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Doubly Eclipsing Systems: Divide Et Impera

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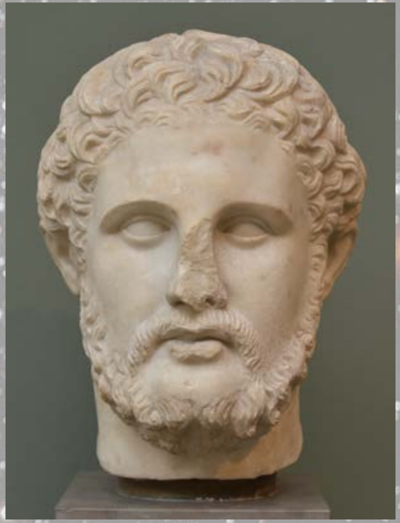
The phrase "Divide et impera"

- Origin not clear
- Usually attributed to Julius Caesar
- Used before by Philip II of Macedon :

  (lived 382-336BC, ruled 359-336BC)



Philip II

Macedon

Silver

tetradrachm

The phrase "Divide et impera"

- Origin not clear
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Cut the problem into smaller pieces

Philip II Macedon

Silver tetradrachm

What are the doubly eclipsing systems?

- More eclipsing periods
  - It can be either (2+2) quadruple, or 2+1, or (2+1)+1, (2+2)+1, etc.
- One point source on the sky
- Range of periods, depths of eclipses, magnitudes, ...
- Selection effects - huge!
- Gravitationally bound system (?)
- Photometric surveys + Kepler + TESS +.. > 99 %

An approach for DEBs analysis

- **We have in principle two different options:**
  - **Separately solve the individual LCs, RVs, ETV, …**
    - **And then merging the solution together to get the self-consistent picture**
    - **I call this "Divide et impera" approach**
  - **Combined photodynamical analysis of all available means**
    - **Very complicated, time consuming, needed a lot of CPU time,….**
    - **Done by group around T.Borkovits and his fellows**

Why doubly eclipsing systems?

- Derive for both binaries: M, R, log g, T_{eff}, …
- Share the same: age, chemical compositions, distance, …
- Study the 2+2 dynamics, perturbations, secular evolution, stability, ETV studies, model the future fate of the system, …
- Statistical studies, modelling of stellar populations, …

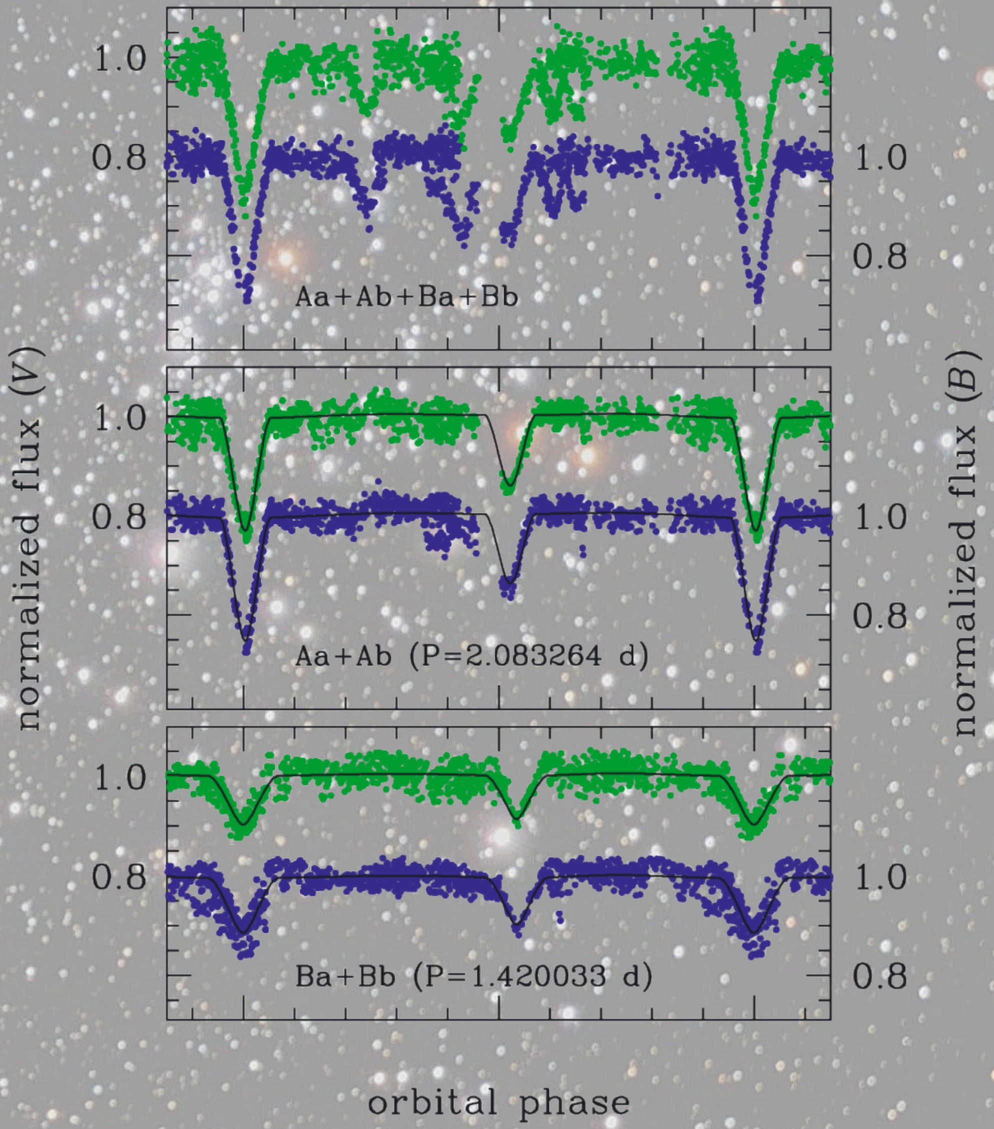
All these set rather strict constraints for the complete solution!

A little statistics

- **Our goal is to detect both periods & prove grav.coupling**
- **Discovery statistics:**
  - **Year 2008: the first one (V994 Her)**
  - **Year 2018: in total 94 known**
  - **Year 2019: in total 146 known**
  - **Year 2020: in total 149 known**
  - **Year 2021: in total 159 known**
  - **Year 2022: in total 352 known**
  - **Year 2023: in total 771 known**
  - **Year 2024: in total 980 known**
- **But among these only 58 have confirmed mutual orbits (i.e. are definitely bound 2+2 quadruples)**

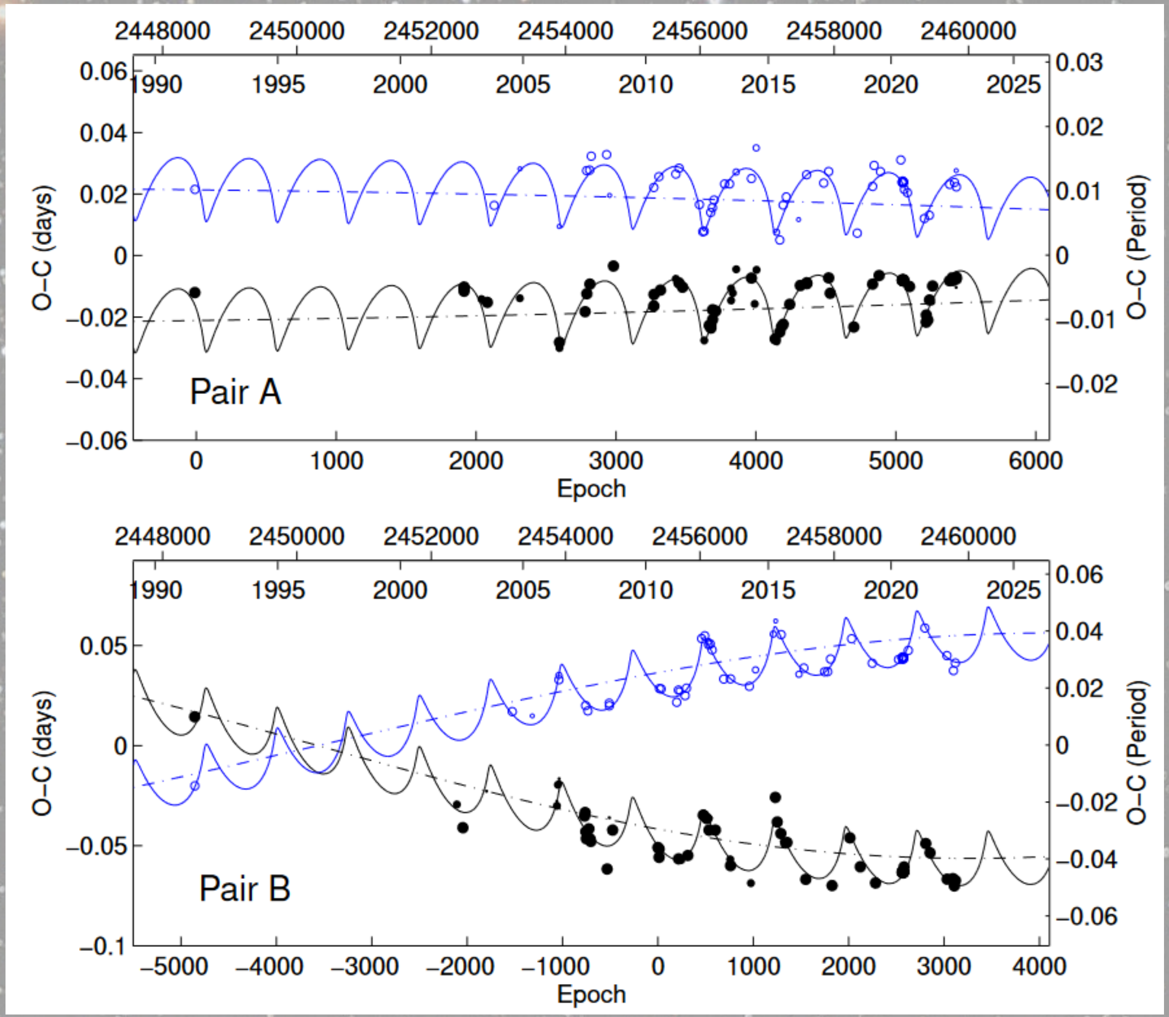
Where the story begun …

- V994 Her: Lee et al. (2008)
- Two eclipsing systems, detached
- Bright star (V = 7mag)
- Distance about 240pc
- Pair A: P=2.08d, sp B8+A0, e=0.03
- Pair B: P=1.42d, sp A2+A4, e=0.08



V994 Her: really bound system

- Zasche & Uhlar (2016)
- Two pairs A+B really orbit
- Mutual period 2.9yr
- Apsidal motion of both A&B

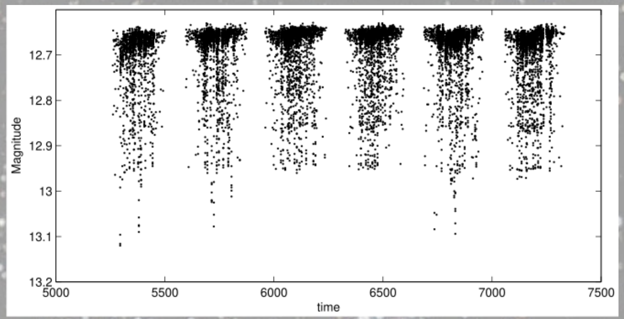


Selection effects

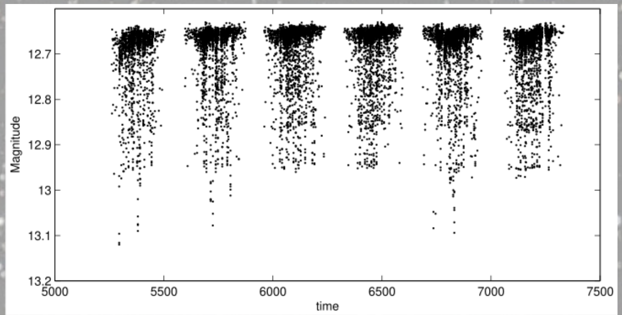
- To detect the doubly eclipsing system :
  - Both inner periods A&B adequately short (too long - problem)
  - Not too short (contact systems - problem)
  - Selection effects due to data cadency of photometric surveys
- Mutual A-B outer period should be:
  - Short enough to be detected
  - Too short period – large dynamical effects
  - Long A-B period – large semimajor axis – interferometric detection

Divide et impera #1 :

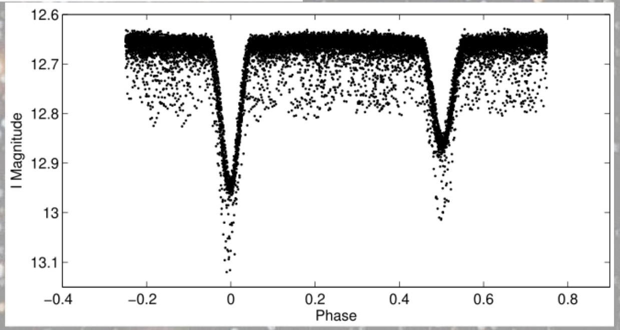
- Complete combined photometry



Divide et impera #1 :



- Complete combined photometry
- Detect the more pronounced period A



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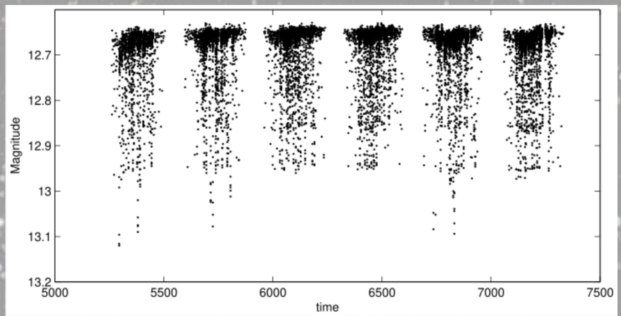
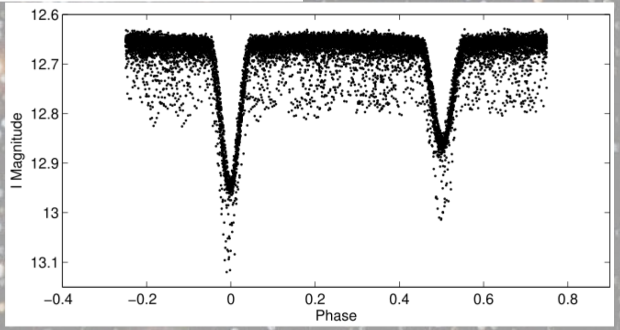
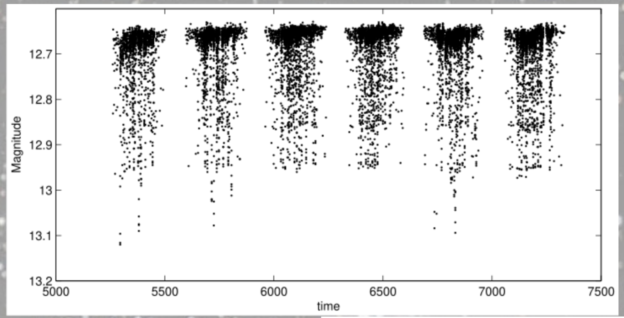


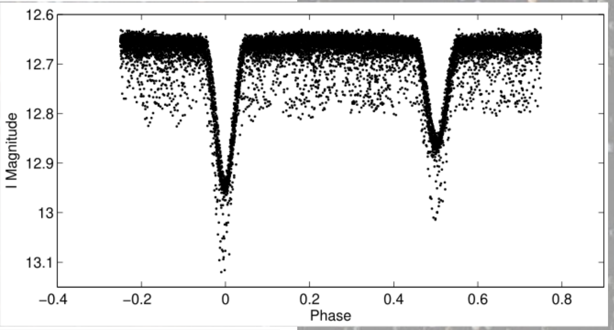
- Complete combined photometry
- Detect the more pronounced period A
- Preliminary fit of pair A light curve

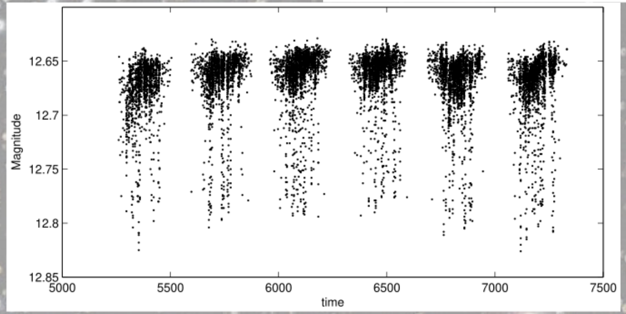


Divide et impera #1 :

- Complete combined photometry
- Detect the more pronounced period A
- Preliminary fit of pair A light curve
- Subtract of pair A → residua
- Detect B and derive its period

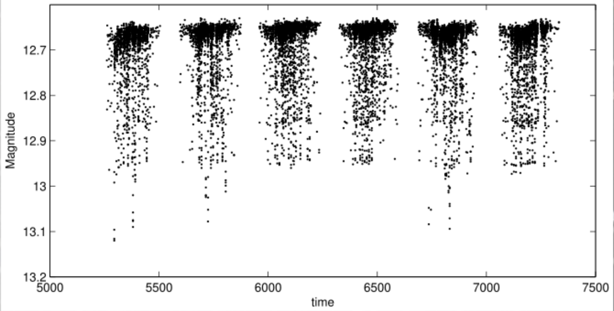


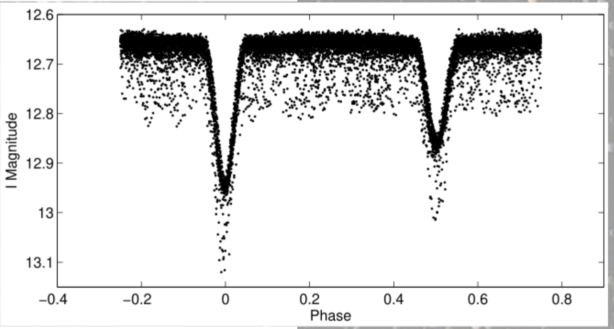


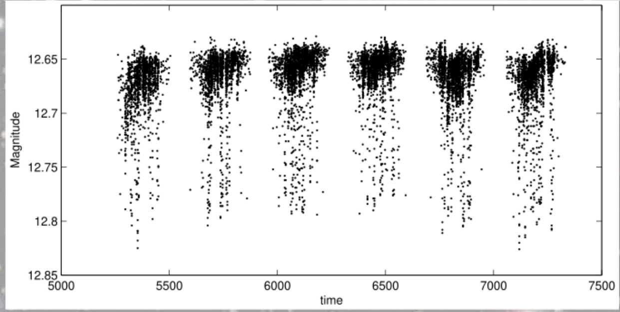


Divide et impera #1 :

- Complete combined photometry
- Detect the more pronounced period A
- Preliminary fit of pair A light curve
- Subtract of pair A → residua
- Detect B and derive its period
- Preliminary fit of pair B

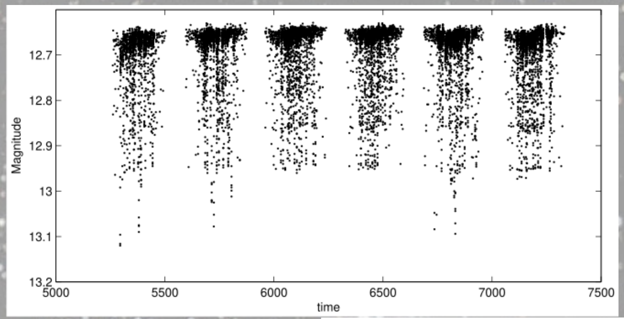


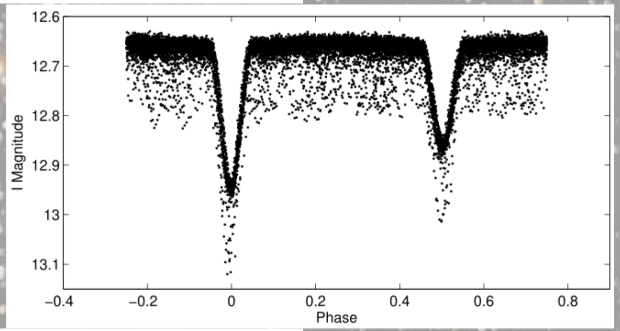


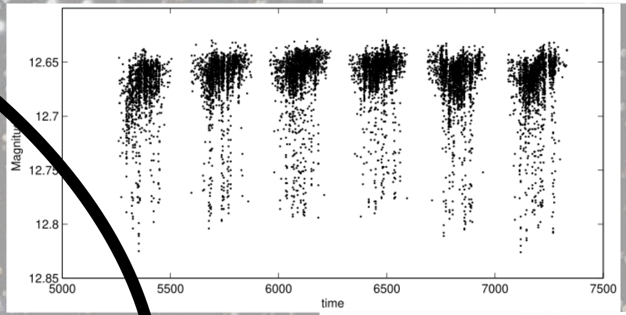


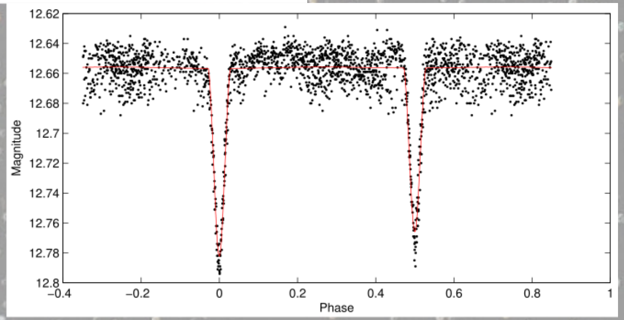
Divide et impera #1 :

- Complete combined photometry
- Detect the more pronounced period A
- Preliminary fit of pair A light curve
- Subtract of pair A → residua
- Detect B and derive its period
- Preliminary fit of pair B
- Subtract pair B from combined photometry









Problematic detection

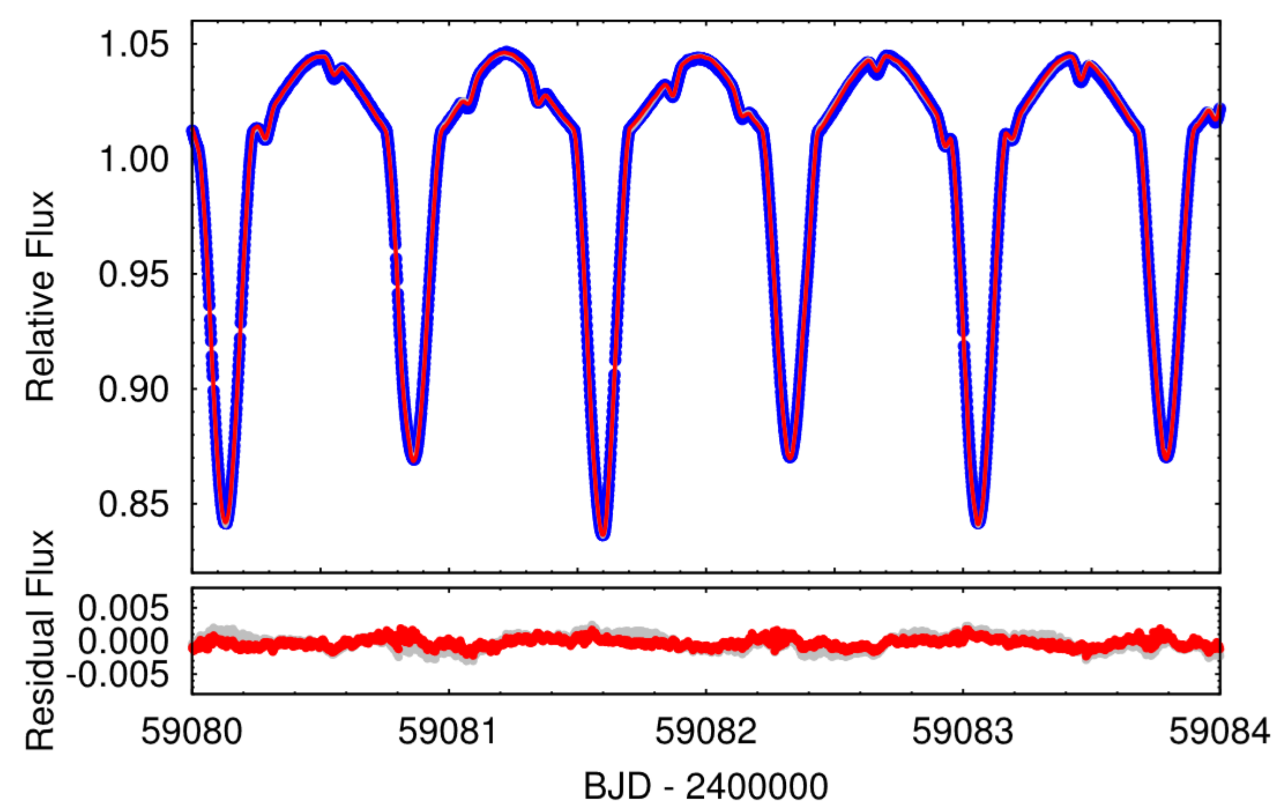
- From our sample: about each 500th EB is multiply eclipsing!!

Several examples here:

- V994 Her: known from 1999, but detected as DEB in 2008
- V482 Per: known from 1966, but detected as DEB in 2017
- AV CMi: known from 1968, but detected as DEB in 2010
- V839 Cep: known from 2006, but detected as DEB in 2021
- V2894 Cyg: known from 2004, but detected as DEB in 2021
- BG Ind: known from 1984, but detected as DEB in 2021
- BU CMi: known from 1999, but detected as DEB in 2021

Problematic detection

- BG Ind



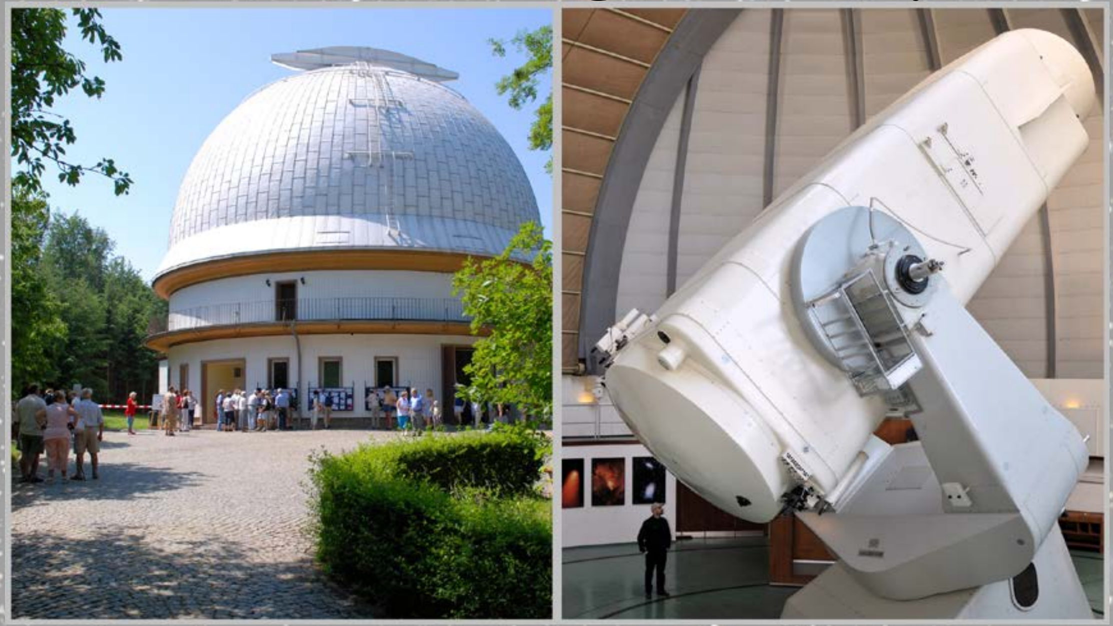
(Borkovits et al. 2021)

One typical example: CzeV1731

- Czech discovery! (Z. Henzl)
- Bright star (10.7mag), northern-hemisphere (DEC +57)
- Many photometric data (NSVS, ASAS-SN, SWASP, KELT)
- Two well-defined periods
- Both detached EA-type
- New data: D65, Henzl, FRAM, TESS
- Detailed study in: Astronomy & Astrophysics 642, A63 (2020)

One typical example: CzeV1731

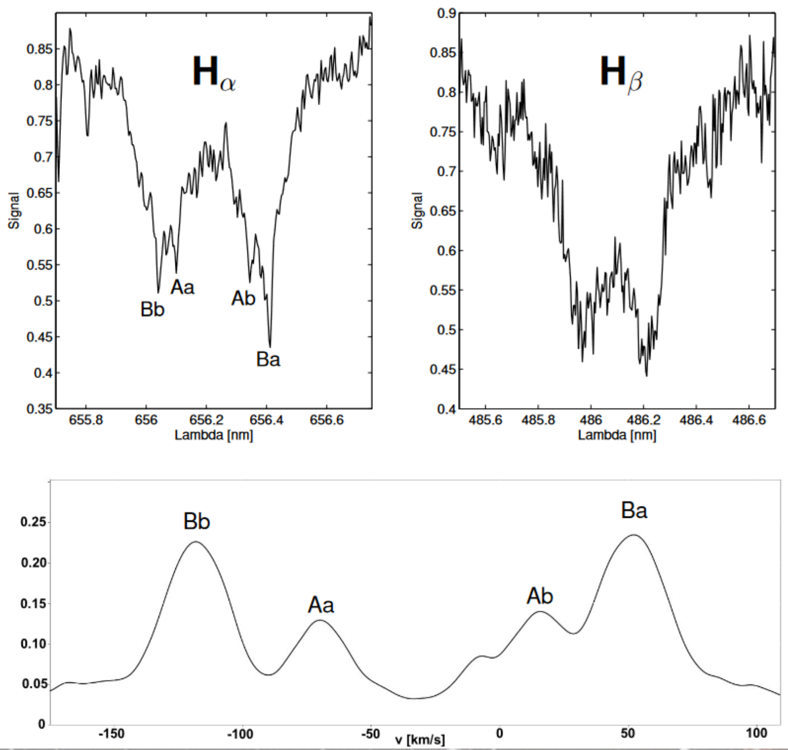
2m Tautenburg telescope

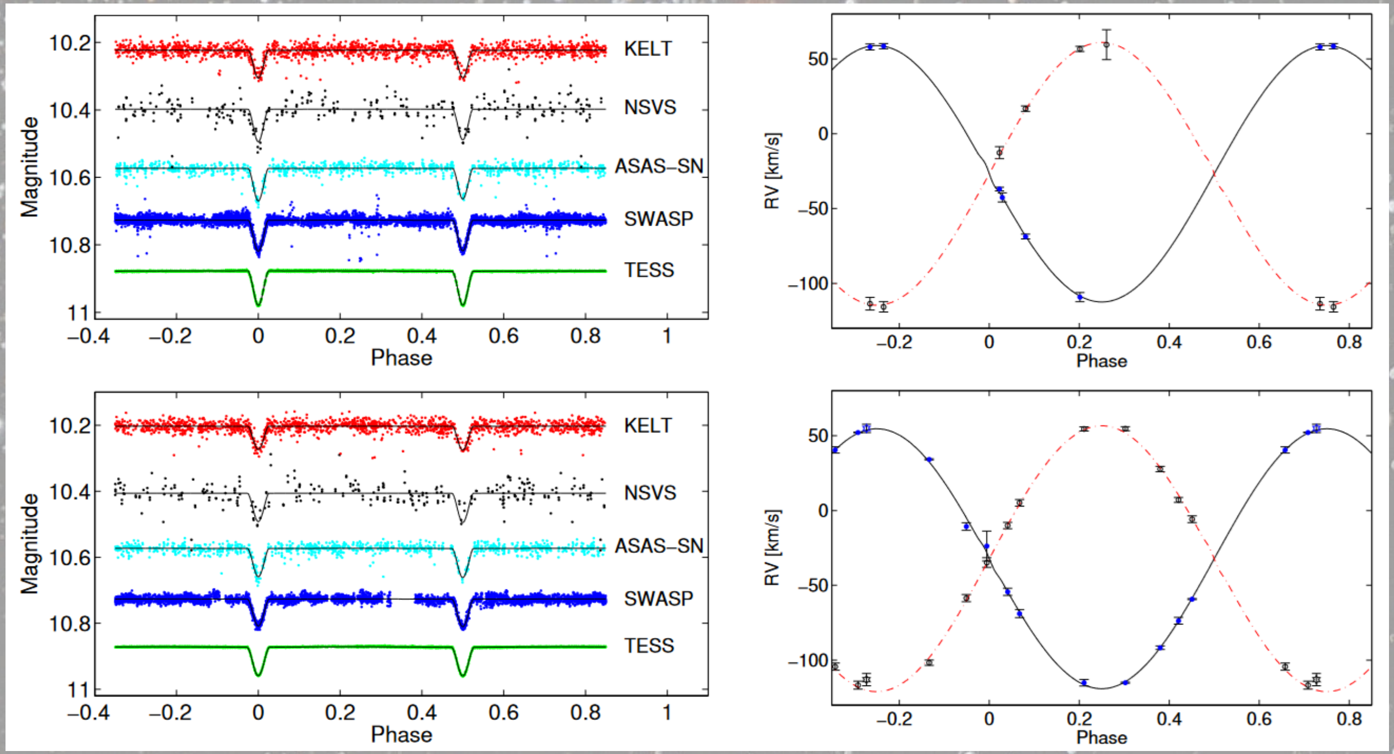


65cm Ondrejov telescope

One typical example: CzeV1731

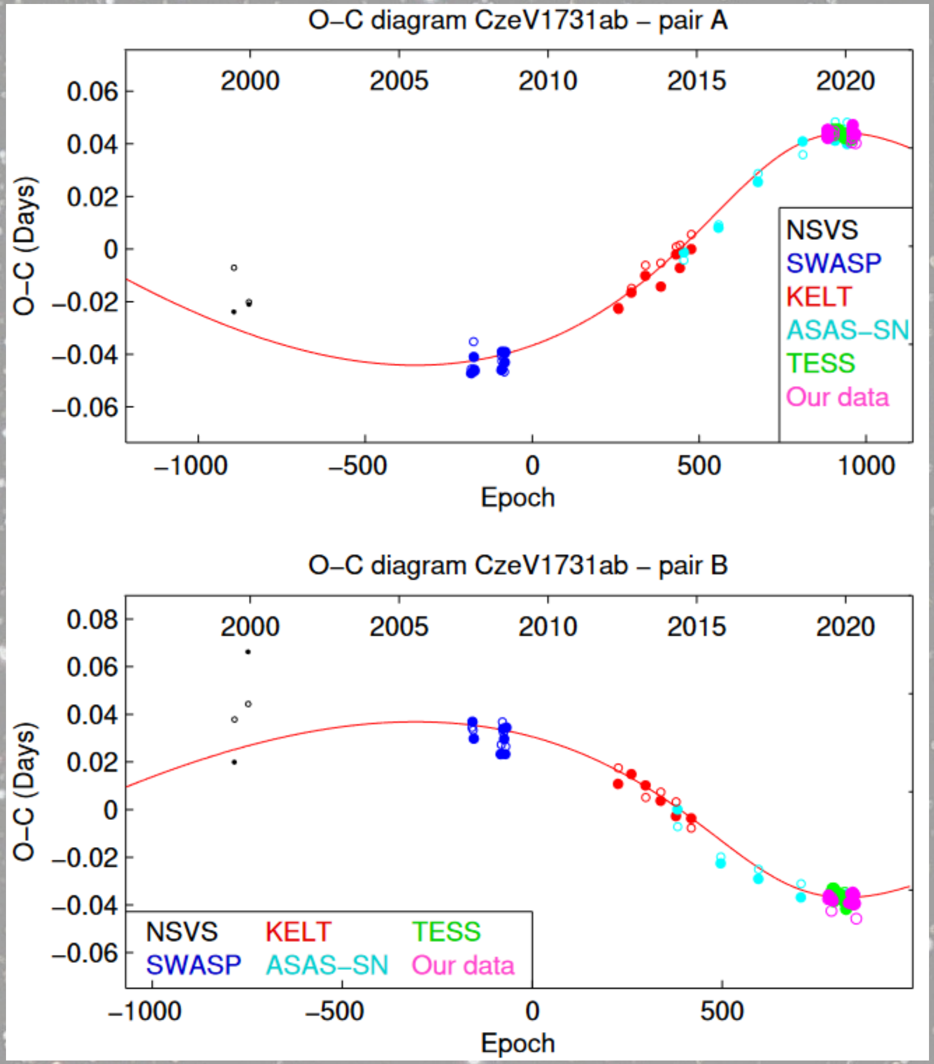
Spectroscopic data from 2m + photometric data --> LC+RV study





One typical example: CzeV1731

- Both pairs ETV period analysis
- Collecting available data
- Ground-based + satellite data
- Range > 20 yr
- Results:
  - P_A = 4.10842 d , e=0.0
  - P_B = 4.67552 d , e=0.0
  - Mutual orbit: p_{AB} = 34 yr, e_{AB} = 0.38
  - M_B/M_A = 1.2
  - Predicted: semiaxis ≈ 59 mas



Divide et impera #2 :

- Cutting the entire data set into smaller parts
- Assuming linear behavior on smaller time scales
- Period constant during shorter time interval
- All LC, RV, and ETV can be handled in this way

➡ Can such an approach be used for all of the systems?

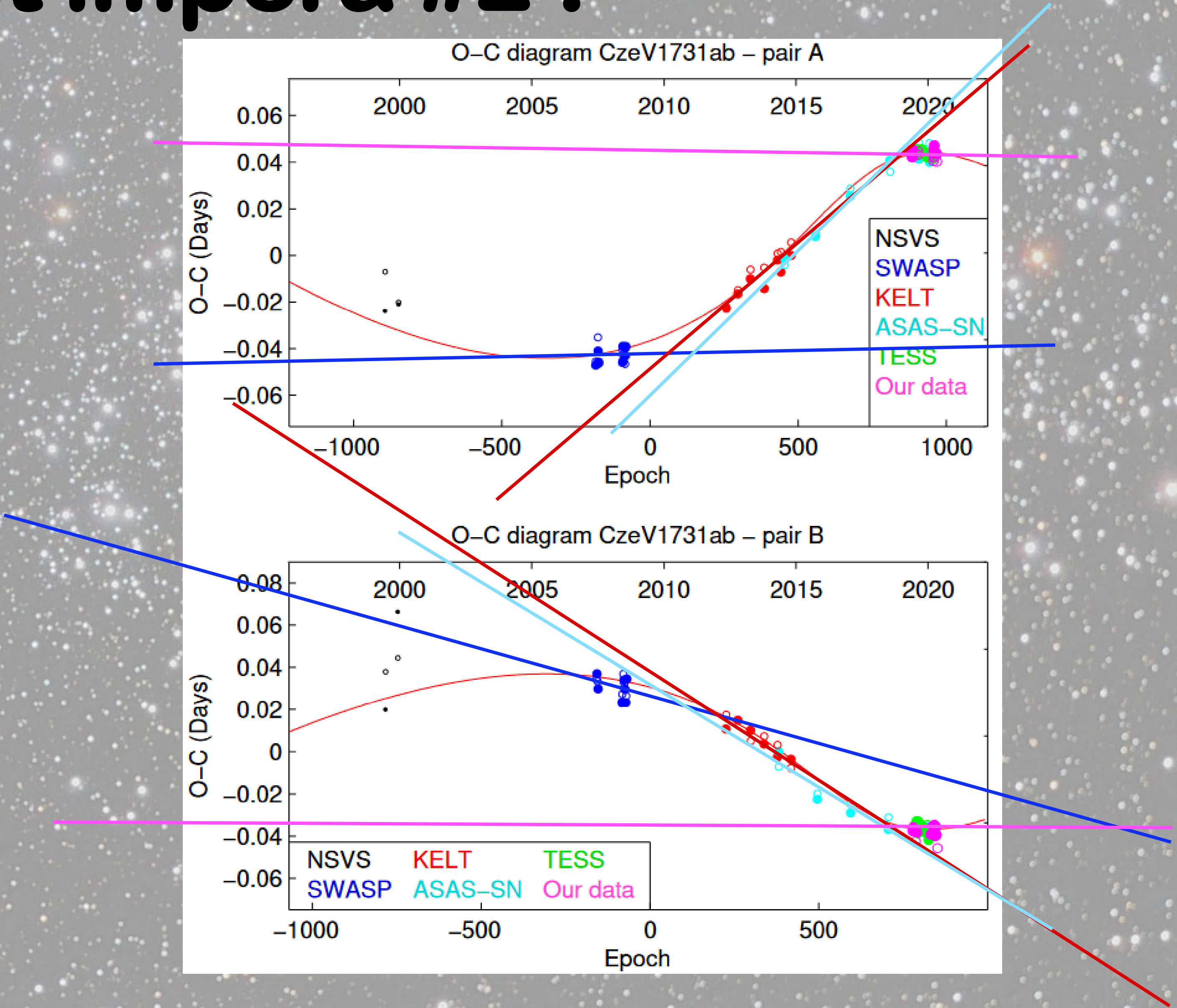
Divide et impera #2 :

- Cutting the entire data set into smaller parts
- Assuming linear behavior on smaller time scales
- Period constant during shorter time interval
- All LC, RV, and ETV can be handled in this way

➡ Can such an approach be used for all of the systems?

DEFINITELY NOT!   BUT SURPRISINGLY.....

Divide et impera #2 :

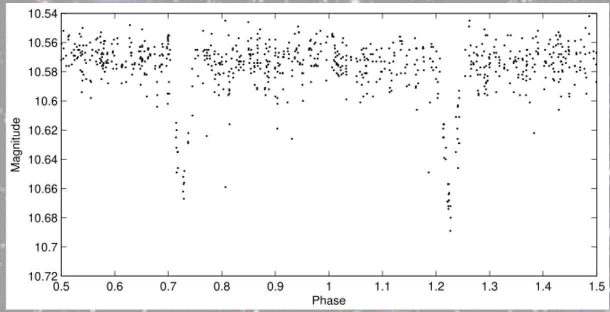


Divide et impera #2 :

- **Breaking the whole dataset to smaller parts is possible <u>only when</u>:**
  - **The outer period is long enough**
  - **The data set span is $\ll$ than the outer period**
  - **The number of data points in the smaller subset is sufficient**

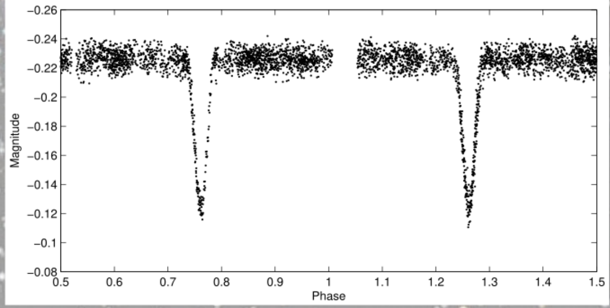
Divide et impera #2 :

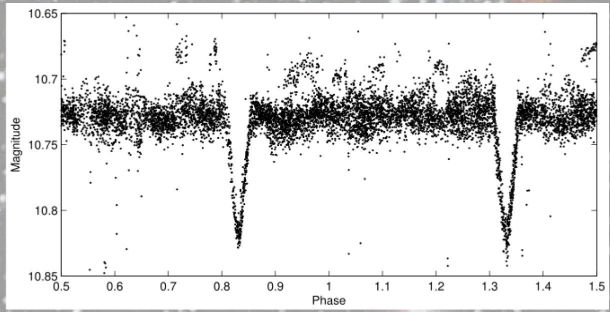
- Some examples of LCs for czev1731 star from various datasets



ASAS-SN

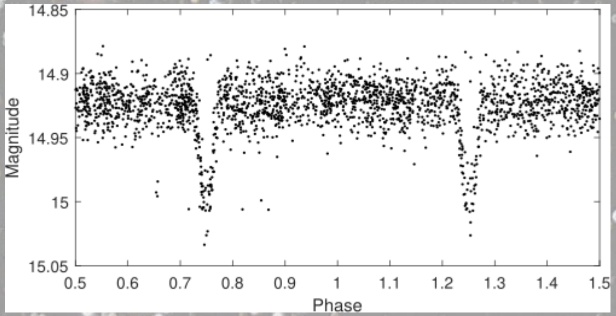
Our data





SuperWASP

KELT



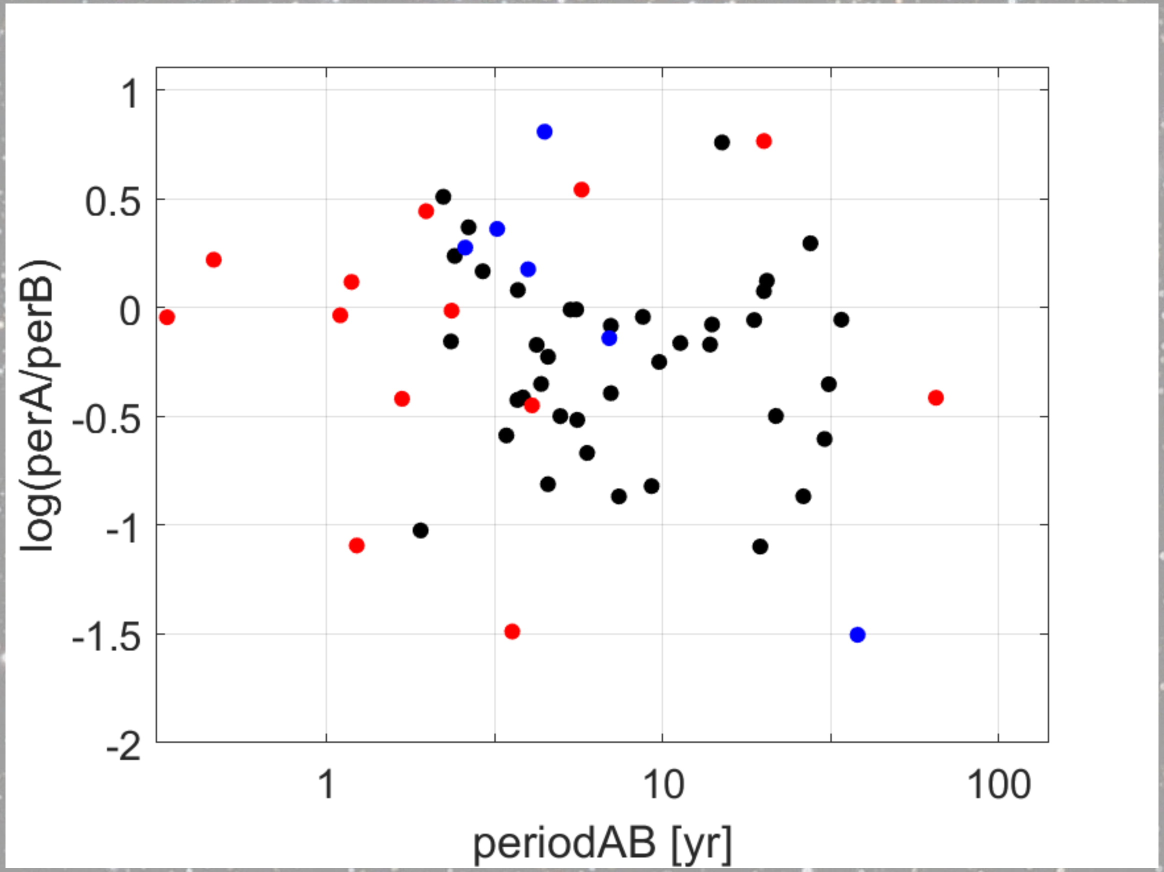
Our results

- **Using our approach we have studied and discovered in total 38 proved 2+2 doubly eclipsing quadruples (from total number of 58 of proved ones yet!)**
- **The statistics: From total number of 58 systems:**
  - **Only 4 have $P_{AB}/P_A < 100$**
  - **Only 6 have $P_{AB}/P_B < 100$**

Therefore, for the huge majority of systems our approach "divide et impera" is substantiated.

Our results - comparison

- **Periods: inner versus mutual**



Black dots: our systems

Red dots: Borkovits et al.

Blue dots: others

Our approach and its assumptions

- **For whole our analysis we assume:**
  - **Constant luminosity fraction of both A&B pairs: L_A/L_B = const.**
  - **Constant value of the third light value (i.e. non-variable third light)**
  - **Inclination of both the orbits also constant**

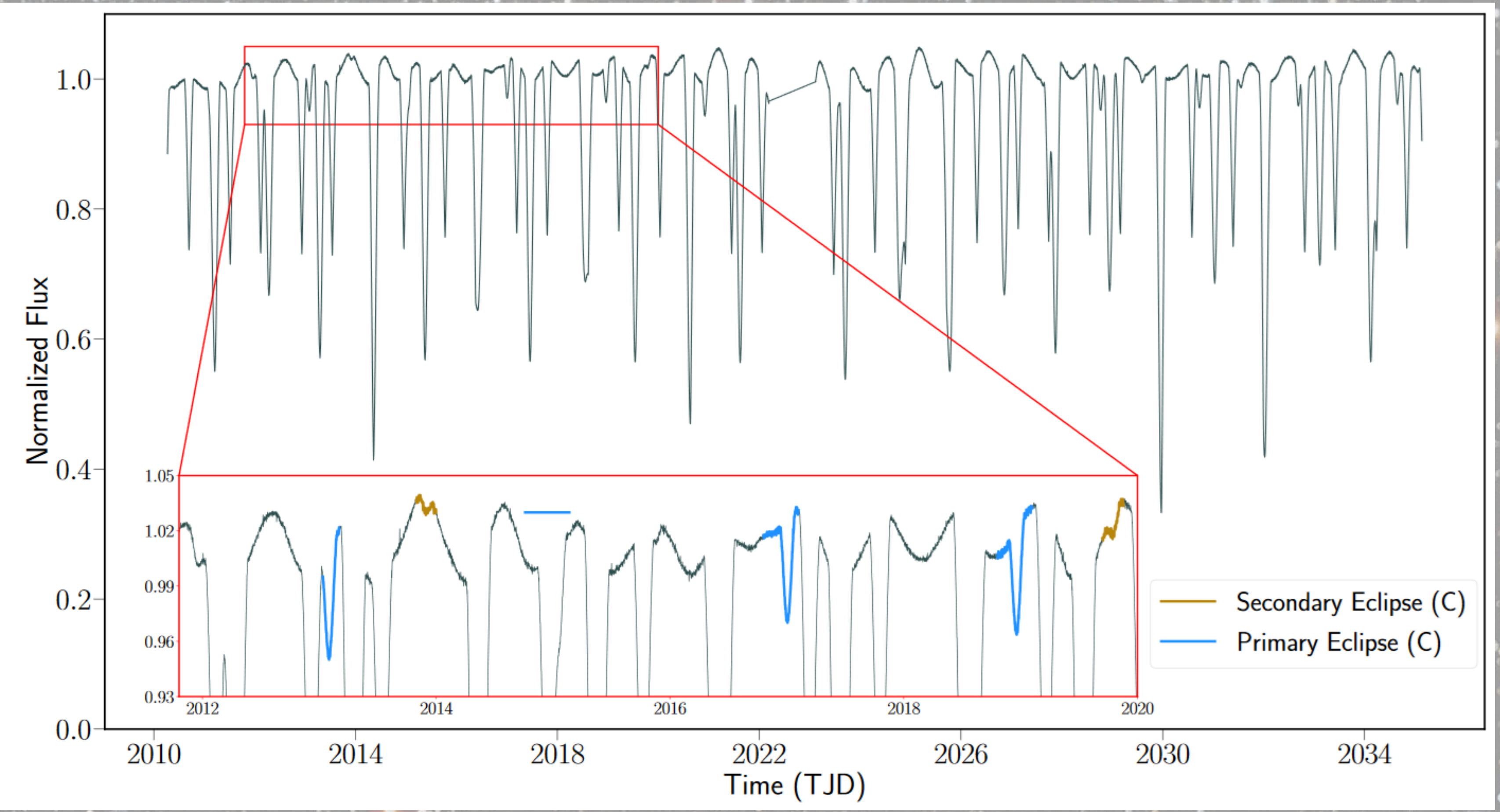
- **On the other hand, what can even change and is computed:**
  - **Periods of both A&B, apsidal motion of both pairs, etc.**

Things are sometimes more complicated

- For some systems these assumptions do not work…
- V994 Her – more complicated system!

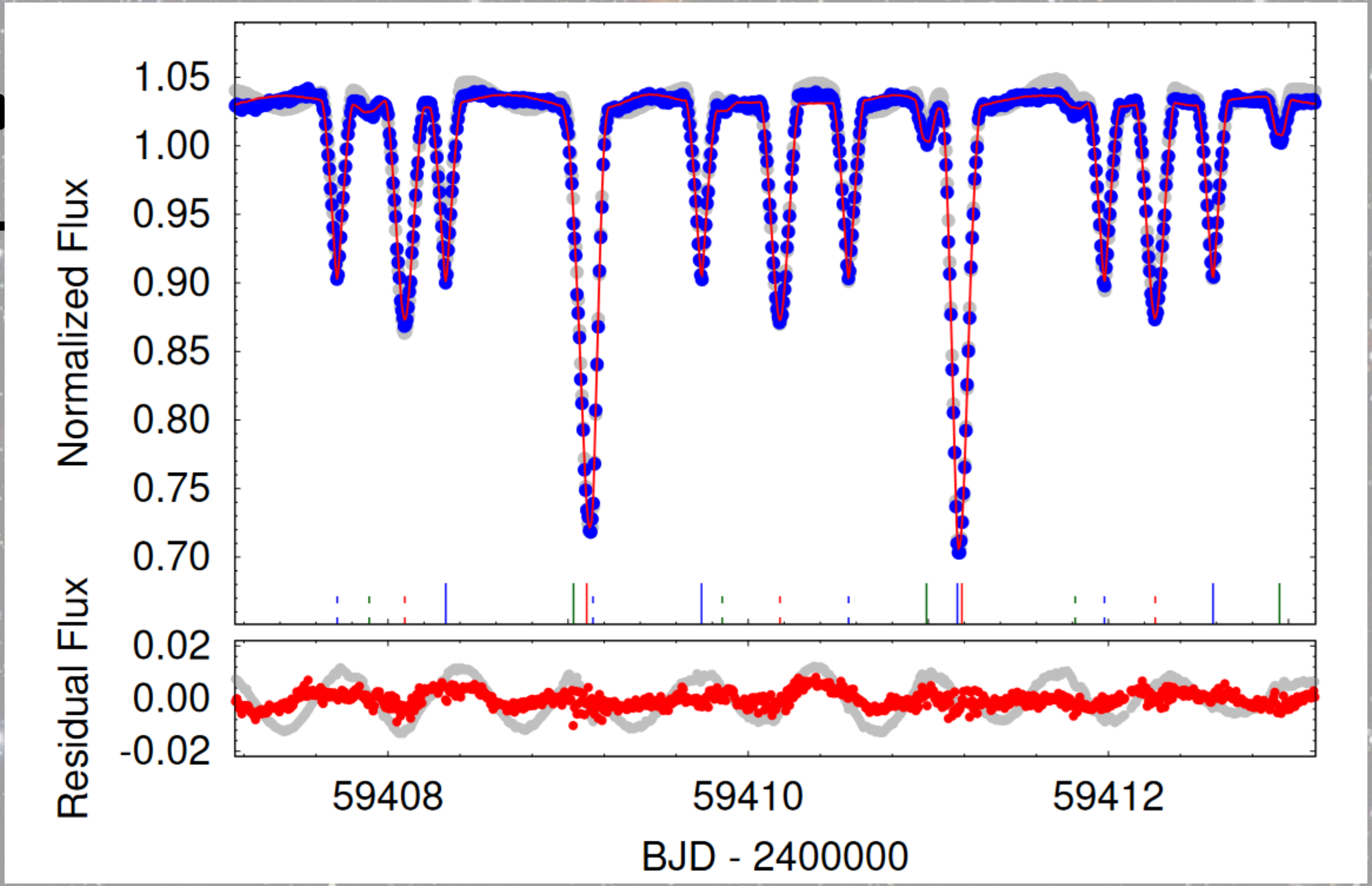
Things are sometimes more complicated

- For sc
- V994



Things are sometimes more complicated

- For so
- V994 H



Things are sometimes more complicated

- For
- V99

Parameter	Binary A	Binary B	Binary C	A–B orbit
P_a [days]	$2.0832039^{+0.0000042}_{-0.0000039}$	$1.4200981^{+0.0000033}_{-0.00000040}$	$1.9601064^{+0.0000018}_{-0.0000018}$	$1062.3^{+2.2}_{-1.6}$
a [$R_\odot$]	$11.90^{+0.18}_{-0.21}$	$8.27^{+0.08}_{-0.07}$	$9.00^{+0.08}_{-0.07}$	911^{+11}_{-12}
i^a [deg]	$84.26^{+0.40}_{-0.36}$	$89.37^{+0.37}_{-0.35}$	$85.90^{+1.17}_{-1.02}$	$85.0^{+3.2}_{-3.7}$
e	$0.0271^{+0.0012}_{-0.0013}$	$0.1187^{+0.0007}_{-0.0007}$	$0.1701^{+0.0064}_{-0.0087}$	$0.694^{+0.027}_{-0.027}$
ω [deg]	$206.2^{+4.3}_{-6.1}$	$173.6^{+2.2}_{-2.8}$	$314.0^{+3.4}_{-2.3}$	$59.1^{+3.0}_{-3.0}$
$\dot{\omega}$ [deg/yr]	$1.85^{+0.70}_{-0.63}$	$3.60^{+0.14}_{-0.18}$	$2.04^{+0.30}_{-0.35}$	–
τ [BJD - 2 400 000]	$59\,010.842^{+0.025}_{-0.035}$	$59\,010.389^{+0.009}_{-0.011}$	$59\,009.338^{+0.018}_{-0.012}$	$58\,167.6^{+9.7}_{-6.9}$
$t_{\rm prim\ eclipse}$ [BJD - 2 400 000]	$59\,011.1822^{+0.0008}_{-0.0010}$	$59\,010.7330^{+0.0017}_{-0.0018}$	$59\,011.1252^{+0.0003}_{-0.0003}$	–
q ($= m_2/m_1$)	$0.760^{+0.008}_{-0.008}$	$1.007^{+0.008}_{-0.007}$	$0.534^{+0.031}_{-0.038}$	$0.724^{+0.021}_{-0.018}$
$K_{\rm pri}$ [km s^{-1}]	124^{+2}_{-3}	149^{+2}_{-1}	82^{+3}_{-4}	25^{+1}_{-1}
$K_{\rm sec}$ [km s^{-1}]	163^{+2}_{-2}	148^{+1}_{-1}	154^{+4}_{-4}	35^{+2}_{-2}
γ [km/s]	–	–	–	$-39.0^{+0.5}_{-0.4}$

individual stars	Aa	Ab	Ba	Bb	Ca	Cb
Relative Quantities:						
fractional radius[b] [R/a]	$0.1773^{+0.0027}_{-0.0022}$	$0.1461^{+0.0017}_{-0.0021}$	$0.1907^{+0.0021}_{-0.0027}$	$0.1915^{+0.0020}_{-0.0028}$	$0.1673^{+0.0019}_{-0.0021}$	$0.0874^{+0.0084}_{-0.0044}$
fractional luminosity in *TESS*-band	$0.4198^{+0.0086}_{-0.0095}$	$0.2077^{+0.0113}_{-0.0121}$	$0.1290^{+0.0023}_{-0.0019}$	$0.1315^{+0.0024}_{-0.0021}$	$0.0930^{+0.0112}_{-0.0126}$	$0.0067^{+0.0012}_{-0.0012}$
fractional luminosity in *V*-band	$0.4406^{+0.0124}_{-0.0176}$	$0.2084^{+0.0130}_{-0.0153}$	$0.1200^{+0.0033}_{-0.0031}$	$0.1232^{+0.0035}_{-0.0034}$	$0.0763^{+0.0130}_{-0.0148}$	$0.0032^{+0.0008}_{-0.0007}$
Physical Quantities:						
$T^c_{\rm eff}$ [K]	11879^{+362}_{-325}	9915^{+289}_{-264}	8643^{+241}_{-179}	8695^{+242}_{-190}	7785^{+351}_{-285}	5181^{+156}_{-220}
mass [$M_\odot$]	$2.957^{+0.133}_{-0.146}$	$2.251^{+0.107}_{-0.125}$	$1.876^{+0.050}_{-0.048}$	$1.889^{+0.055}_{-0.049}$	$1.662^{+0.052}_{-0.055}$	$0.888^{+0.039}_{-0.046}$
radius[c] [$R_\odot$]	$2.110^{+0.024}_{-0.023}$	$1.741^{+0.039}_{-0.057}$	$1.580^{+0.024}_{-0.032}$	$1.586^{+0.024}_{-0.034}$	$1.507^{+0.020}_{-0.023}$	$0.789^{+0.073}_{-0.044}$
luminosity[c] [$L_\odot$]	$79.5^{+11.4}_{-9.4}$	$26.3^{+4.4}_{-4.1}$	$12.5^{+1.4}_{-1.1}$	$12.9^{+1.5}_{-1.2}$	$7.5^{+1.4}_{-1.1}$	$0.40^{+0.08}_{-0.07}$
[$M_{\rm bol}$]	$0.02^{+0.14}_{-0.15}$	$1.22^{+0.18}_{-0.17}$	$2.03^{+0.10}_{-0.12}$	$2.00^{+0.10}_{-0.12}$	$2.59^{+0.17}_{-0.18}$	$5.76^{+0.22}_{-0.20}$
$\log g^c$ [cgs]	$4.260^{+0.014}_{-0.019}$	$4.309^{+0.007}_{-0.006}$	$4.314^{+0.011}_{-0.009}$	$4.314^{+0.011}_{-0.009}$	4.302	$4.597^{+0.026}_{-0.075}$

log(age) [dex]	$7.79^{+0.26}_{-0.21}$
$(M_V)^c_{\rm tot}$	$-0.24^{+0.07}_{-0.08}$
distance [pc]	271^{+7}_{-6}

Things are sometimes more complicated

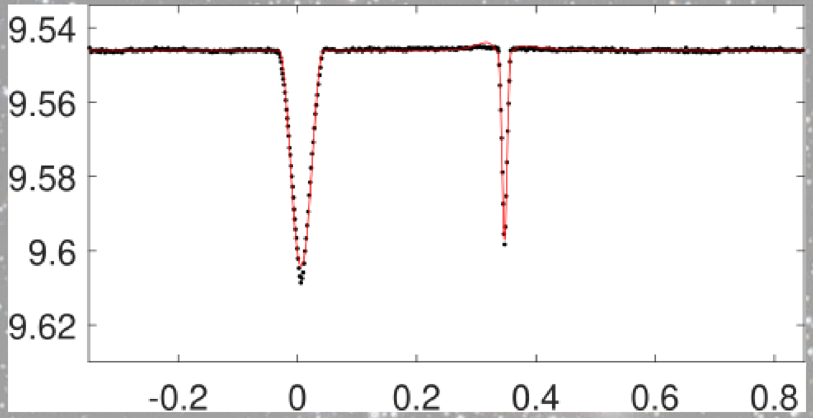
- **For some systems these assumptions do not work…**
- **The star named CzeV4315:**
  - Discovered by Z.Henzl
  - Bright star, V = 9.6mag
  - In nebula, dense area, near galactic plane
  - Visual double star (2", $\Delta M \approx$ 2 mag), or CPM pair
  - Several spectral type estimates: A0, B8, B9

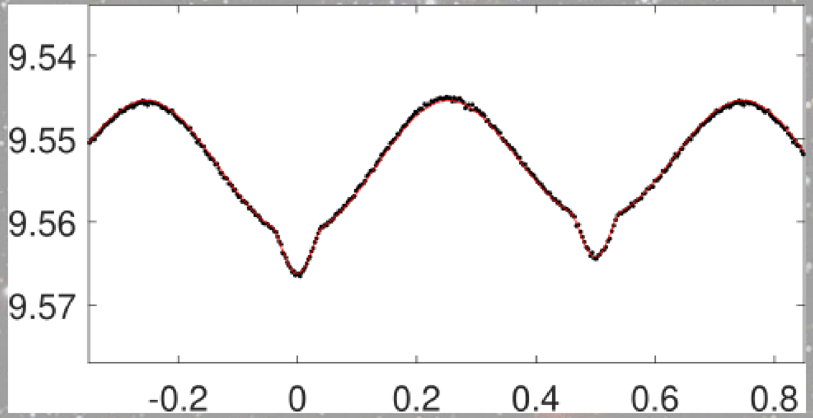
CzeV4315

- TESS data shows two periodicities:
- 1:
  - Detached LC, period 6.74d
  - Very eccentric orbit
  - Prim eclipse: 12h, sec eclipse 3.5h
- 2:
  - Close but still detached pair, period 0.919d
  - Eclipses on TESS data deeper and deeper

- Unfortunately, no other usable photometry (ZTF, SWASP, Atlas, ASASsn)

CzeV4315

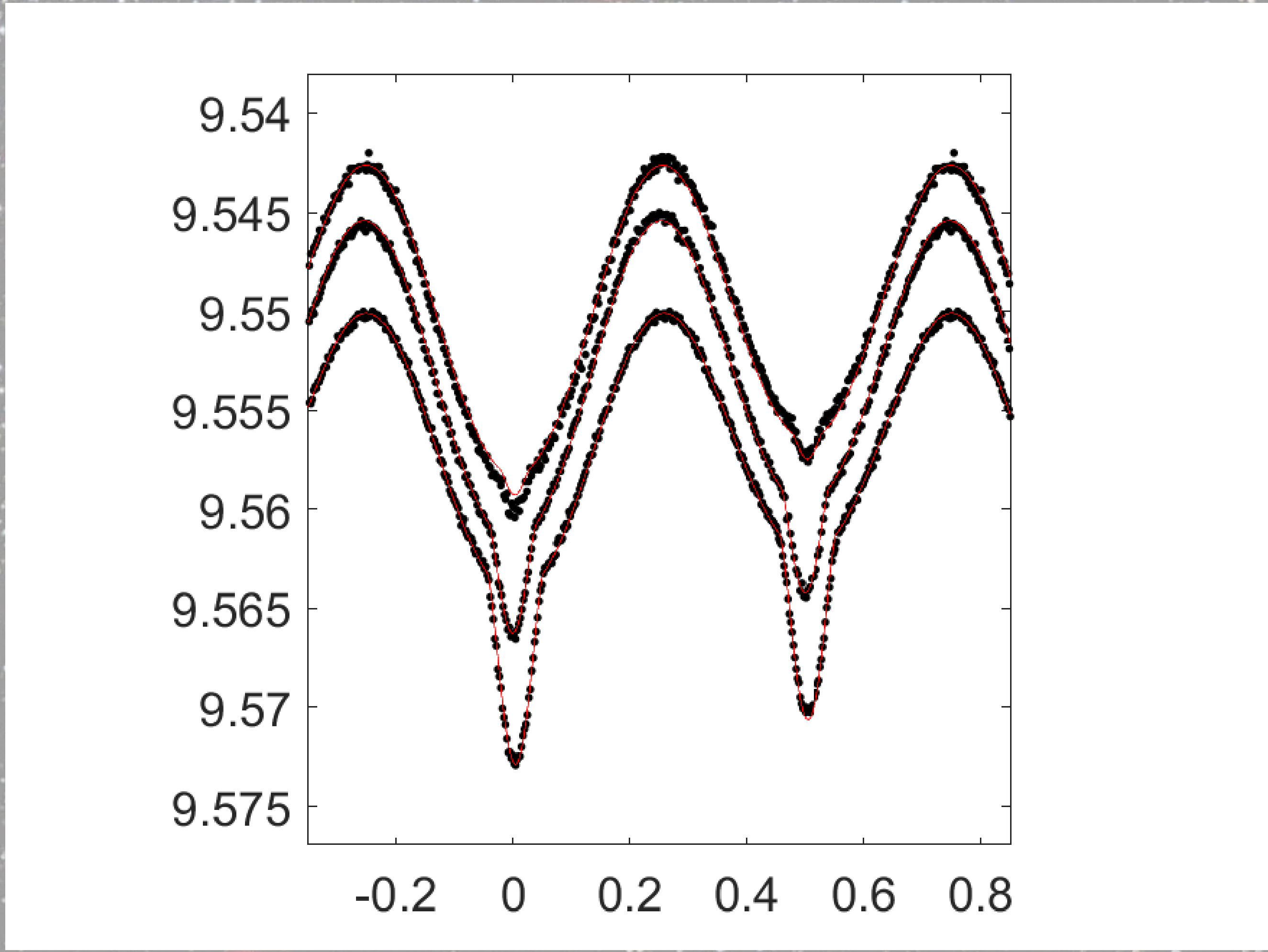




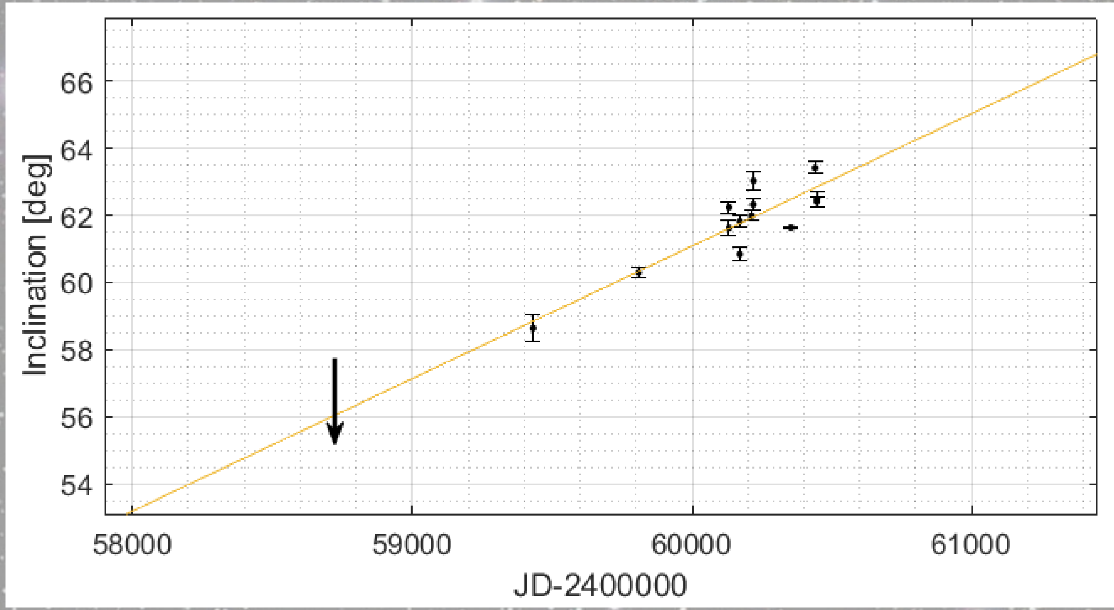
- **Preliminary pair A:**
  - **P = 6.739 d**
  - **e = 0.69**
  - **Slow apsidal motion**
  - **Constant inclination**

- **Preliminary pair B**
  - **P = 0.9193 d, circular**
  - **TESS sect 14+15: only ELL variations**
  - **TESS sect 41: start of eclipses**
  - **TESS sect 55: clearly visible eclipses**
  - **TESS sect 75: deep enough for ground based observations**

CzeV4315 – evolution during TESS sectors

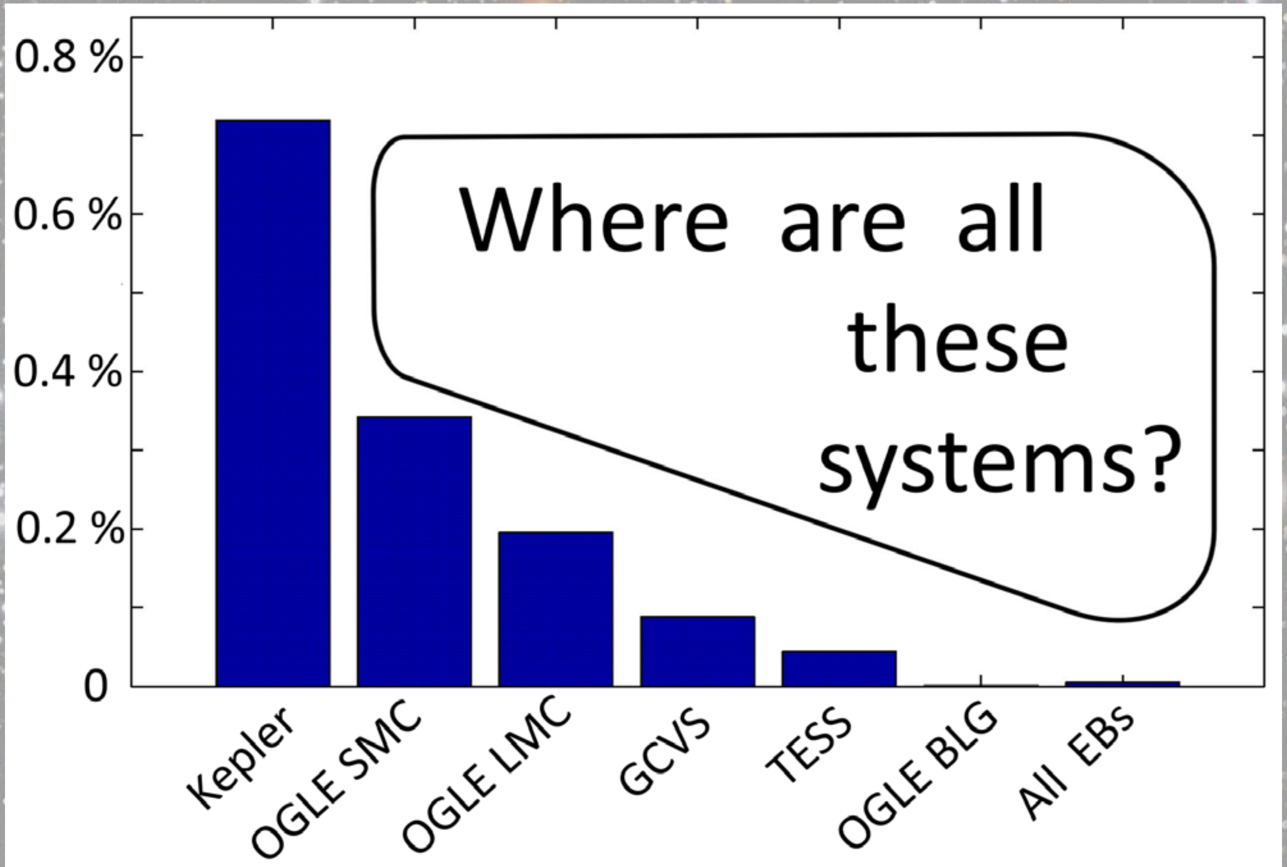


CzeV4315 – inclination change



- Rapid inclination change
- Now visible on ground-based data
- Rough estimation of nodal precession: second fastest!
- Rough estimation of mutual period A-B ≈ 200-300 days

Inclination changing stars – very rare!

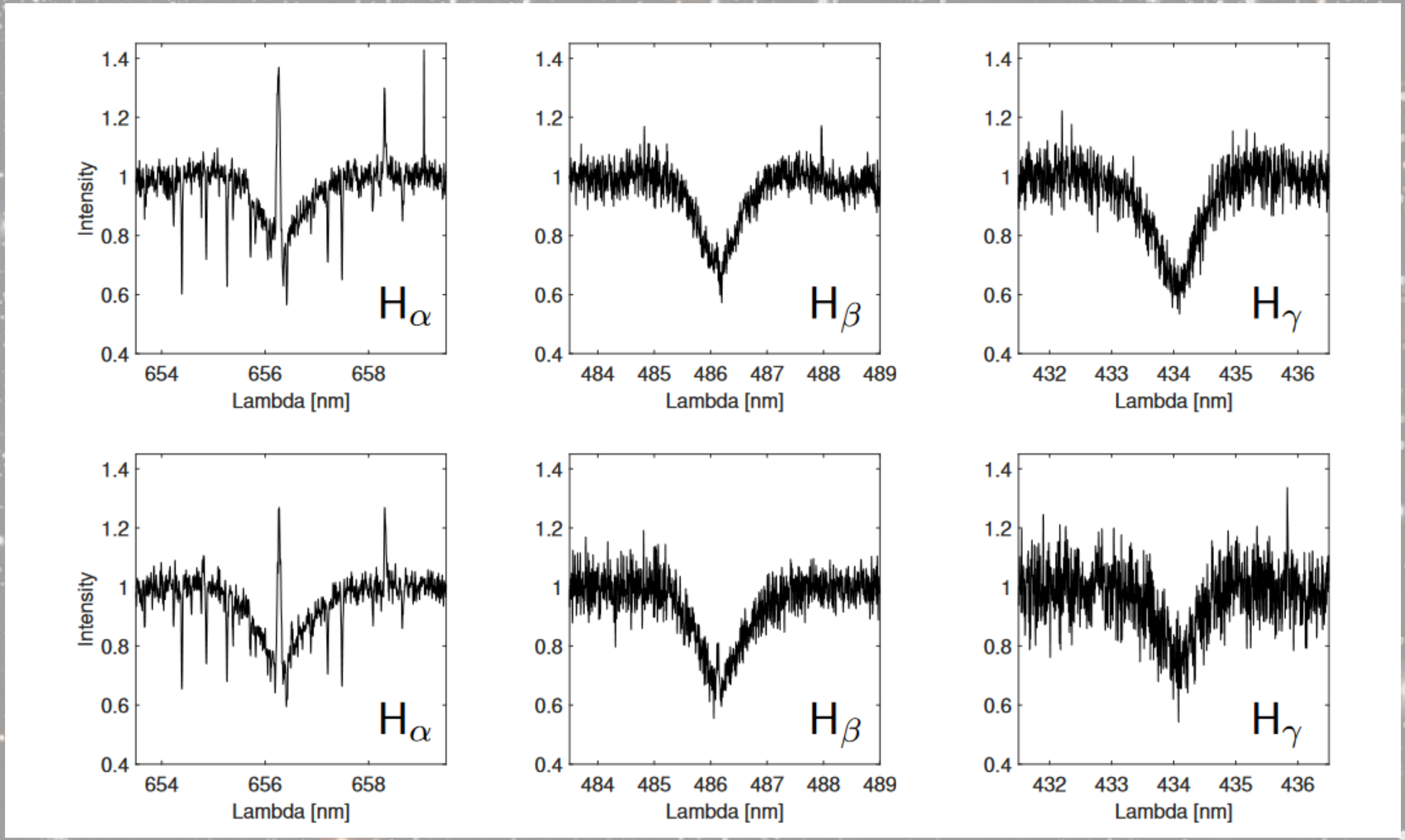


Conclusion

- Doubly eclipsing systems as unique celestial mechanics laboratory
- Complicated for modelling – taking all constraints into account
- Still very limited number of proved 2+2 quadruples
- For most of them the "divide et impera" method sufficient
- In general, the dynamical interactions should always be tested

This is the end…

my only friend, the end



Intensity
Lambda [nm]
Hα
Hβ
Hγ
Intensity
Lambda [nm]
Hα
Hβ
Hγ