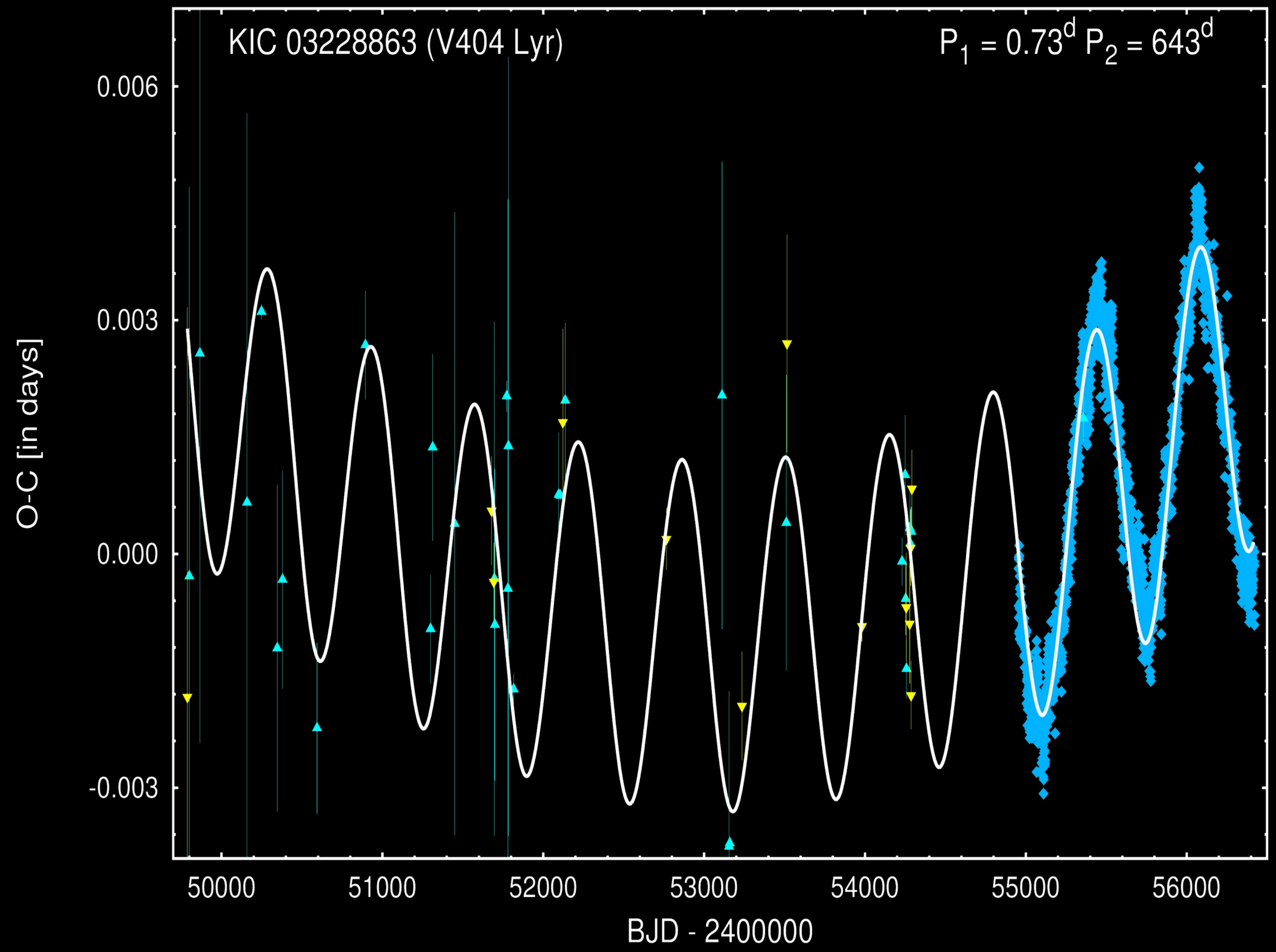
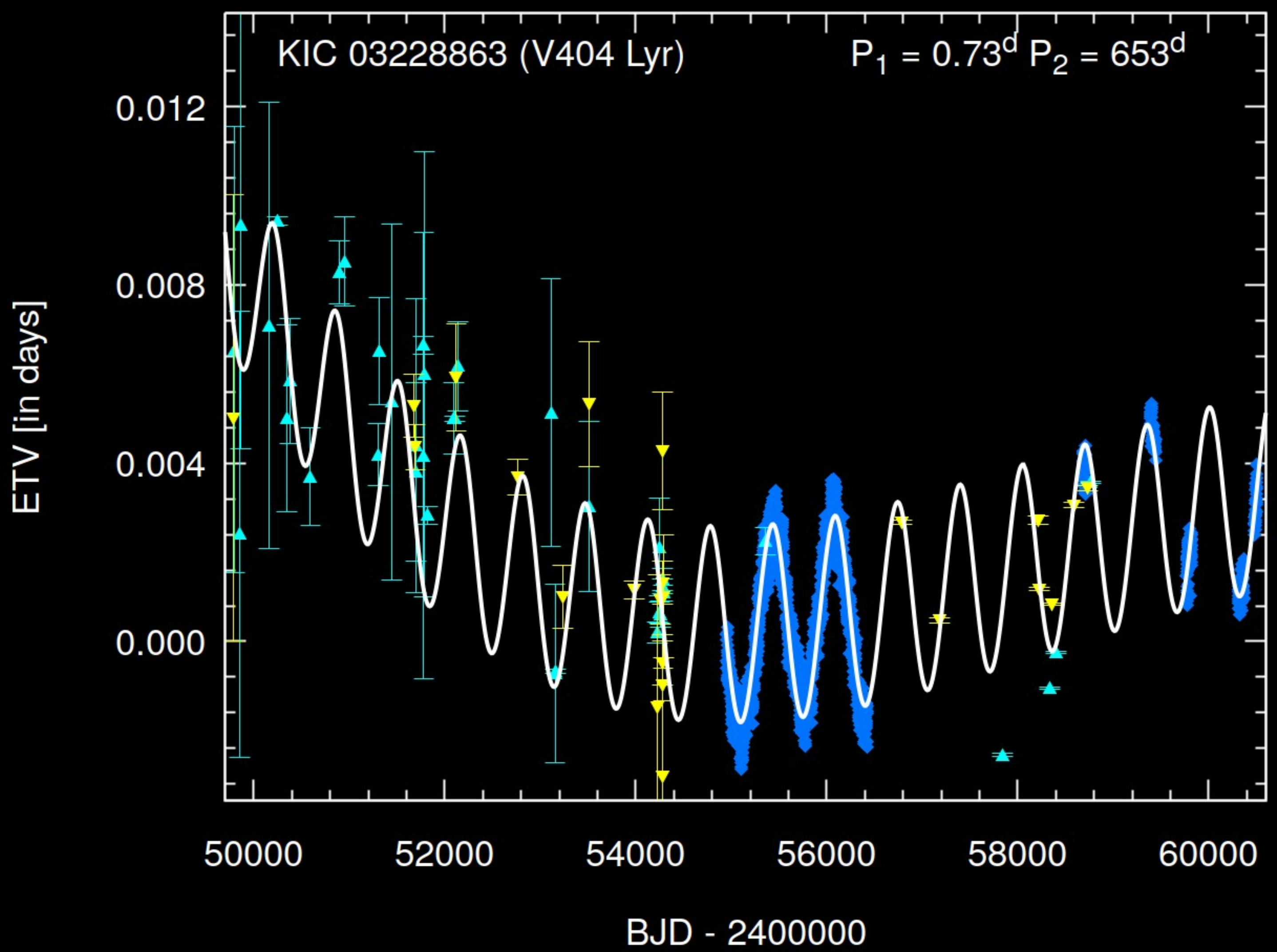


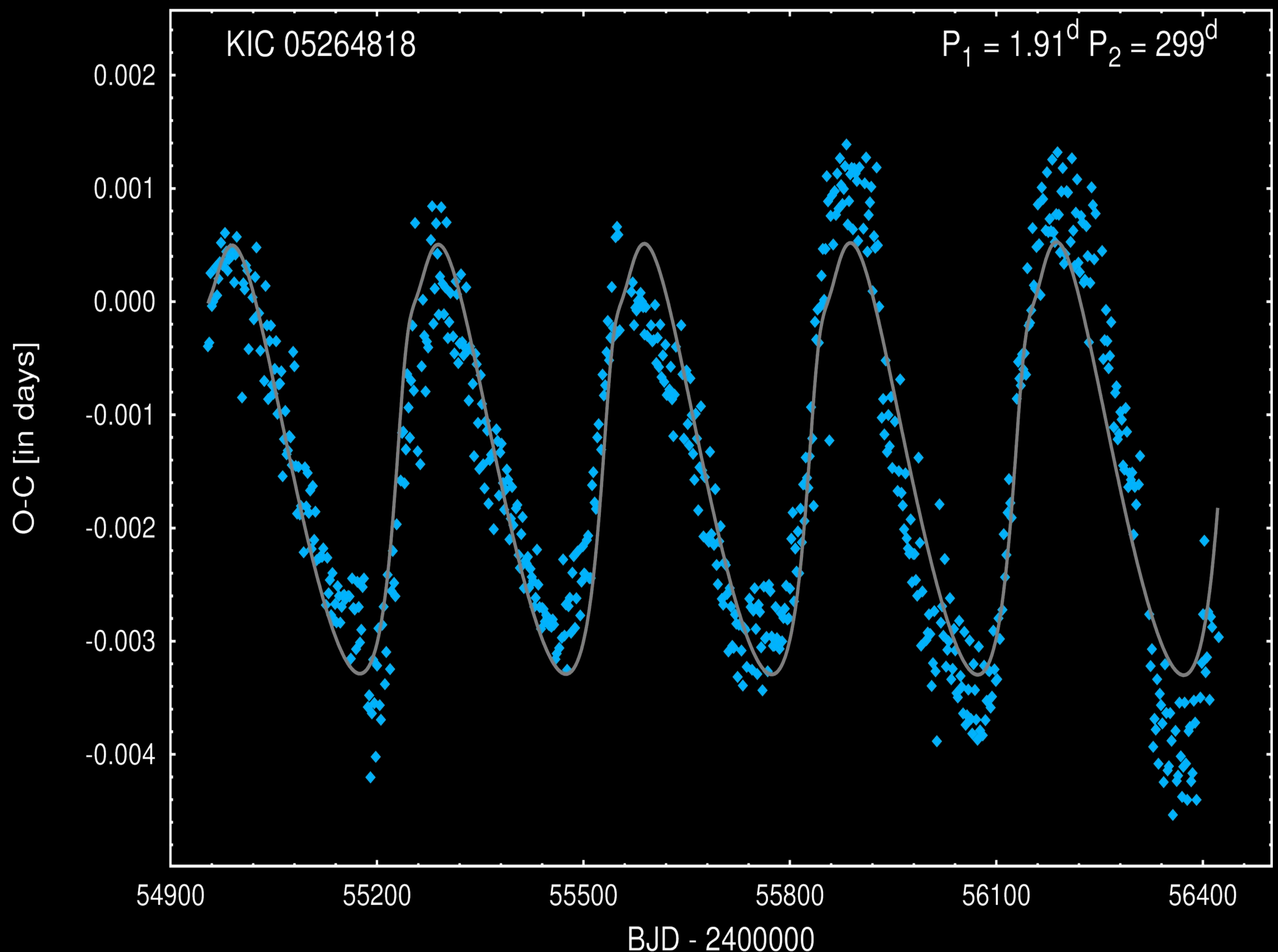
Other funny ETVs



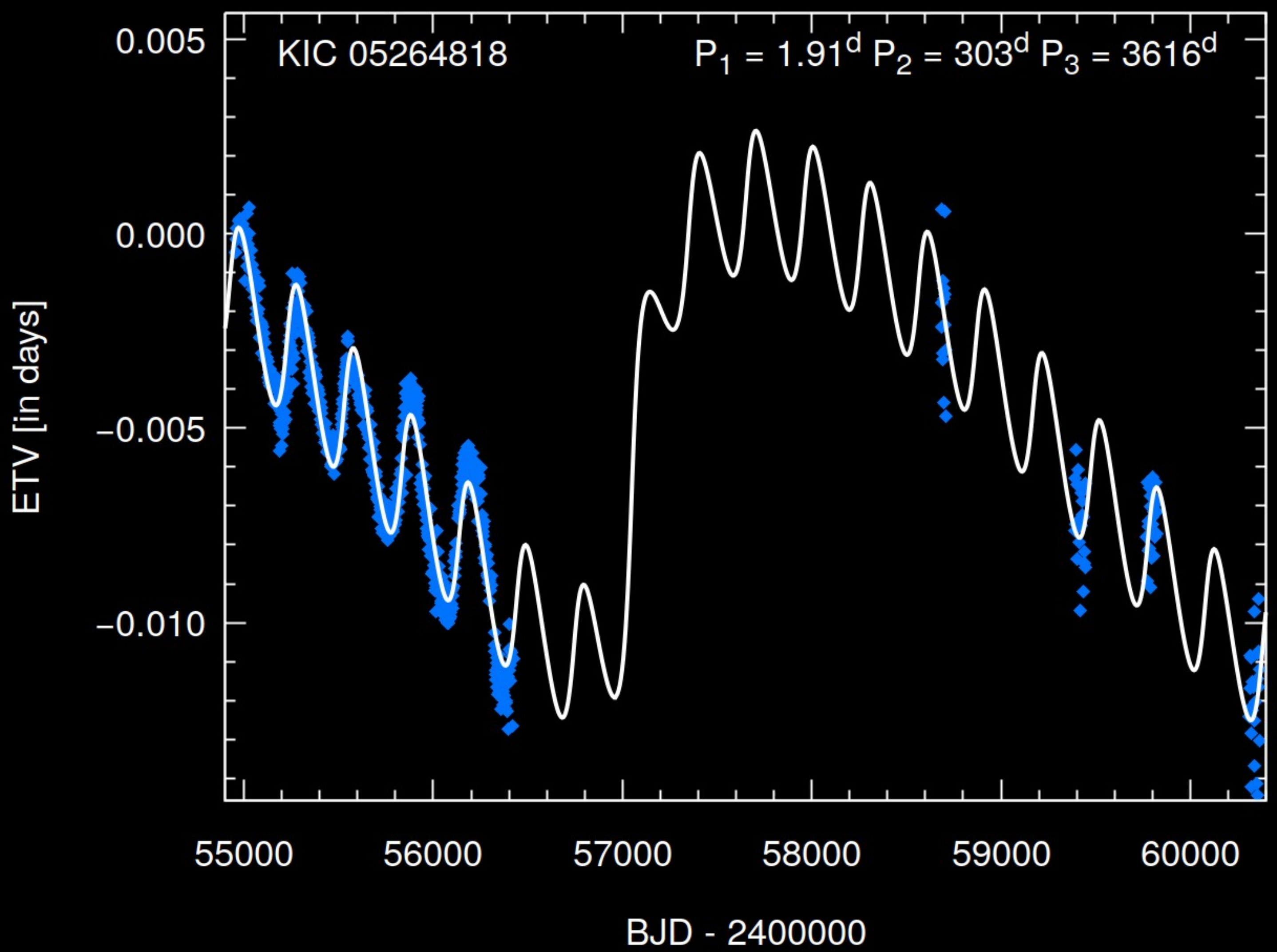
Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

Other funny ETVs



Other funny ETVs



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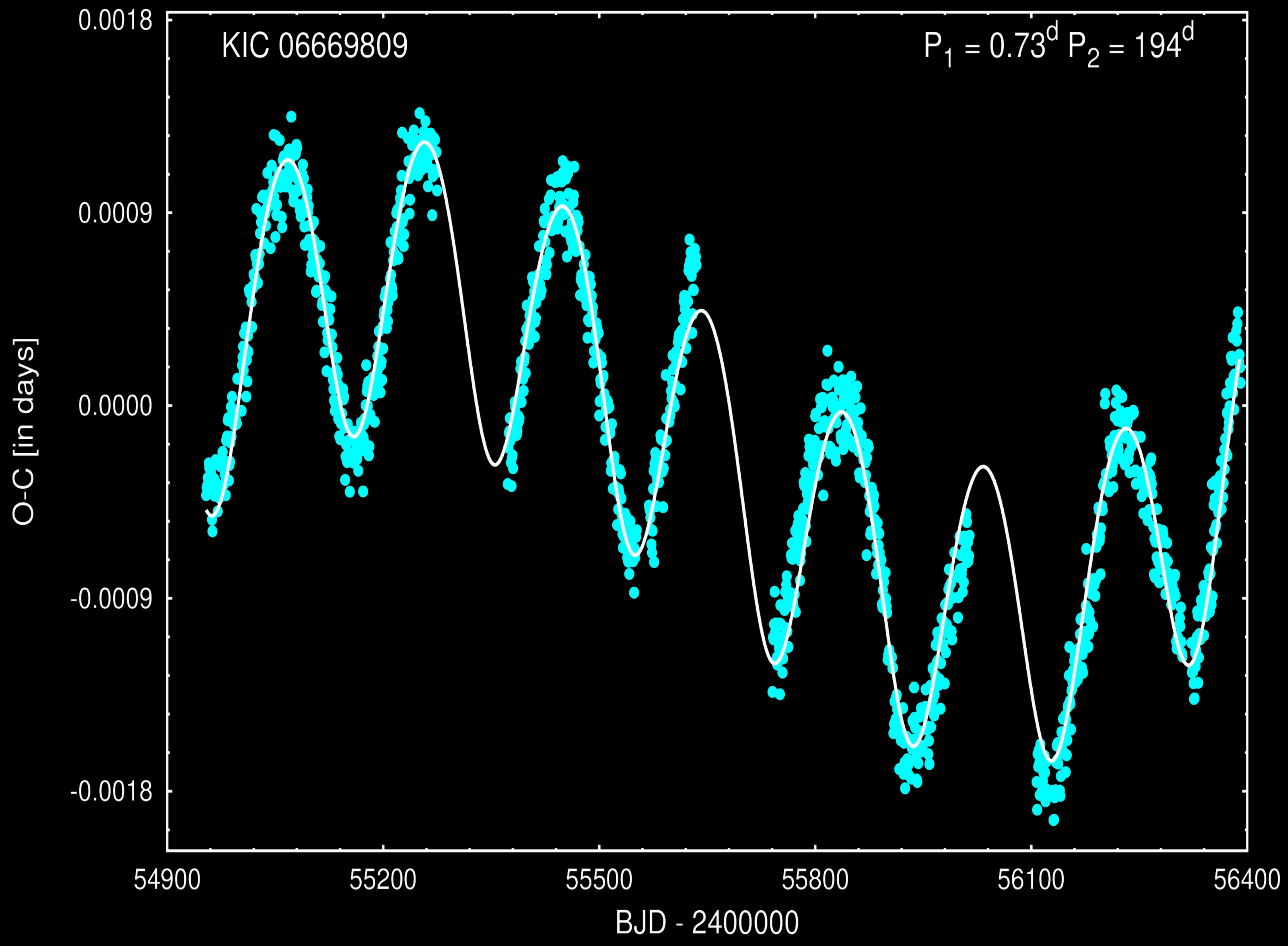
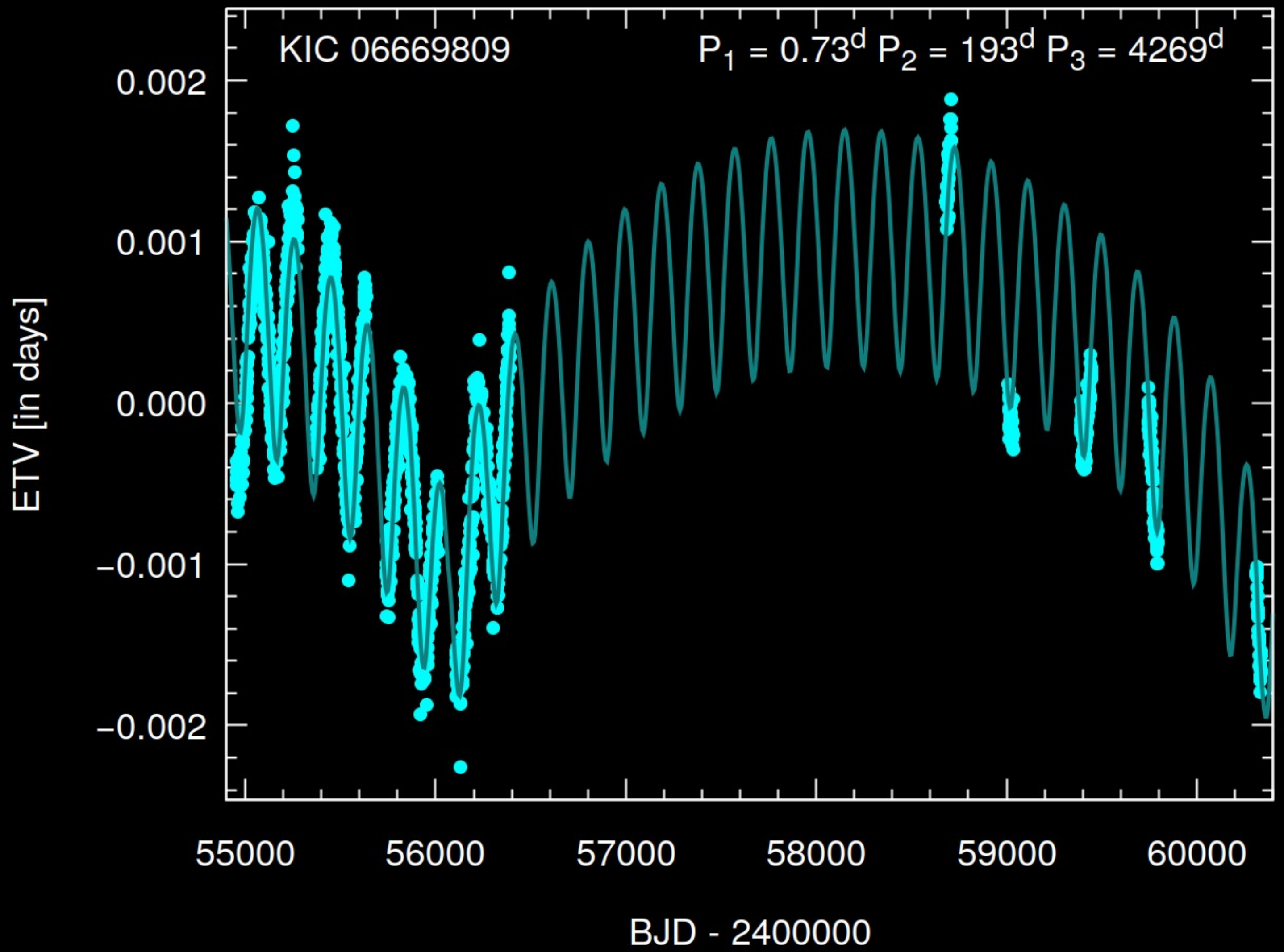
Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

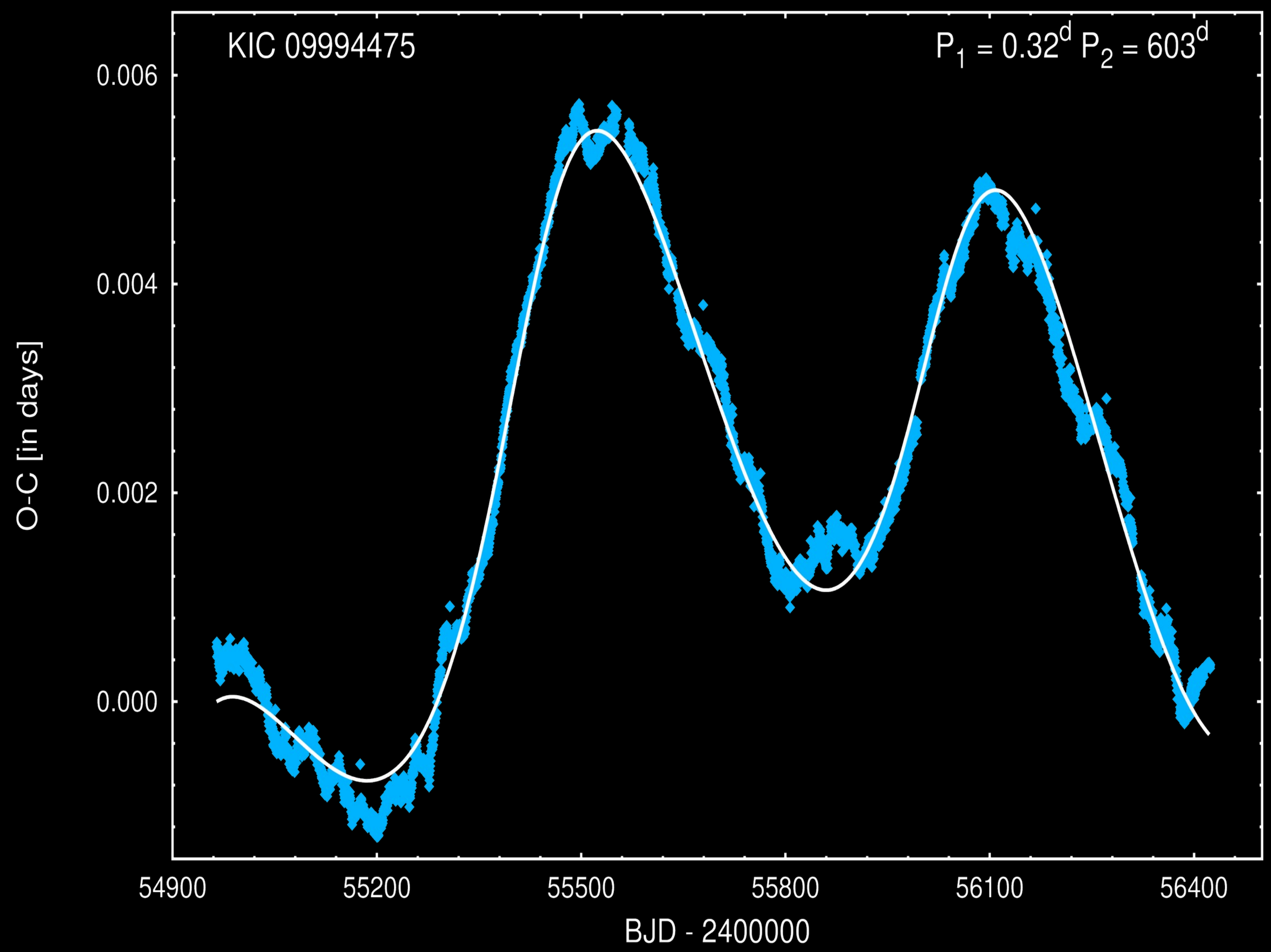
Other funny ETVs



Other funny ETVs



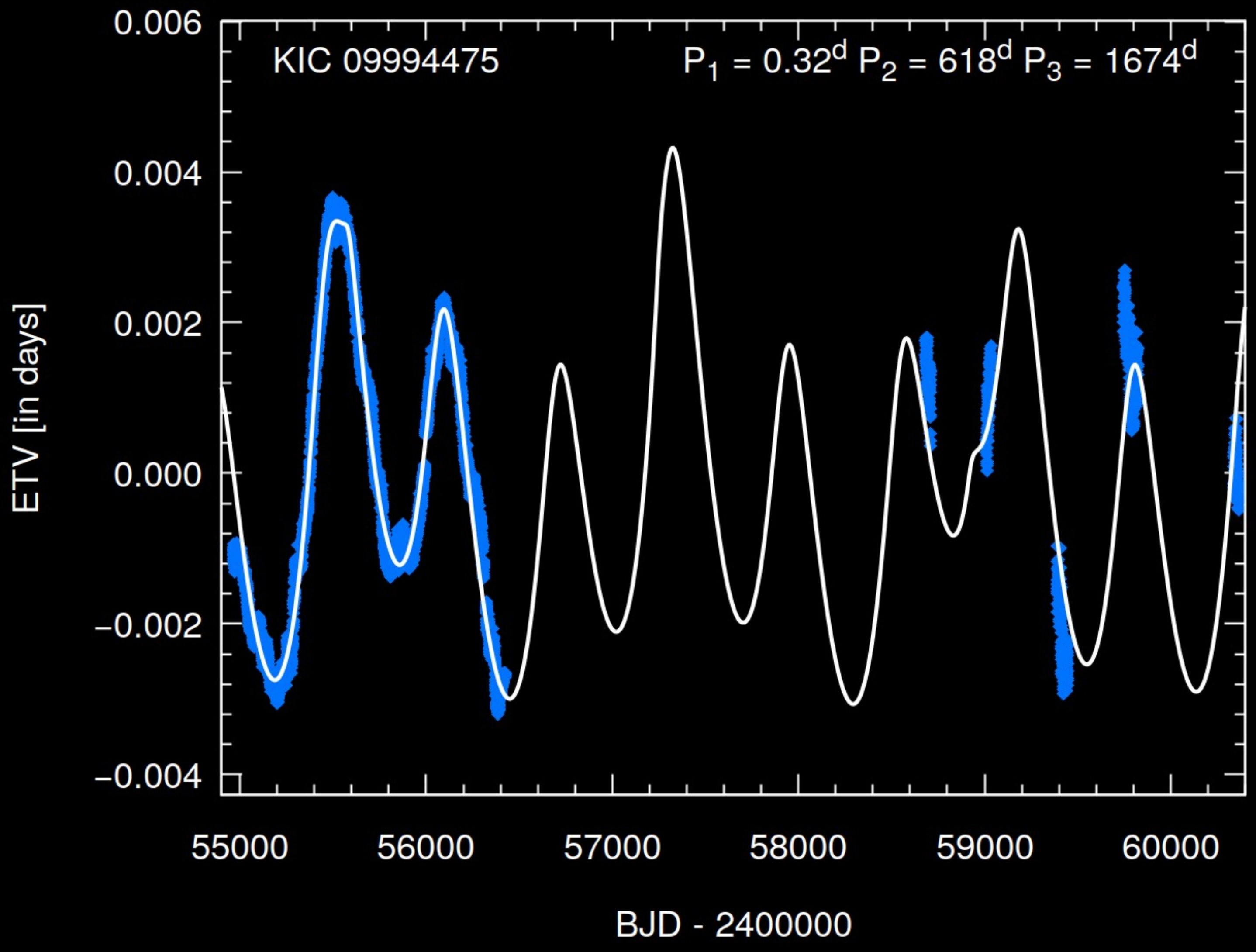
Other funny ETVs



Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

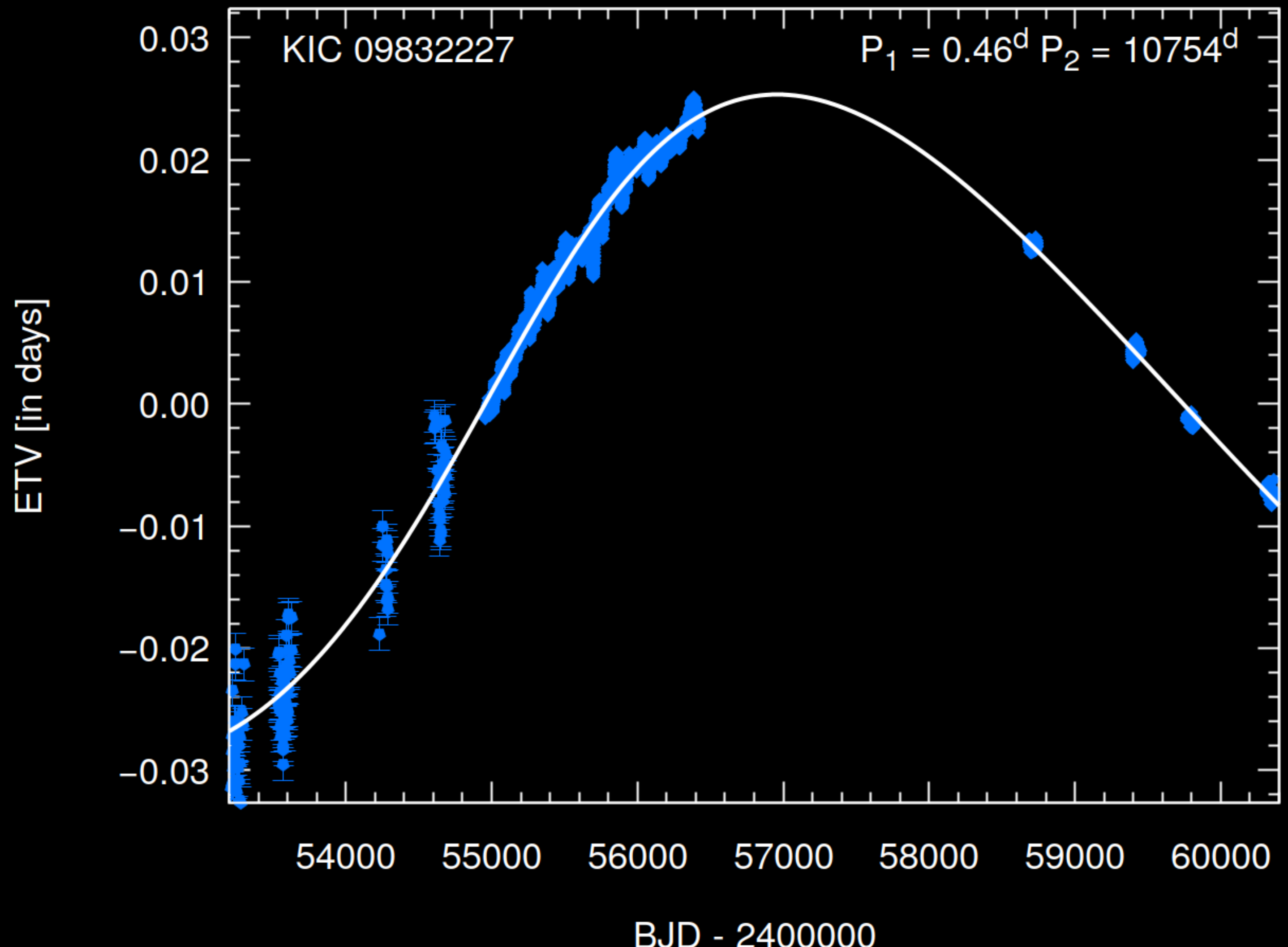
Other funny ETVs



Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

An ordinary (non funny) ETV – related to Ondřej's talk



Yes, this is the formerly expected red nova!

The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

- Light-Travel Time Effect (LITE, LTTE – Rømer-delay)

$$\Delta_{\mathrm{LTTE}} = -\frac{a_{\mathrm{AB}}\sin i_2}{c}\frac{(1-e_2^2)\sin(v_2+\omega_2)}{1+e_2\cos v_2}$$

a_{AB} – semi-major axis of the EB's orbit around the CM of the triple
e_2, i_2, ω_2, v_2 – eccentricity, inclination, argument of periastron and true anomaly of the relative orbit of the third body
c – speed of light

The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

- Light-Travel Time Effect (LITE, LTTE – Rømer-delay)

Changing to eccentric anomaly ($\mathcal{E}_2$) :

$$\Delta_{\rm LTTE} = -\frac{a_{\rm AB}\sin i_2}{c}\left[\sqrt{1-e_2^2}\sin\mathcal{E}_2\cos\omega_2+(\cos\mathcal{E}_2-e_2)\sin\omega_2\right]$$
$$= -\frac{a_{\rm AB}\sin i_2}{c}\left[\sqrt{1-e_2^2\cos^2\omega_2}\sin(\mathcal{E}_2+\phi)-e_2\sin\omega_2\right],$$

Amplitude:

$$\mathcal{A}_{\rm LTTE} = \frac{a_{\rm AB}\sin i_2}{c}\sqrt{1-e_2^2\cos^2\omega_2}$$

Phase:

$$\phi = \tan^{-1}\left(\frac{\sin\omega_2}{\sqrt{1-e_2^2}\cos\omega_2}\right)$$

The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

- Light-Travel Time Effect (LITE, LTTE – Rømer-delay)

Introducing the mass function:

$$f(m_{\mathrm{C}}) = \frac{m_{\mathrm{C}}^3 \sin^3 i_2}{m_{\mathrm{ABC}}^2} = \frac{4\pi^2 a_{\mathrm{AB}}^3 \sin^3 i_2}{G P_2^2}$$

and thus, the amplitude of LTTE can be written as

$$\mathcal{A}_{\mathrm{LTTE}} = \frac{G^{1/3}}{c}\left(\frac{P_2}{2\pi}\right)^{2/3} f(m_{\mathrm{C}})^{1/3}\sqrt{1-e_2^2\cos^2\omega_2}$$

$$\approx 1.1\times10^{-4}\frac{m_{\mathrm{C}}\sin i_2}{m_{\mathrm{ABC}}^{2/3}}P_2^{2/3}\sqrt{1-e_2^2\cos^2\omega_2},$$

The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

- Dynamical perturbations of a third body

Three different time-scales

Classifications of periodic perturbations	Period	Relative amplitude
Short period perturbations	$\sim P_1$	$\sim (P_1/P_2)^2$
Medium period perturbations	$\sim P_2$	$\sim P_1/P_2$
Long period perturbations	$\sim P_2^2/P_1$	1

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

The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

- Medium-period perturbations of a third body

Quadrupole-terms (Borkovits, Csizmadia, Forgács-Dajka, Hegedüs, 2011)

$$
\begin{aligned}
(O-C)_{v_2} = {} & \frac{P_1}{2\pi} A_{\rm L} \left\{ \left(1-e_1^2\right)^{1/2} \left\{ \left[\frac{4}{5} f_1(e_1) + \frac{6}{5} K_1(e_1,\omega_1)\right] \left[\left(I^2 - \frac{1}{3}\right)\mathcal{M} + \frac{1}{2}\left(1-I^2\right)\mathcal{S}(2v_2+2g_2)\right] \right.\right. \\
& + \left[\frac{51}{20} e_1^2 f_2(e_1)\cos 2g_1 + 2K_2(e_1,\omega_1,g_1) + \frac{1}{8} e_1^2 K_4(e_1,\omega_1,g_1)\right] \left[\left(1-I^2\right)\mathcal{M} + \frac{1}{2}\left(1+I^2\right)\mathcal{S}(2v_2+2g_2)\right] \\
& \left. - \frac{1}{2}\left[\frac{51}{20} e_1^2 f_2(e_1)\sin 2g_1 + 2K_3(e_1,\omega_1,g_1) + \frac{1}{8} e_1^2 K_5(e_1,\omega_1,g_1)\right] 2I\mathcal{C}(2v_2+2g_2) \right\} \\
& + \frac{\sin i_{\rm m} \cot i_1}{\left(1-e_1^2\right)^{1/2}} \left\{ \left[-\frac{2}{5}\left(1+\frac{3}{2}e_1^2\right)\cos u_{\rm m1} + e_1^2 \cos(2g_1+u_{\rm m1})\right] \left[1+2K_1(e_1,\omega_1)\right] I \left[\mathcal{M} - \frac{1}{2}\mathcal{S}(2v_2+2g_2)\right] \right. \\
& \left.\left. + \frac{1}{2}\left[\frac{2}{5}\left(1+\frac{3}{2}e_1^2\right)\sin u_{\rm m1} + e_1^2 \sin(2g_1+u_{\rm m1})\right] \left[1+2K_1(e_1,\omega_1)\right] \mathcal{C}(2v_2+2g_2) \right\}\right\},
\end{aligned}
$$

The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

- Medium-period perturbations of a third body – special cases

Circular inner orbit (Borkovits, Érdi, Forgács-Dajka, Kovács T., 2003)

$$\Delta_{\mathrm{L10}} = \frac{P_1}{2\pi}\frac{m_C}{m_{ABC}}\frac{P_1}{P_2}\left[\left(1-\frac{3}{2}\sin^2 i_m\right)\mathcal{M}+\frac{3}{4}\sin^2 i_m\mathcal{S}\right]+\ldots$$

Both orbits circular

$$\Delta_{\mathrm{L10}}^{e_2=0} = \frac{P_1}{2\pi}\frac{m_C}{m_{ABC}}\frac{P_1}{P_2}\frac{3}{4}\sin^2 i_m \sin(2u_2-2n_2)$$

Circular inner orbit – coplanar orbits (Agol et al., 2005)

$$\Delta_{\mathrm{L10}}^{\mathrm{copl}} = \frac{P_1}{2\pi}\frac{m_C}{m_{ABC}}\frac{P_1}{P_2}\left(3e_2\sin v_2-\frac{3}{4}e_2^2\sin 2v_2+\frac{1}{3}e_2^3\sin 3v_2\right)+O(e_2^4)$$

Two circular & coplanar orbits (Trinity)

$$\Delta_{\mathrm{L10}} = 0$$

The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

- Medium-period perturbations of a third body

– Comparison of the amplitudes with the LTTE--terms:

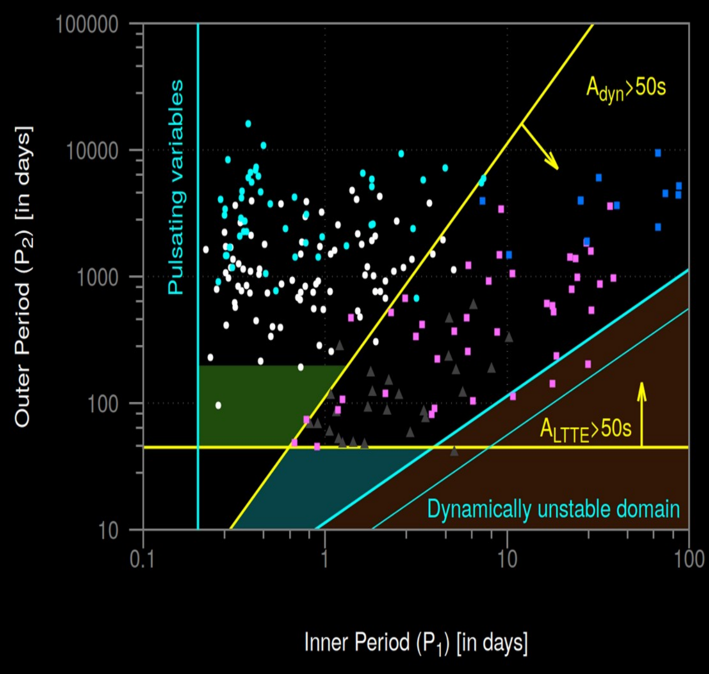
$$\frac{\mathcal{A}_{\mathrm{dyn}}}{\mathcal{A}_{\mathrm{LTTE}}} = \frac{c}{(2\pi G m_{\mathrm{ABC}})^{1/3}\sin i_2}\mathcal{E}(e_2,\omega_2)\left(\frac{P_1}{P_2}\right)^2 P_2^{1/3}, \quad (13)$$

where

$$\mathcal{E}(e_2,\omega_2) = \left(1-e_2^2\right)^{-3/2}\left(1-e_2^2\cos^2\omega_2\right)^{-1/2} \quad (14)$$

and therefore, for a given total mass

$$\frac{\mathcal{A}_{\mathrm{dyn}}}{\mathcal{A}_{\mathrm{LTTE}}} \geqslant \frac{c}{(2\pi G m_{\mathrm{ABC}})^{1/3}}\left(\frac{P_1}{P_2}\right)^2 P_2^{1/3} \geqslant 1.45\times 10^3 m_{\mathrm{ABC}}^{-1/3}\frac{P_1^2}{P_2^{5/3}}.$$



The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

- Medium-period perturbations of a third body

– Comparison of the amplitudes with the LTTE--terms:

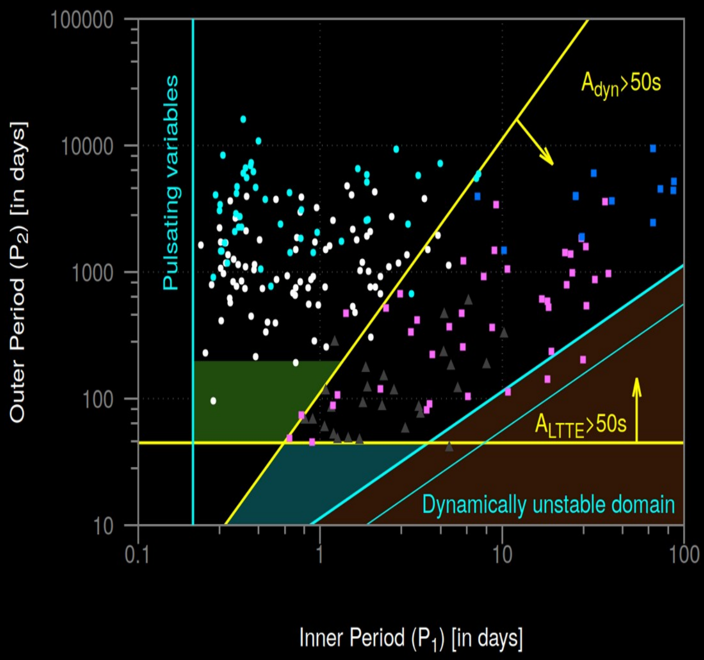
$$\frac{\mathcal{A}_{\rm dyn}}{\mathcal{A}_{\rm LTTE}} = \frac{c}{(2\pi G m_{\rm ABC})^{1/3}\sin i_2}\mathcal{E}(e_2,\omega_2)\left(\frac{P_1}{P_2}\right)^2 P_2^{1/3}, \quad (13)$$

where

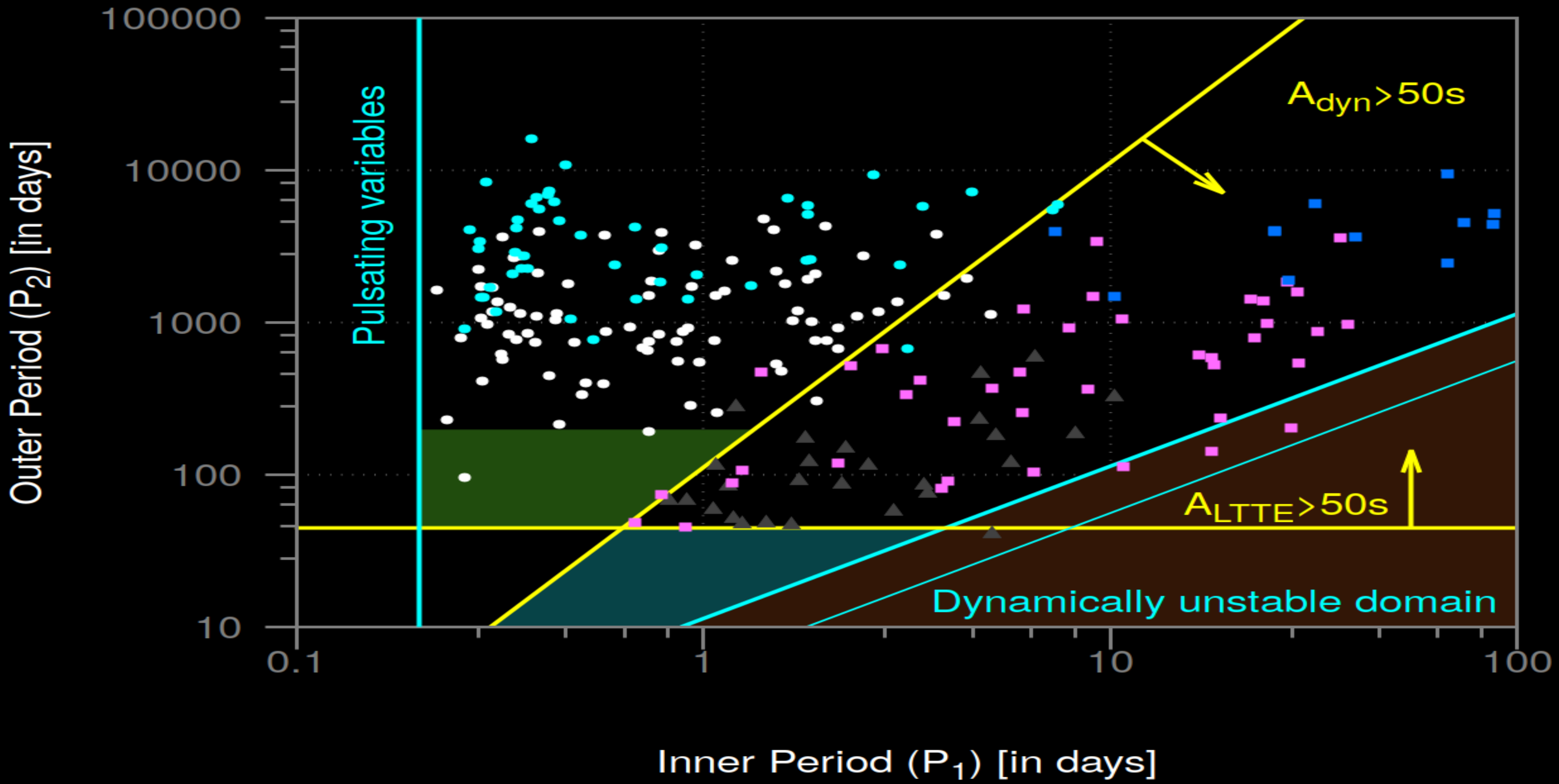
$$\mathcal{E}(e_2,\omega_2) = \left(1-e_2^2\right)^{-3/2}\left(1-e_2^2\cos^2\omega_2\right)^{-1/2} \quad (14)$$

– For Kepler
(the life-time of the original mission ~ 1470 days):

$$\frac{\mathcal{A}_{\rm dyn}}{\mathcal{A}_{\rm LTTE}} \geqslant m_{\rm ABC}^{-1/3}\left(\frac{P_1}{11.46}\right)^2\left(\frac{1470}{P_2}\right)^{5/3}$$



The Royal Road: Eclipse Timing Variation Analysis



The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

- "Apse-node" timescale perturbations

For the closest Kepler triples apsidal motion and nodal regression timescale is shorter than a decade! These must be taken into account!

General form of apsidal motion (irrespective on its origin):

$$\Delta_{\mathrm{apse}} = \frac{P_1}{2\pi}\left[\arctan\left(\frac{\pm e_1\cos\omega_1}{1+\sqrt{1-e_1^2}\mp e_1\sin\omega_1}\right) \pm \sqrt{1-e_1^2}\frac{e_1\cos\omega_1}{1\mp e_1\sin\omega_1}\right]$$

In case of third-body perturbations the variation of ω_1 no longer linear in time and furthermore, e_1 and P_1 also vary!

The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

- "Apse-node" timescale perturbations

The period of the dynamical apsidal advance (and nodal regression)

$$P_{\rm apse} \sim \frac{8}{15}\frac{m_{\rm ABC}}{m_{\rm C}}\frac{P_2^2}{P_1}f(e_1, e_2, i_{\rm m}, g_1, g_2)$$

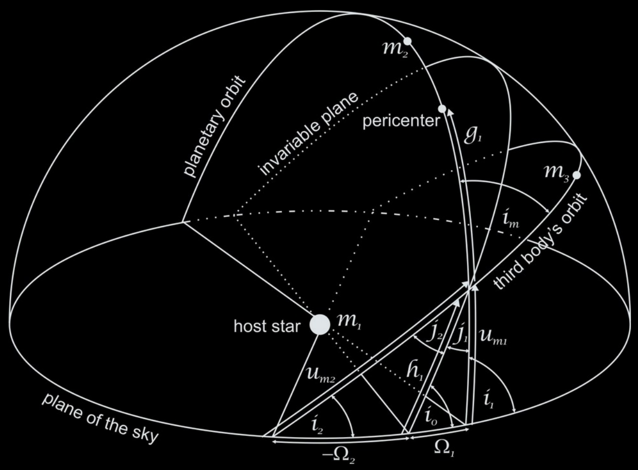
It can be calculated from the long-term+LTTE third body solution, therefore, it is constrained – helps to resolve some degeneracies

(see Borkovits et al. 2015 for details, especially Appendix C)

The Royal Road: Eclipse Timing Variation Analysis

The effects of the third body:

Why are these good for us?



- LTTE + dynamical perturbations:

- **light-time effect:** P_2, $a_{AB}\sin i_2$ [in km], e_2, ω_2, $f(m_C)$
- **grav. 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 completely unknown for compact triples before *Kepler*-era, although they are very important for dynamical evolution studies

Search for hierarchical triples in the *Kepler* sample

Steps of the analysis

3. Search for third-body solution

- Levenberg-Marquardt non-linear LSQ search.

The general form:

$$\Delta = \sum_{i=0}^{3} c_i E^i + \left[\Delta_{\mathrm{LTTE}} + \Delta_{\mathrm{dyn}} + \Delta_{\mathrm{apse}}\right]_0^E .$$

where the expected O-C itself is

$$\Delta = T(E) - T_0 - P_s E$$

Always included: **linear polynom** + **LTTE terms** (2+5 parameters)

Dynamical term(s) added where the shape and/or the estimated Adyn/ALTTE ratio makes it necessary (9 or less extra parameters – some of them may be constrained!)

Apsidal motion terms for eccentric inner orbits (3 parameters included in the above)

Quadratic (or, very rarely, **cubic plynom**) in a very limited cases (+1 or 2 parameters)

Search for hierarchical triples in the *Kepler* sample

Results from 2024 (2016)

Summary

- A total of 189 (222) third-body ETV solution was found

	LTTE only	LTTE+dyn	Sum
Group I	54 (38)	37 (31)	91 (69)
Group II	31 (64)	4 (14)	35 (78)
Group III	50 (58)	13 (17)	63 (75)
Sum total	135 (160)	54 (62)	189 (222)
False positive	0 (8)	0 (0)	187 (230)

- **Group I: More than two outer orbital periods are covered (or extra eclipses verifythe third body)**
- **Group II: More than one, but less than two outer periods**
- **Group III: Less than one outer orbital period**
- **False Positive: The signal from LTTE but the source is not an EB**

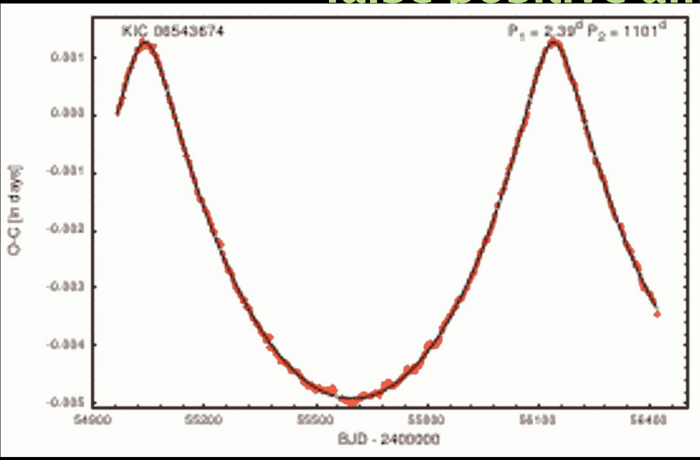
Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

Results on hierarchical triples in the *Kepler* sample

Group I systems (2024 – not final)

- 96d<P2<2714d – pure LTTE systems
- 45d<P2<1581d – LTTE+dyn systems
- 12 systems with extra eclipses – one of them identified in TESS data (extra eclipses in TESS data: 6 EBs)
- These are the most certain ones – although there might be a few false positive amongst them.



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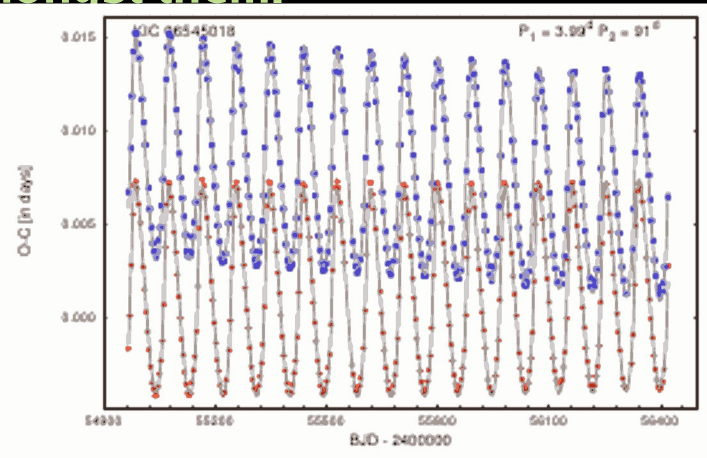

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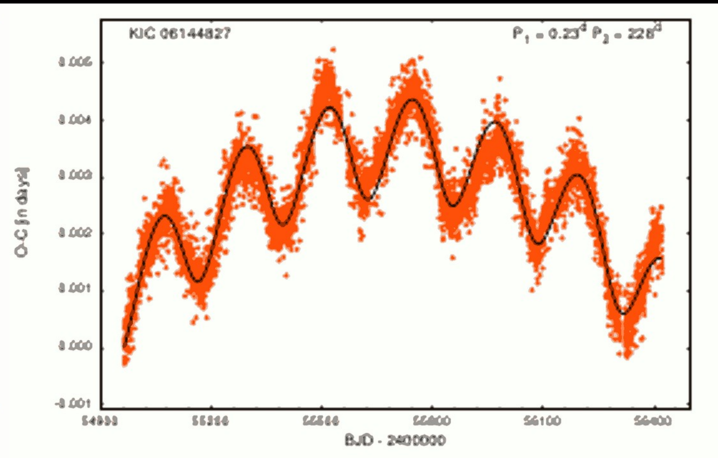
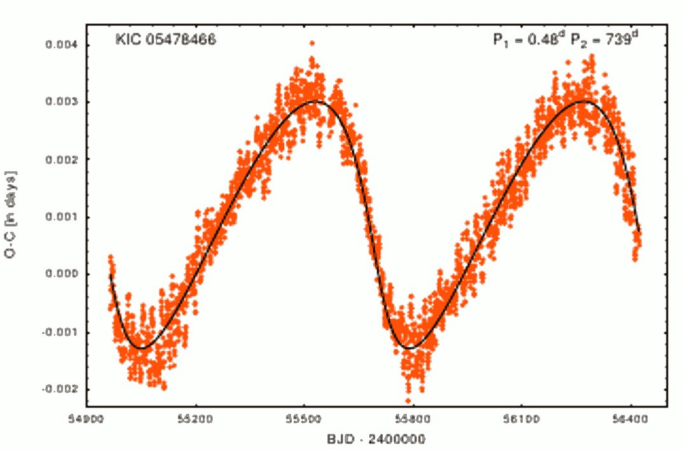


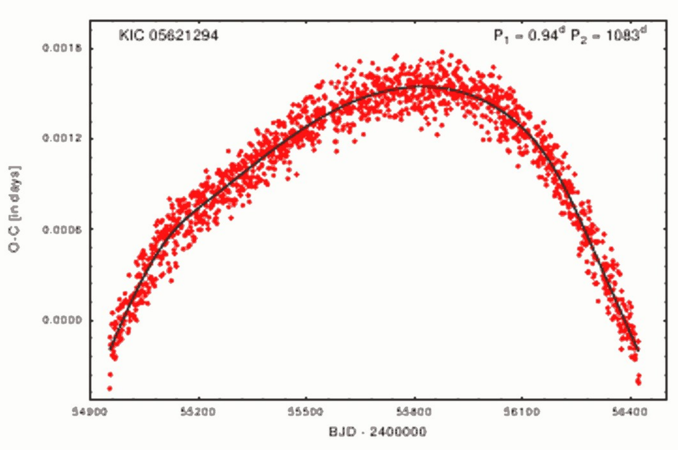
KIC 06144827

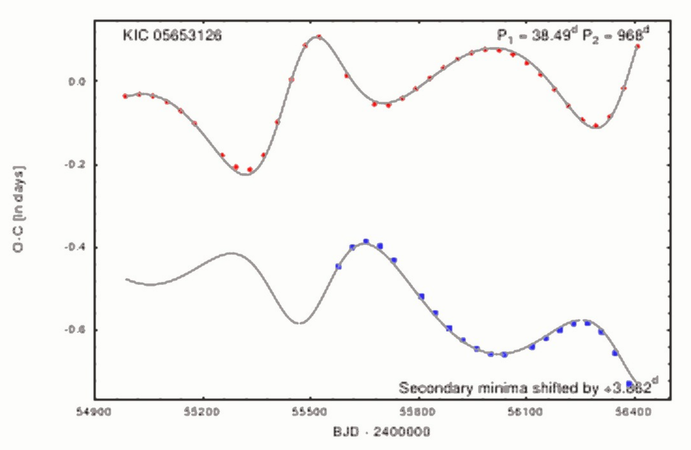
Results on hierarchical triples in the *Kepler* sample

Group II systems

- 618d<P2<4770d – pure LTTE systems
- 1385d<P2<3418d – LTTE+dyn systems
- LTTE+dyn systems seems to be certain enough, but for pure LTTE cases there is a greater probability of false 3rd body interpretation







KIC 05478466 KIC 05621294 KIC 05653126

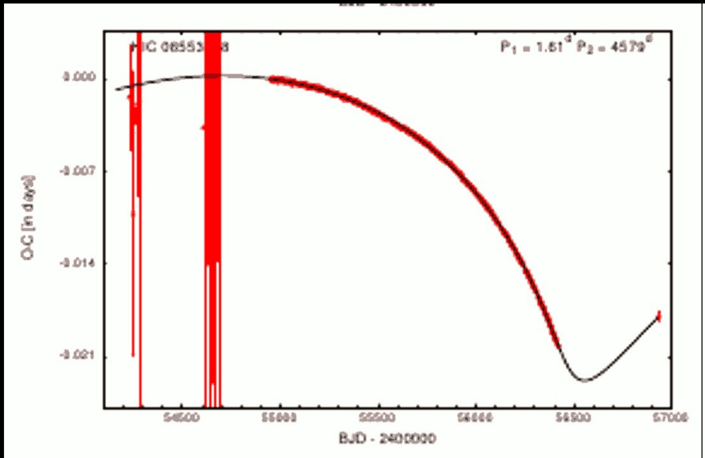
Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS

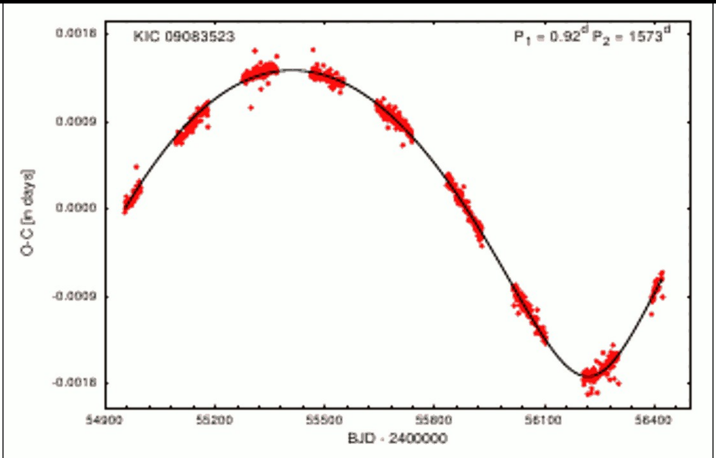
Results on hierarchical triples in the *Kepler* sample

Group III systems

- 765d<P2<16003d – pure LTTE systems
- 1487<P2<9402d – LTTE+dyn systems
- Most uncertain cases, but many of them most probably real triple



KIC 08553788



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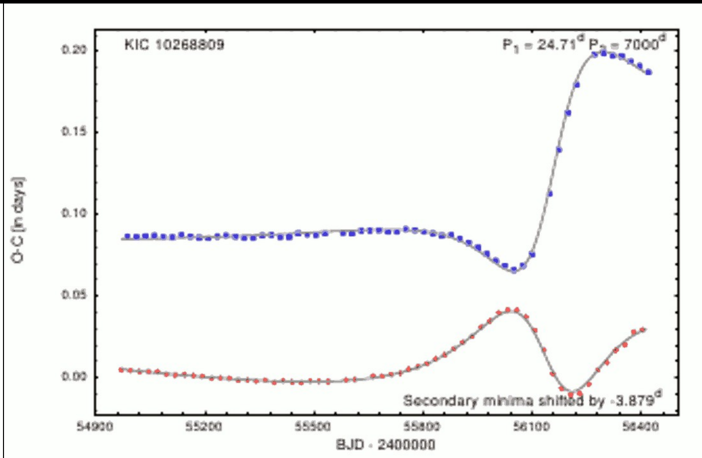
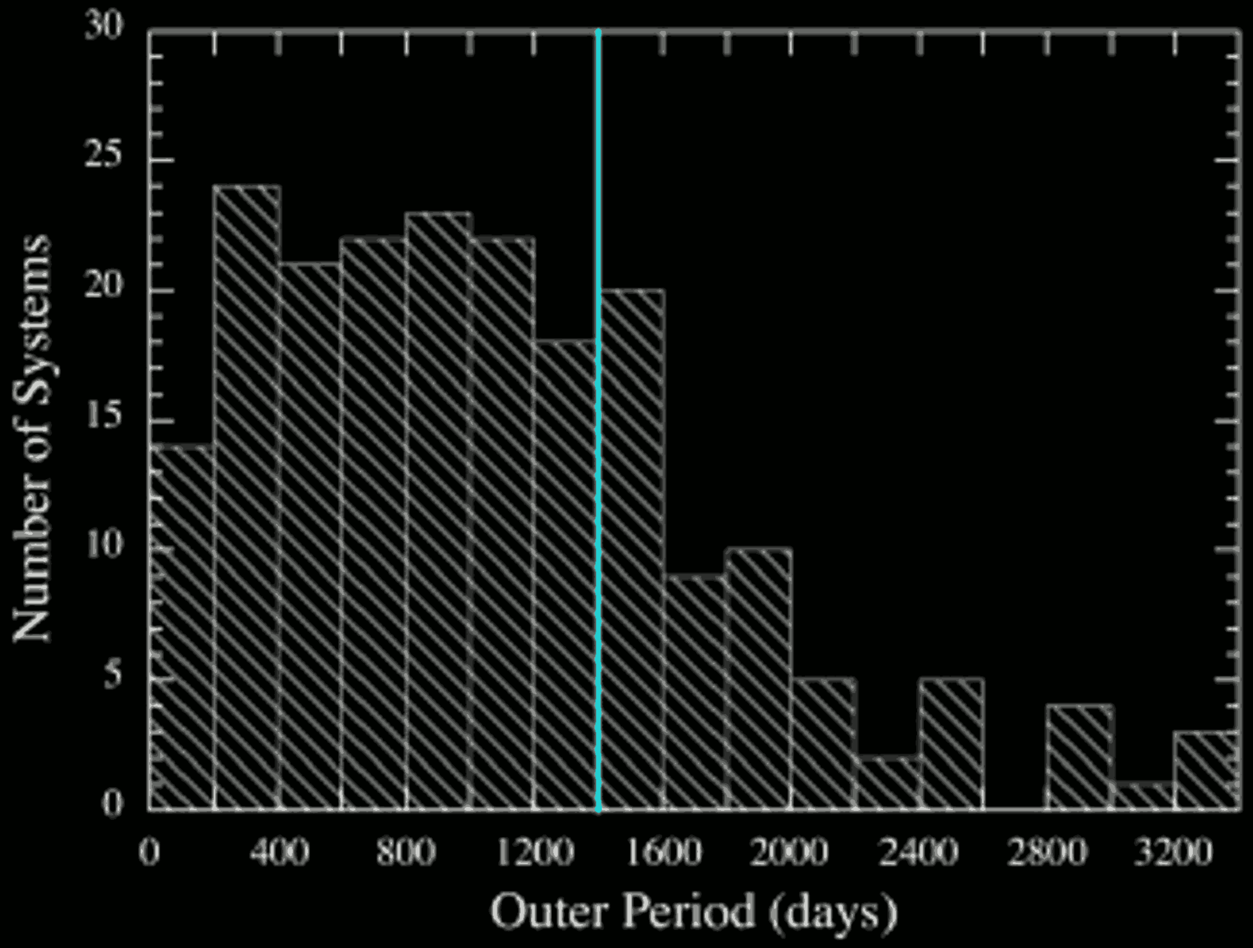


KIC 10268809

Results on hierarchical triples in the *Kepler* sample

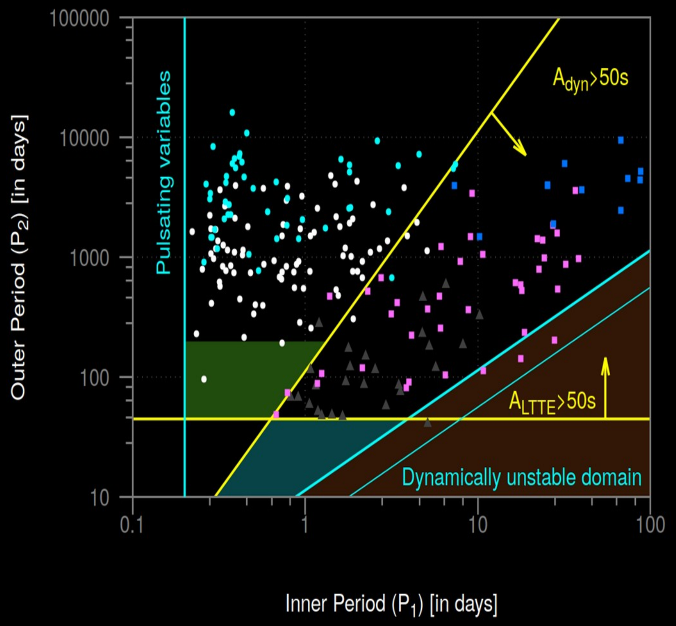
Statistics



Results on hierarchical triples in the *Kepler* sample

Statistics

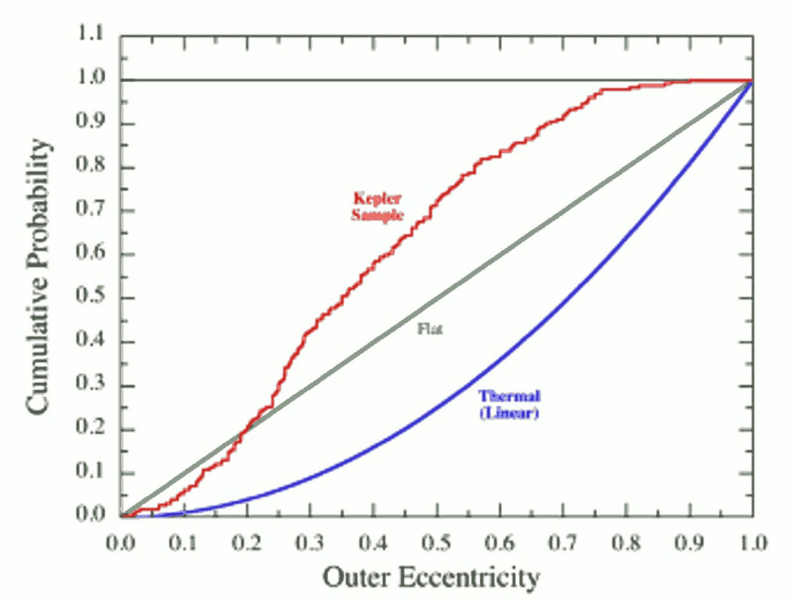
- **Lower end of outer period distribution:**
  The tightest binaries have no close ternary companions.
  (See the empty yellow ergion!)
  This might indicate some differences of
  the evolution (formation) of contact binaries.



Results on hierarchical triples in the *Kepler* sample

Statistics

- **Eccentricity distribution:**
  It is similar to that which was shown in Duchene & Kraus 2013 for different samples of wider field-binaries



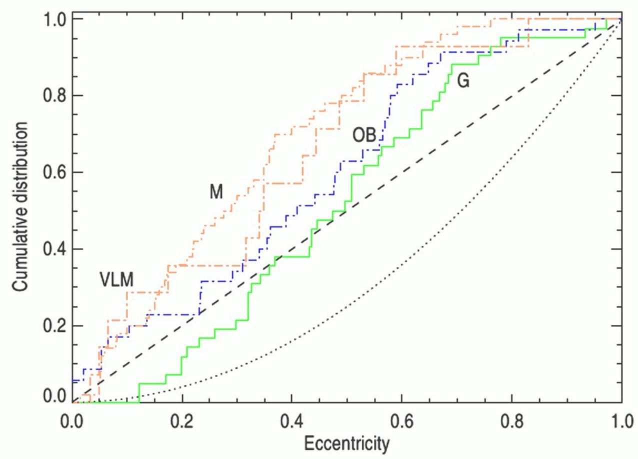


Figure 3:

Cumulative distribution of eccentricities for systems with $2 \leq \log P \leq 4$ for field multiple systems among solar-type stars (green curve; Raghavan et al. 2010), low-mass stars (orange curve; from the SB9 catalog, Pourbaix et al. 2004), VLM stars and BDs (red curve; Dupuy & Liu 2011), high-mass stars (blue curve; from the SB9 catalog and Abt 2005, Sana et al. 2012a). The dot-dashed curves indicate incomplete samples, for which the eccentricity distribution is potentially biased. The dashed and dotted curves represent the expected distribution for a flat and thermal distribution, $f(e) = 2e$, respectively.

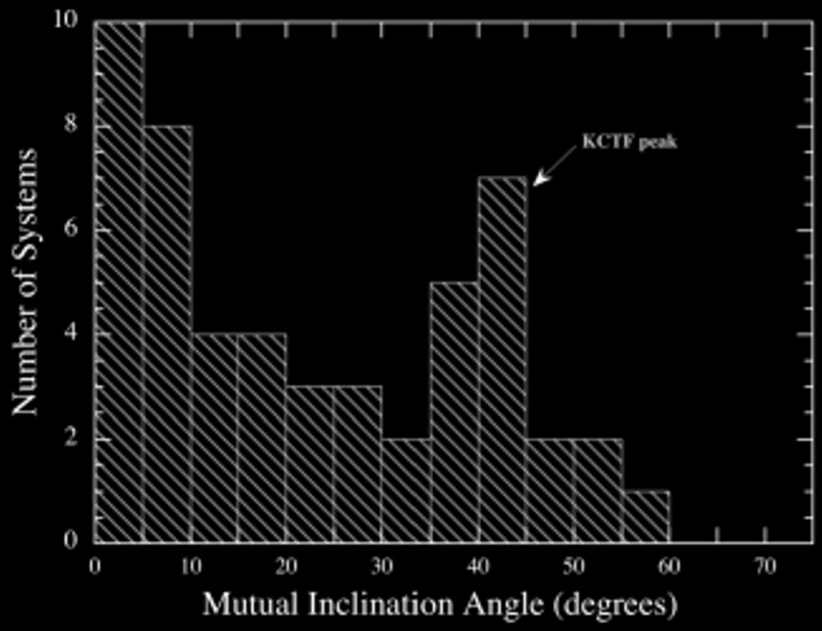
Results on hierarchical triples in the *Kepler* sample

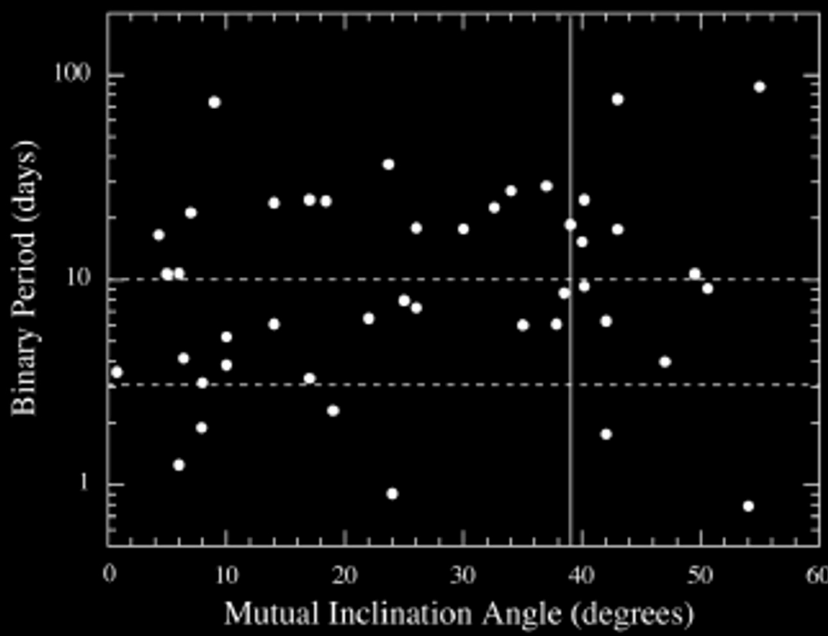
Statistics

- **Mutual inclination:**

  (It can be calculated only for dynamial systems)

  - The peak at i_m~40° may be a good evidence for KCTF mechanism





Tamás Borkovits – Then and now:

Eclipse Timing Variation Analyses of *Kepler* triples – after TESS