Beyond the regular:
Census of Non-evolutionary effects on period change from O-C study of 7000+ Magellanic Cepheids

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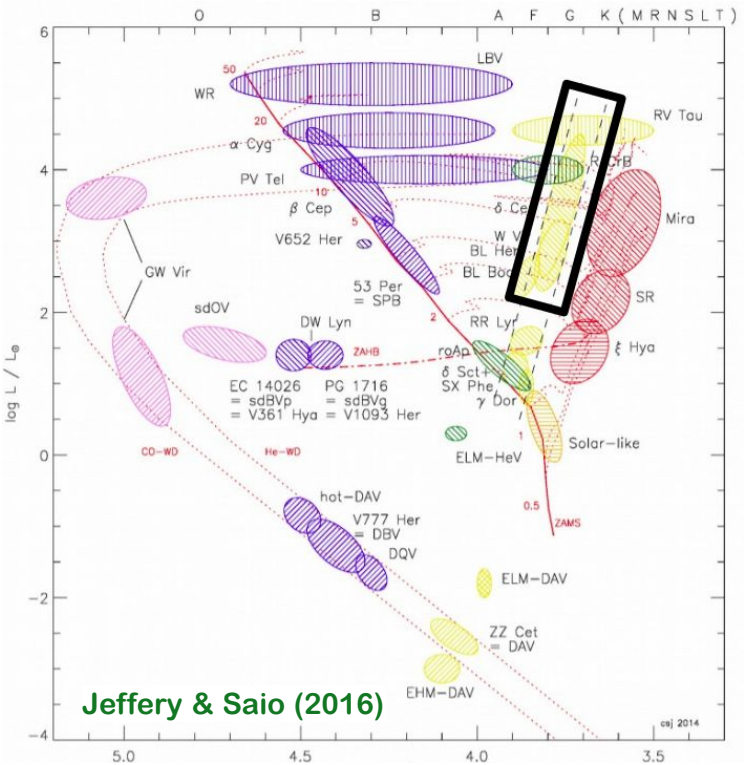
CEPHEIDS

- Classical Cepheids: mainly core He burning stars
  Period: 1–100 days
  Mass: ~3–13 M⊙

- Excellent for extragalactic distance indicators

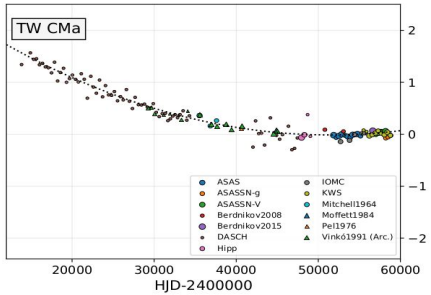
- Perfect for stellar evolution and pulsation studies



Taxonomy of Period Changes (PC)

Evolutionary
($\sim 10^4$-10^7 yr)

Positive



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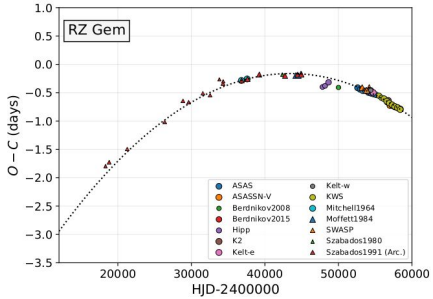

G. Csörnyei et al. (2021)

Taxonomy of Period Changes (PC)

Evolutionary ($\sim 10^4$-10^7 yr)

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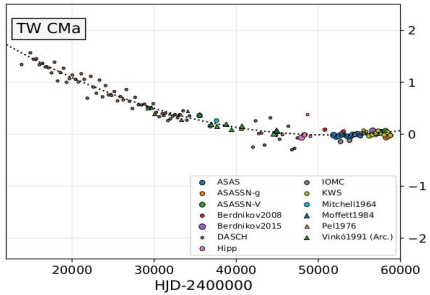

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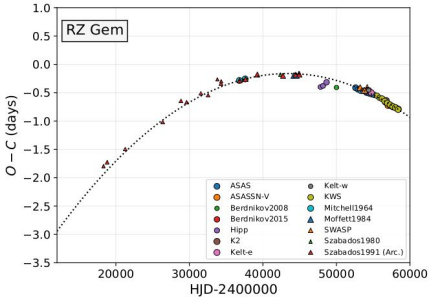
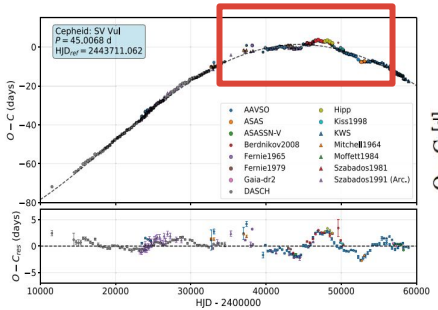


G. Csörnyei et al. (2021)

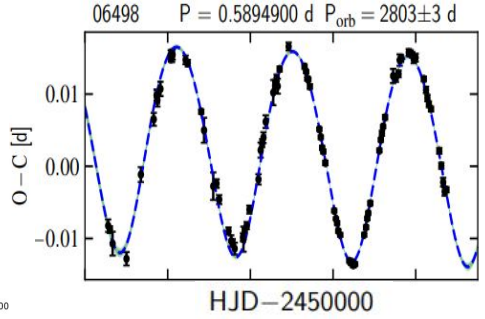
Non-evolutionary ($\sim 10^3$ days)

Irregular



G. Csörnyei et al. (2021)

Periodic



G. Hajdu et al. (2021)

Taxonomy of Period Changes (PC)

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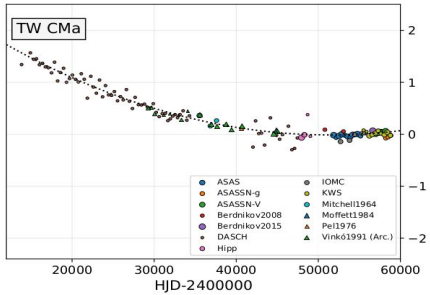

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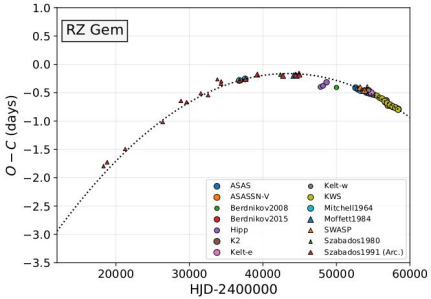
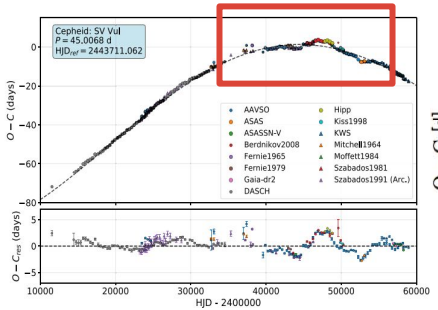


G. Csörnyei et al. (2021)

Non-evolutionary ($\sim 10^3$ days)

Irregular ??



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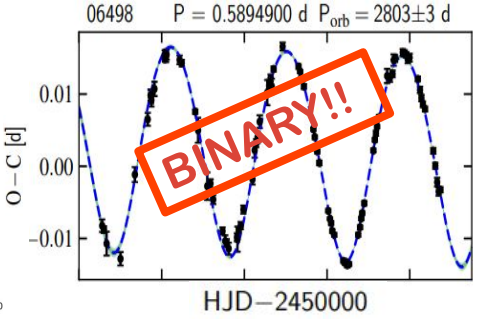


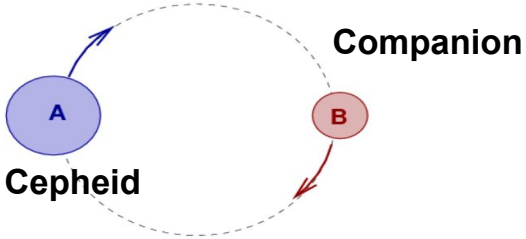
G. Hajdu et al. (2021)

NON-EVOLUTIONARY PC-I

Binary hunt begins

Rathour et al. 2024a (Published)

MOTIVATION



- **Data: OGLE survey (15+ years data)**
- **LMC/SMC fields: Completeness near 100%**
  Soszyński et al. (2017) **with 9649 Cepheids**
- **Context: ~25 LMC (~5 EBs)**
  (Pilecki et al. 2021; Szabados & Nehez 2012)
  ~ 9 SMC (~2 EBs)
  (Szabados & Nehez 2012)
  BIND Cepheids 9 new SB2 (Pilecki et al. 2024)

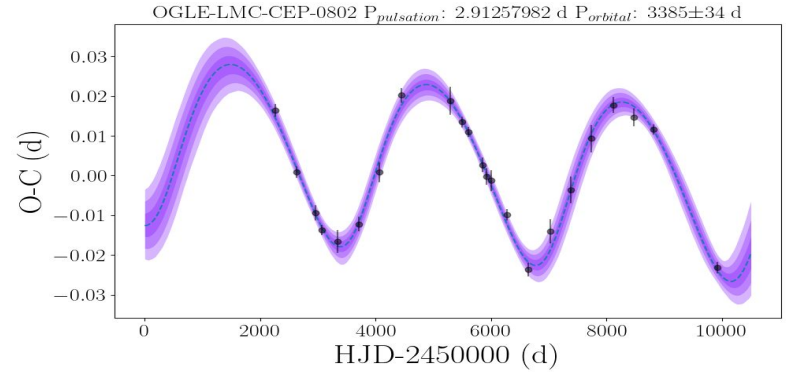
RESULTS: Binary Statistics

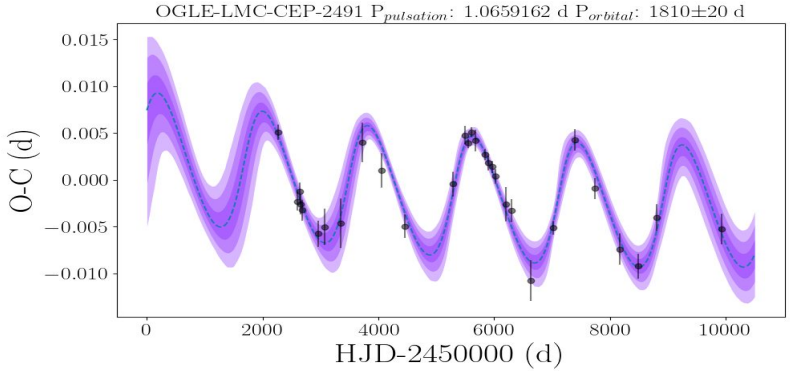
	LMC F	LMC 1O	SMC F	SMC 1O
Starting sample:	1801	1238	2582	1617
O-C + stat. Inspection:	39	52	102	133
Posterior filtering:	30	22	85	60

Eight parameters: P(orb), T(per), e, asini, omega, PCR, K and f(m)

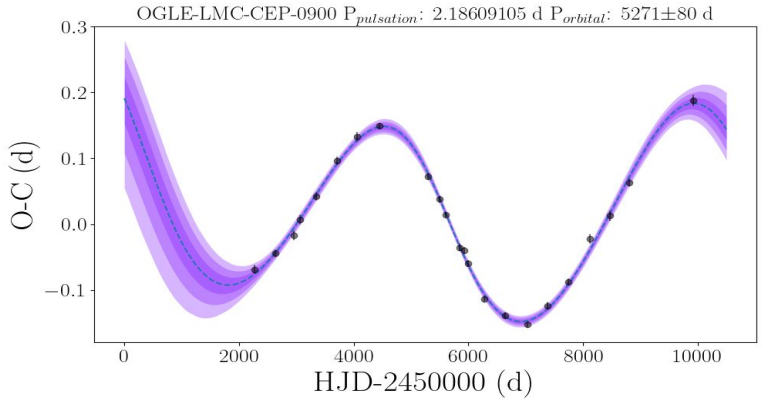
LMC Binary candidates

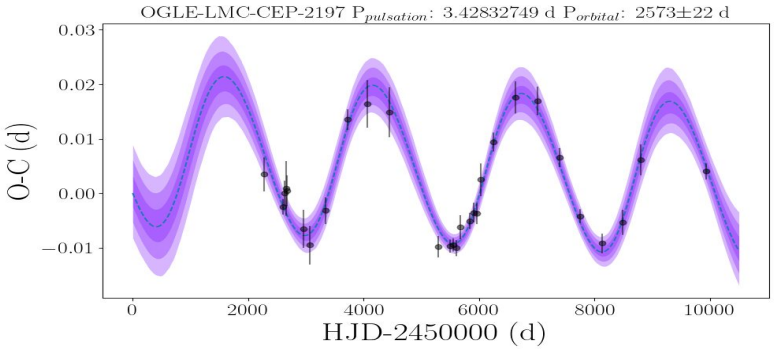
Fundamental



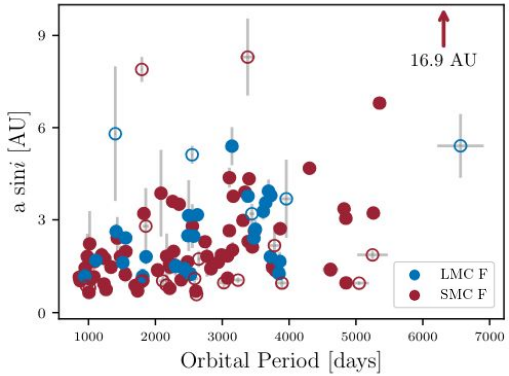


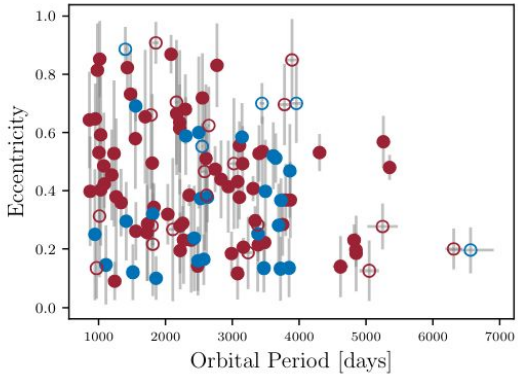
Overtone

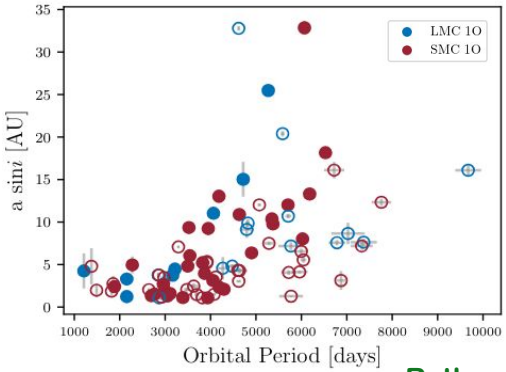


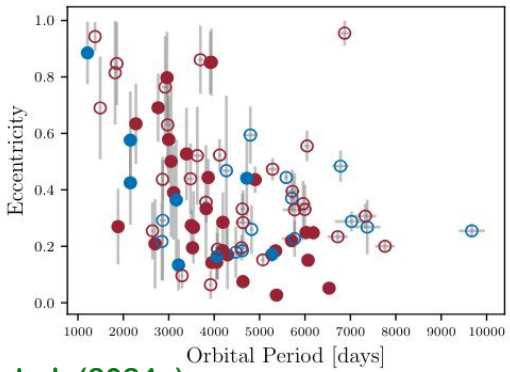


RESULTS: Orbital Parameters



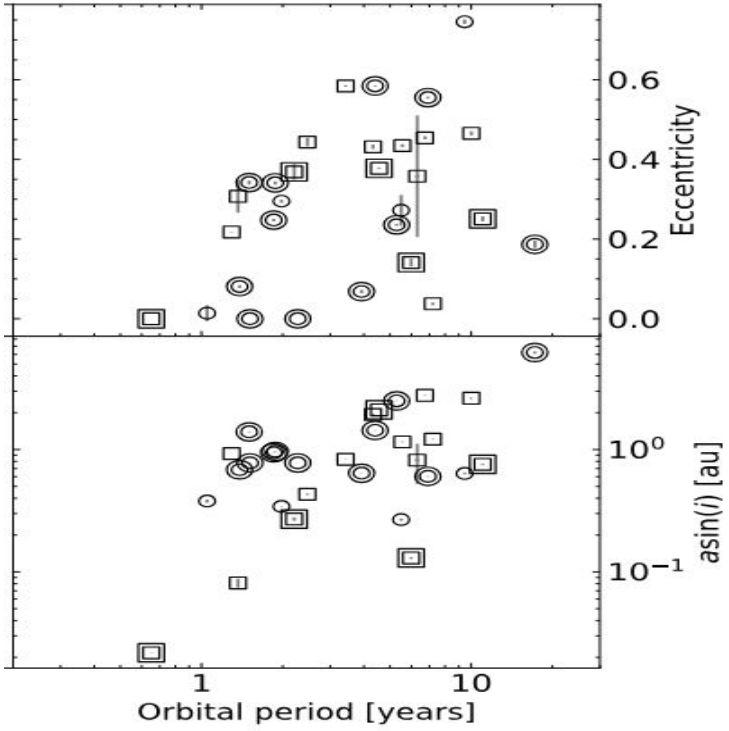






Rathour et al. (2024a)

GALACTIC (VELOCE SURVEY)



Shetye et al. (2024)

CEPHEID COMPANIONS

RESULTS: Mass Estimation

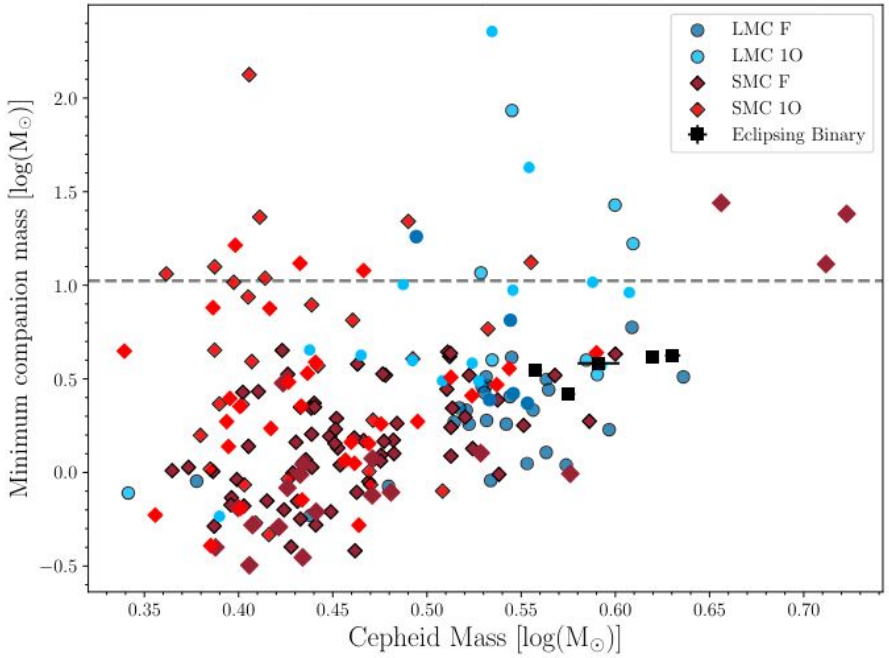
- **Minimum companion mass relation**

$$f(m) = \frac{m_c^3 \sin^3 i}{(m_{cep} + m_c)^2},$$

- **Cepheid mass estimated with P-M relation** Groenewegen & Lub (2023)

$$\log(M/M_\odot) = (0.368 \pm 0.022) + (0.352 \pm 0.018) \log P.$$

RESULTS: Mass Estimation



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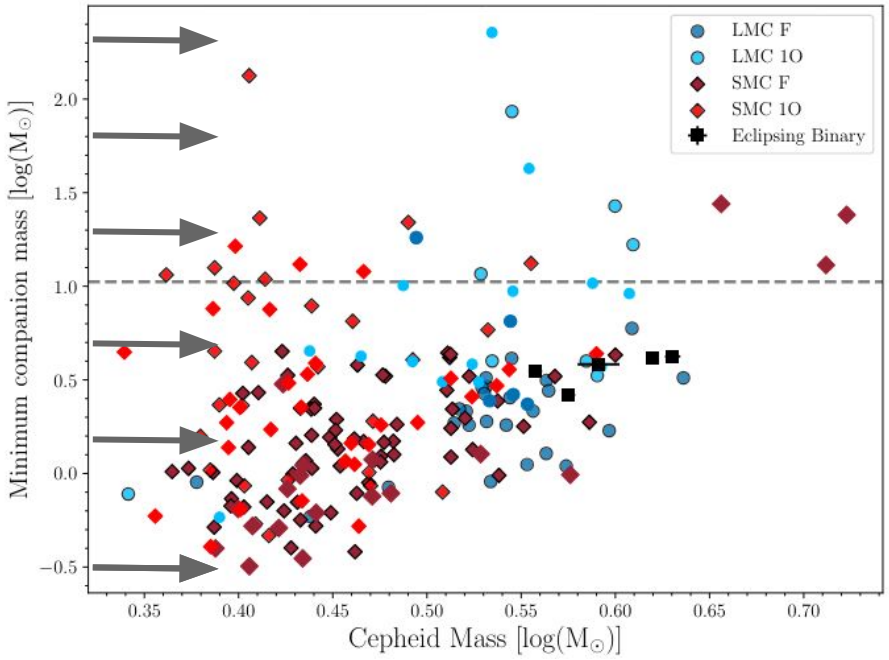
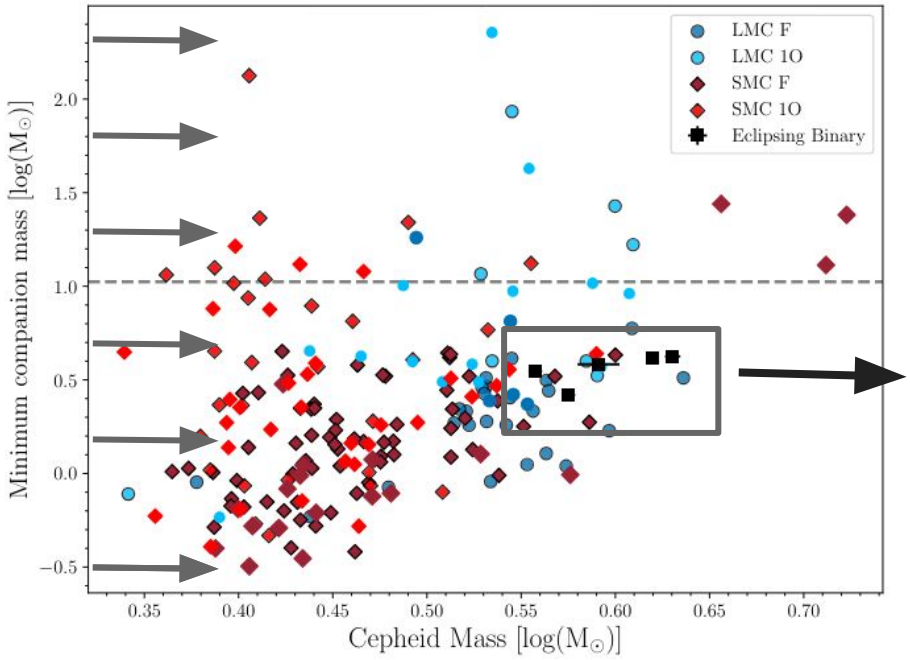


Caveat!

Cepheid Masses are systematically underestimated by ~1 $M_\odot$

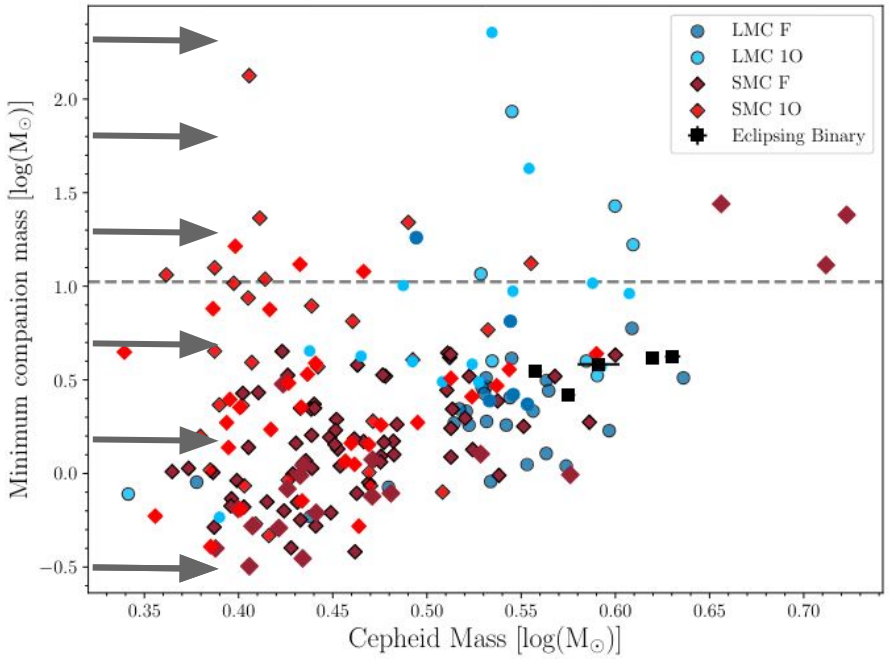
Need better P-M relation at short periods!

RESULTS: Mass Estimation



Cepheids in eclipsing binaries

RESULTS: Mass Estimation



Probably unphysical!

Massive companions!

(Non-evolutionary PC? Triple systems? Black holes?)

: | **:o** **:O**

RESULTS: Mass Estimation

A cautionary tale of interpreting O−C diagrams: period instability in a classical RR Lyr Star Z CVn mimicking as a distant companion

M. Skarka,[1,2★] J. Liška,[2,3★] R. Dřevěný,[2,4] E. Guggenberger,[5,6] Á. Sódor,[1] T. G. Barnes[7] and K. Kolenberg[8,9]

ABSTRACT

We present a comprehensive study of Z CVn, an RR Lyrae star that shows long-term cyclic variations of its pulsation period. A possible explanation suggested from the shape of the O−C diagram is the light travel-time effect, which we thoroughly examine. We used original photometric and spectroscopic measurements and investigated the period evolution using available maximum times spanning more than one century. If the binary hypothesis is valid, Z CVn orbits around a black hole with minimal mass of 56.5 $\mathfrak{M}_\odot$ on a very wide ($P_{\rm orbit} = 78.3$ yr) and eccentric orbit ($e = 0.63$). We discuss the probability of the formation of a black hole–RR Lyrae pair, and, although we found it possible, there is no observational evidence of the black hole in the direction to Z CVn. However, the main objection against the binary hypothesis is the comparison of the systemic radial velocity curve model and spectroscopic observations that clearly show that Z CVn cannot be bound in such a binary. Therefore, the variations of pulsation period are likely intrinsic to the star. This finding represents a discovery/confirmation of a new type of cyclic period changes in RR Lyrae stars. By the analysis of our photometric data, we found that the Blazhko modulation with period of 22.931 d is strongly dominant in amplitude. The strength of the phase modulation varies and is currently almost undetectable. We also estimated photometric physical parameters of Z CVn and investigated their variations during the Blazhko cycle using the inverse Baade–Wesselink method.

Massive companions!

(Non-evolutionary PC? Triple systems? Black holes?)

: | **:o** **:O**

RESULTS: Mass Estimation

HIGH-MASS TRIPLE SYSTEMS: THE CLASSICAL CEPHEID Y CARINAE[1]

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Received 2004 November 29; accepted 2005 March 22

Massive companions!

(Non-evolutionary PC? Triple systems? Black holes?)

: | **:o** **:O**

ABSTRACT

We have obtained a *Hubble Space Telescope* STIS ultraviolet high-dispersion echelle-mode spectrum of the binary companion of the double-mode classical Cepheid Y Car. The velocity measured for the hot companion from this spectrum is very different from reasonable predictions for binary motion, implying that the companion is itself a short-period binary. The measured velocity changed by 7 km s^{-1} during the 4 days between two segments of the observation, confirming this interpretation. We summarize "binary" Cepheids that are in fact members of a triple system and find that at least 44% are triples. The summary of information on Cepheids with orbits makes it likely that the fraction is underestimated.

RESULTS: Mass Estimation

A Sun-like star orbiting a black hole

Kareem El-Badry [1,2,3★] Hans-Walter Rix,[3] Eliot Quataert [4] Andrew W. Howard,[5] Howard Isaacson,[6,7]
Jim Fuller [5] Keith Hawkins [8] Katelyn Breivik,[9] Kaze W. K. Wong,[9] Antonio C. Rodriguez,[5]
Charlie Conroy,[1] Sahar Shahaf [10] Tsevi Mazeh [11] Frédéric Arenou,[12] Kevin B. Burdge [13]
Dolev Bashi [11] Simchon Faigler,[11] Daniel R. Weisz [6] Rhys Seeburger [3] Silvia Almada Monter[3]
and Jennifer Wojno[3]

Massive companions!

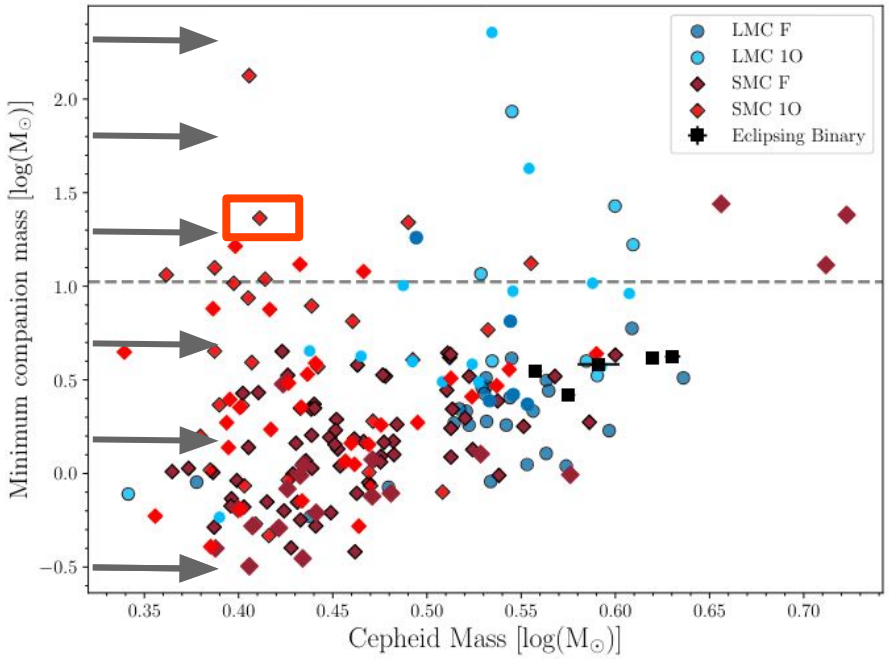
(Non-evolutionary PC? Triple systems? Black holes?)

: | **:o** **:O**

A red giant orbiting a black hole

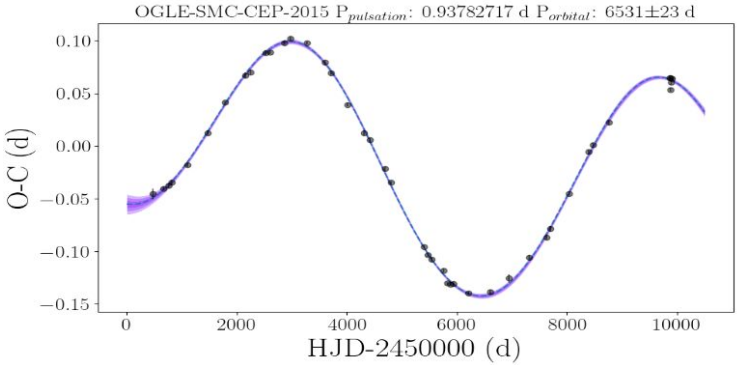
Kareem El-Badry [1,2,3,4★] Hans-Walter Rix,[3] Yvette Cendes,[1] Antonio C. Rodriguez,[4] Charlie Conroy,[1]
Eliot Quataert [5] Keith Hawkins [6] Eleonora Zari,[3] Melissa Hobson,[3] Katelyn Breivik,[7] Arne Rau,[8]
Edo Berger,[1] Sahar Shahaf [9] Rhys Seeburger [3] Kevin B. Burdge [10] David W. Latham,[1]
Lars A. Buchhave [11] Allyson Bieryla,[1] Dolev Bashi [12] Tsevi Mazeh [12] and Simchon Faigler[12]

RESULTS: Mass Estimation

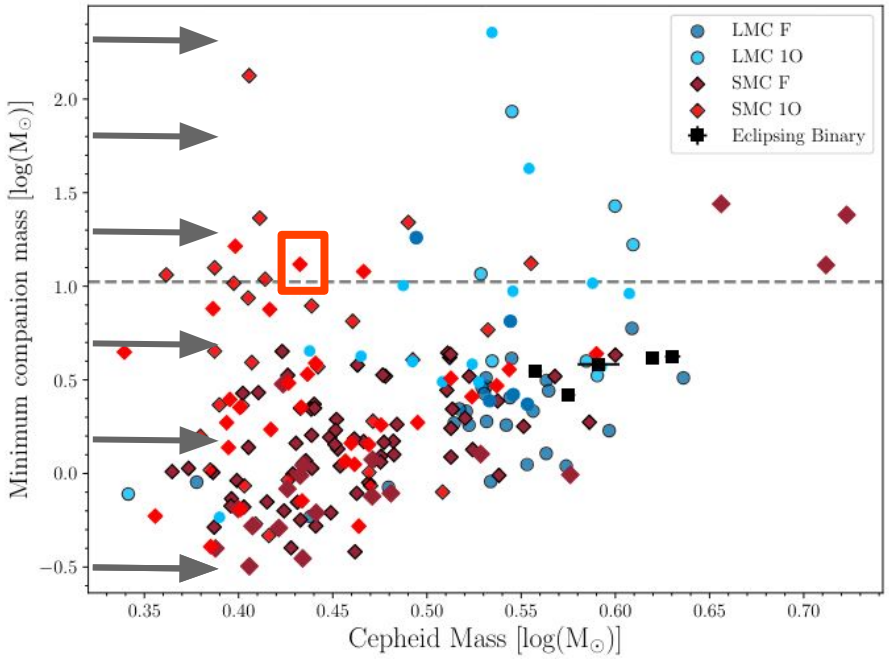


Massive companions!

(Non-evolutionary PC? Triple systems? Black holes?)



RESULTS: Mass Estimation



Massive companions!

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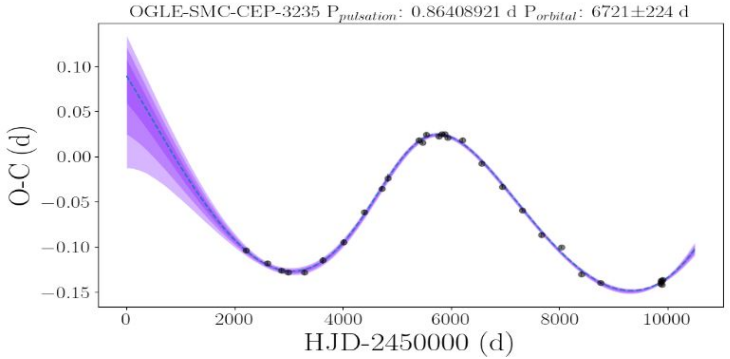
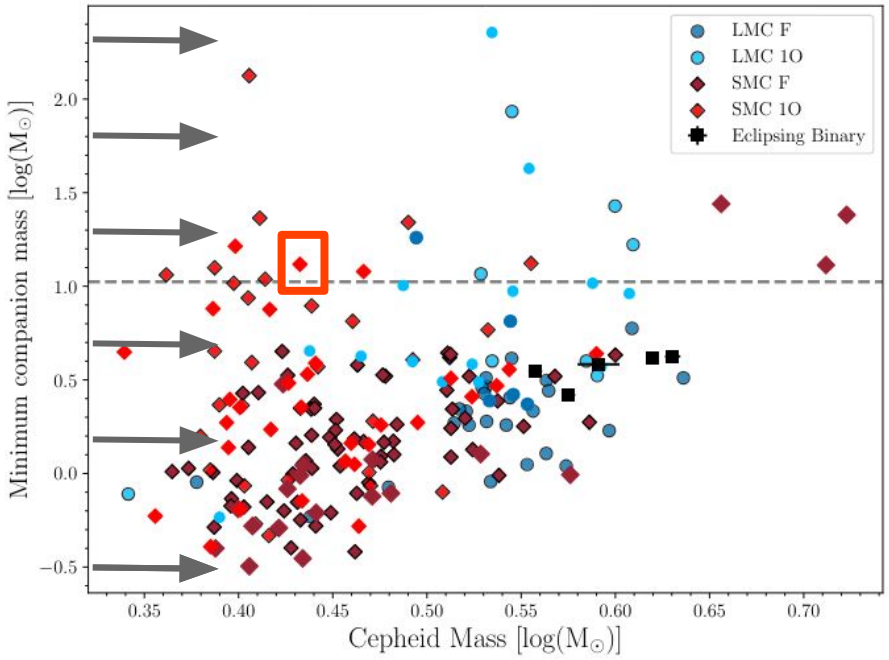


RESULTS: Mass Estimation



Massive companions!

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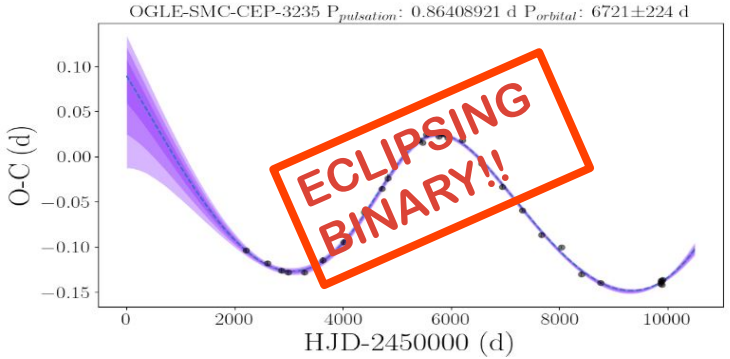
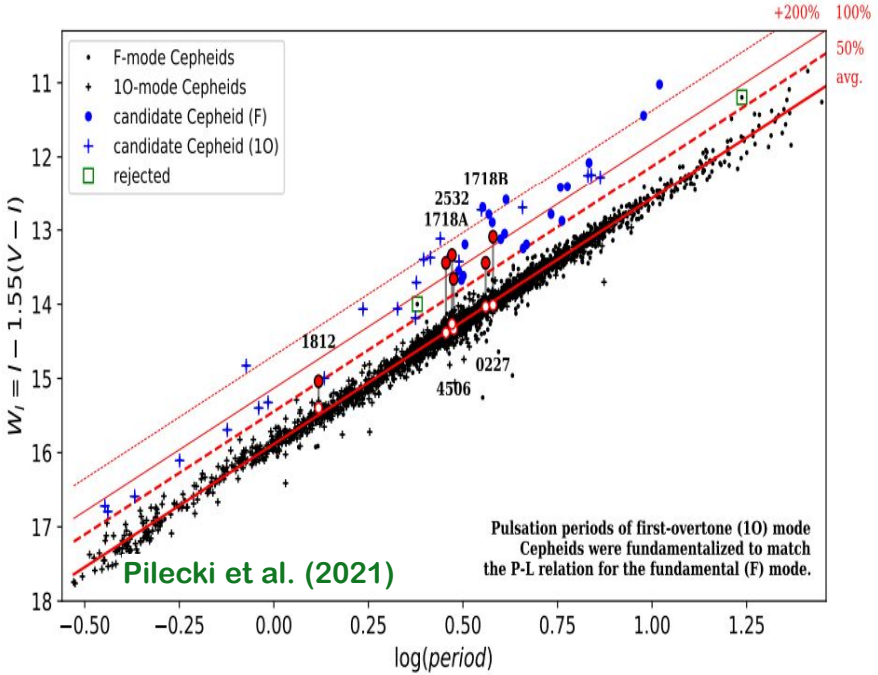


Preparing SALT proposal for spectroscopic confirmation on best candidates

COMPANION NATURE

Curious case of “overbright” Cepheids!

Finding companions with Period-Wesenheit relation?

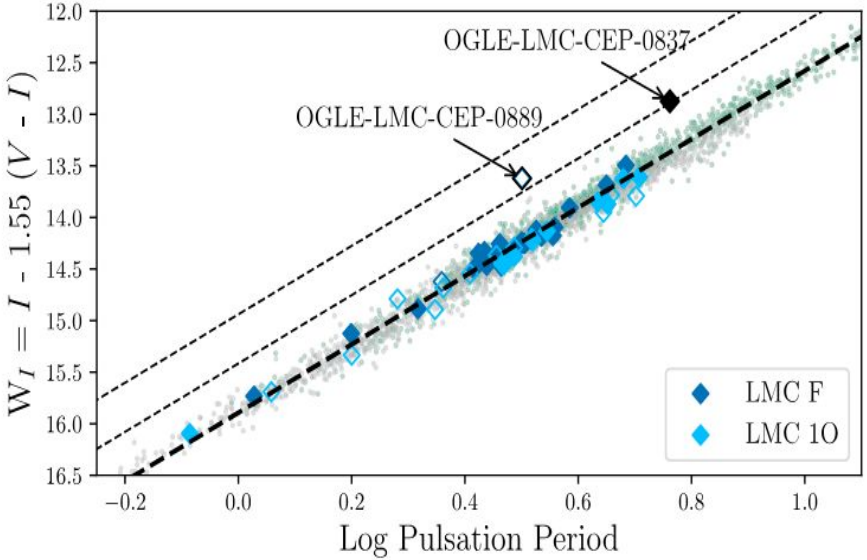


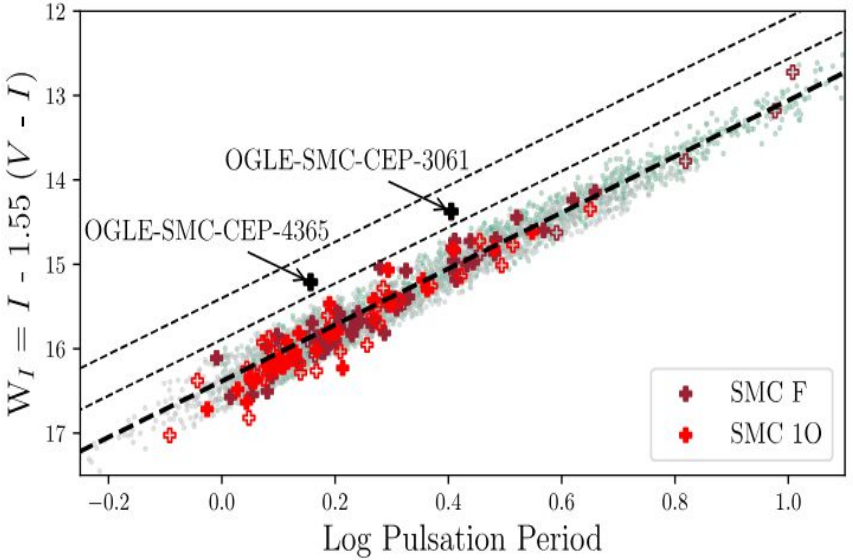
2. The Hypothesis

As described above, there is a great need for an independent source of Cepheids in binary systems that are well suited for mass determination. The most valuable would be those in double-lined spectroscopic binaries, for which lines of both components are present in the spectra. To meet these conditions, one has to find Cepheids accompanied by stars of similar luminosity, and preferentially of late spectral types, i.e., at a subgiant or later stage of evolution. To identify them, we can consider at least three observable features caused by such companions:

1. the total observed brightness of a Cepheid should increase significantly;
2. its photometric pulsation amplitude (expressed in magnitudes) should decrease;
3. its color should be either similar or redder (we expect companions mostly on the red giant branch or the blue loop).

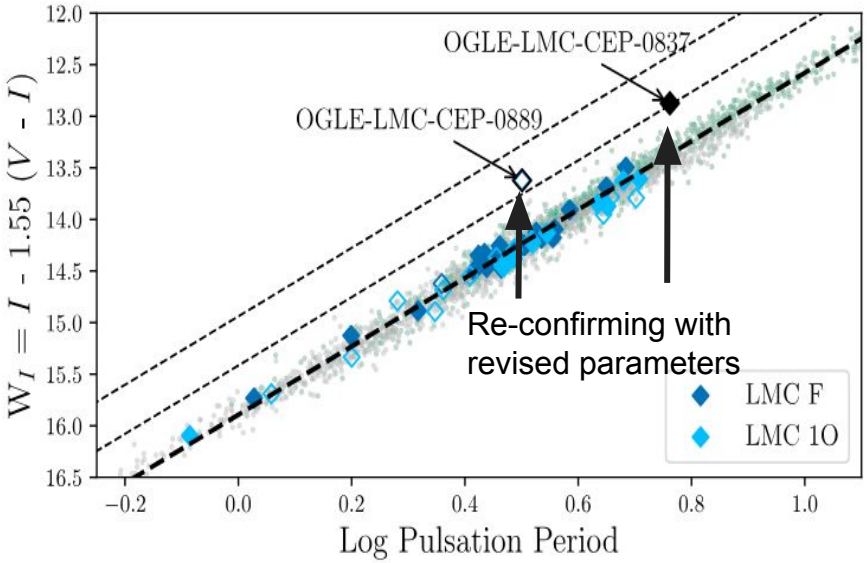
Finding companions with Period-Wesenheit relation?

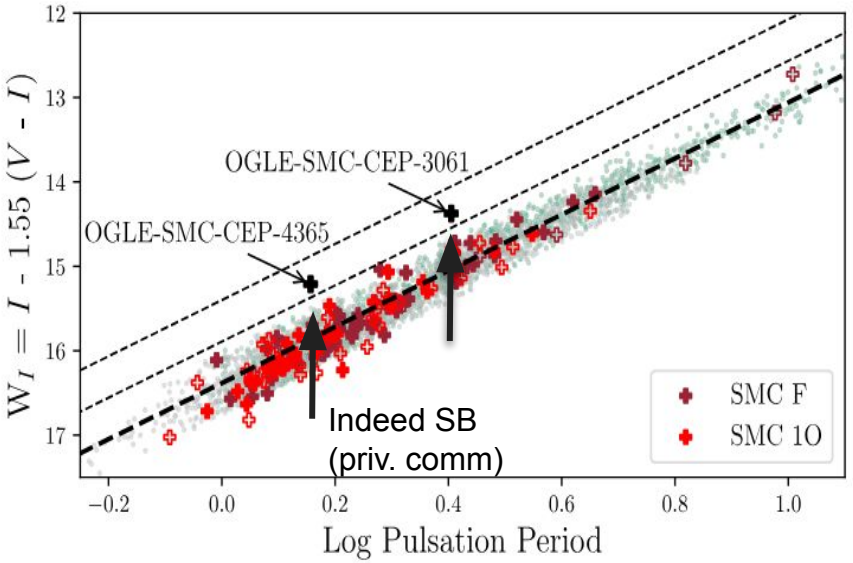




Makes sense!: Synthetic populations of binary Cepheids suggest upto 90% main sequence and upto 5% giant evolved companions! (Karczmarek et al. 2022)

Finding companions with Period-Wesenheit relation?





GIANT TYPE COMPANIONS!

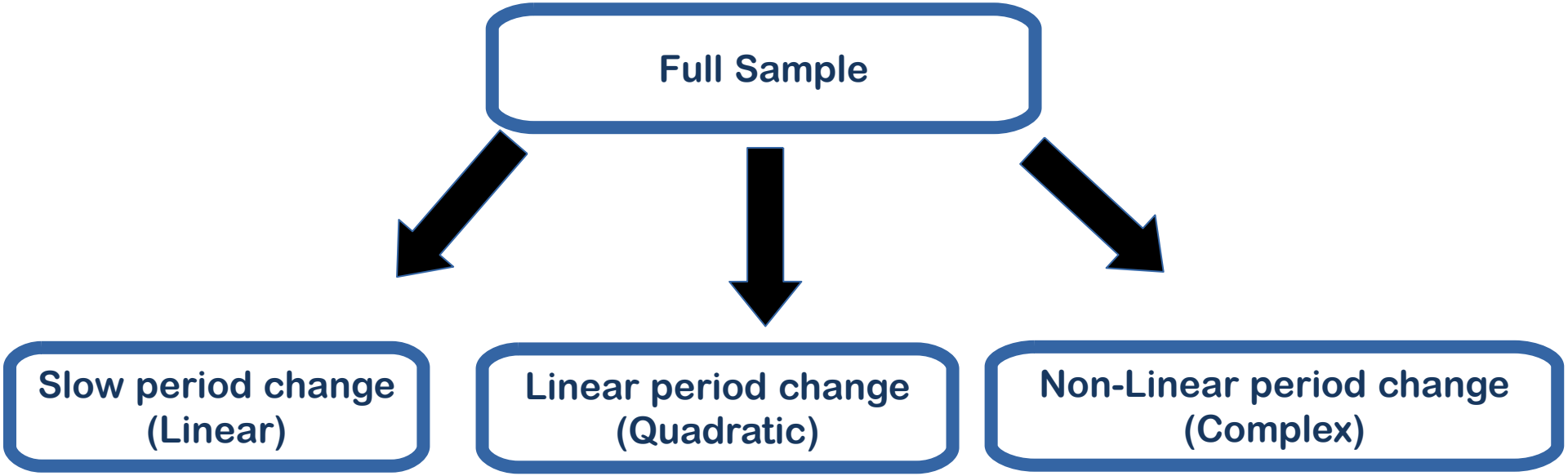
IN PROGRESS
(SNEAK PEEK)

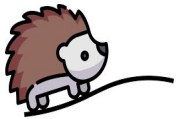
NON-EVOLUTIONARY PC-II

The irregular mess

Rathour et al. 2024b (in prep.)

Filtering Process

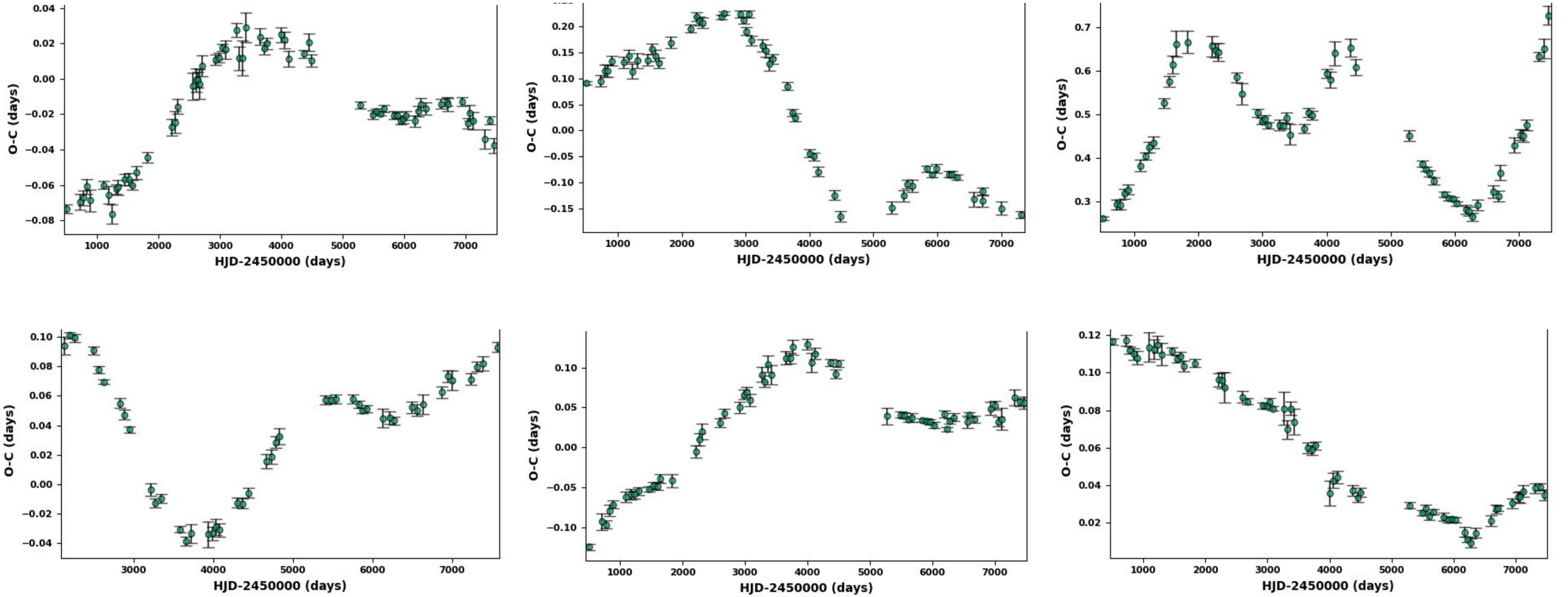


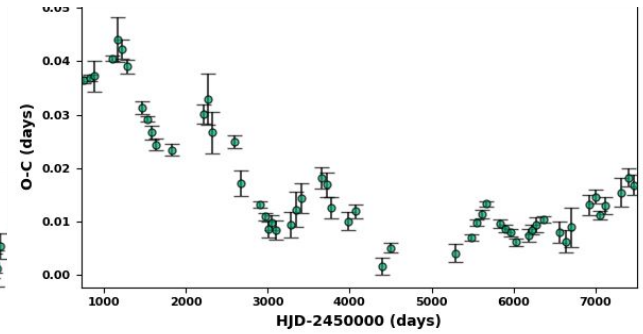


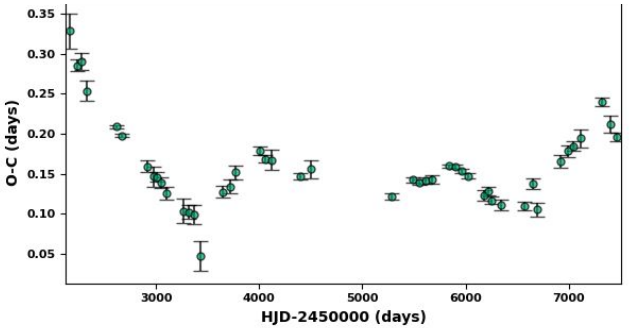
UltraNest

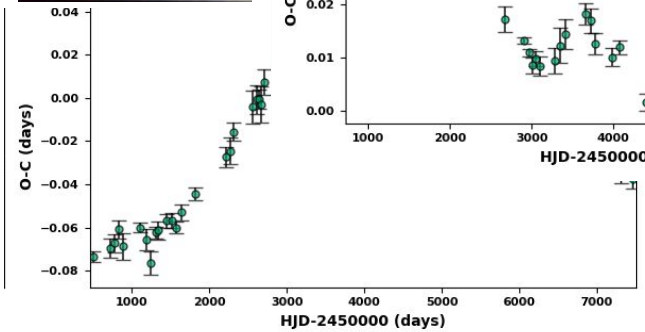
Buchner (2014,2019)

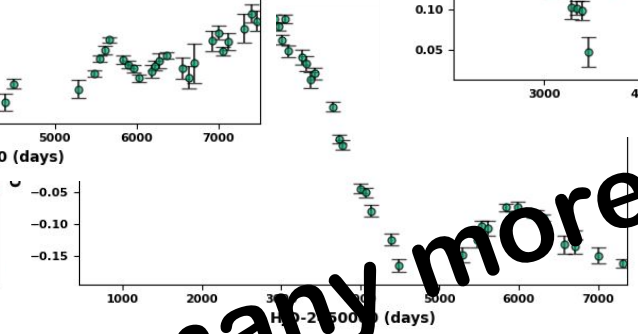
SOME EXAMPLES

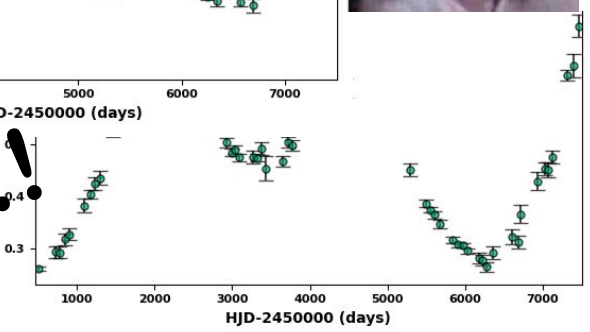




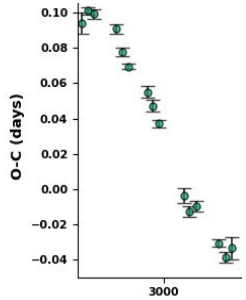


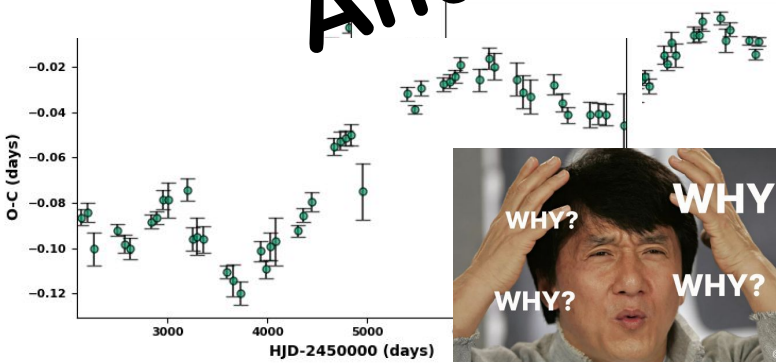


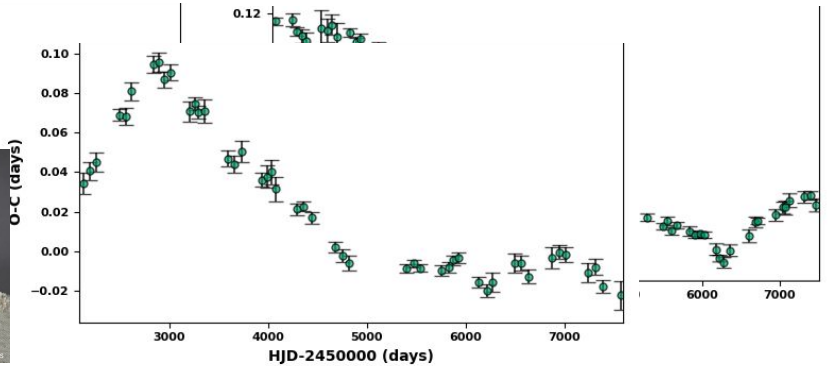




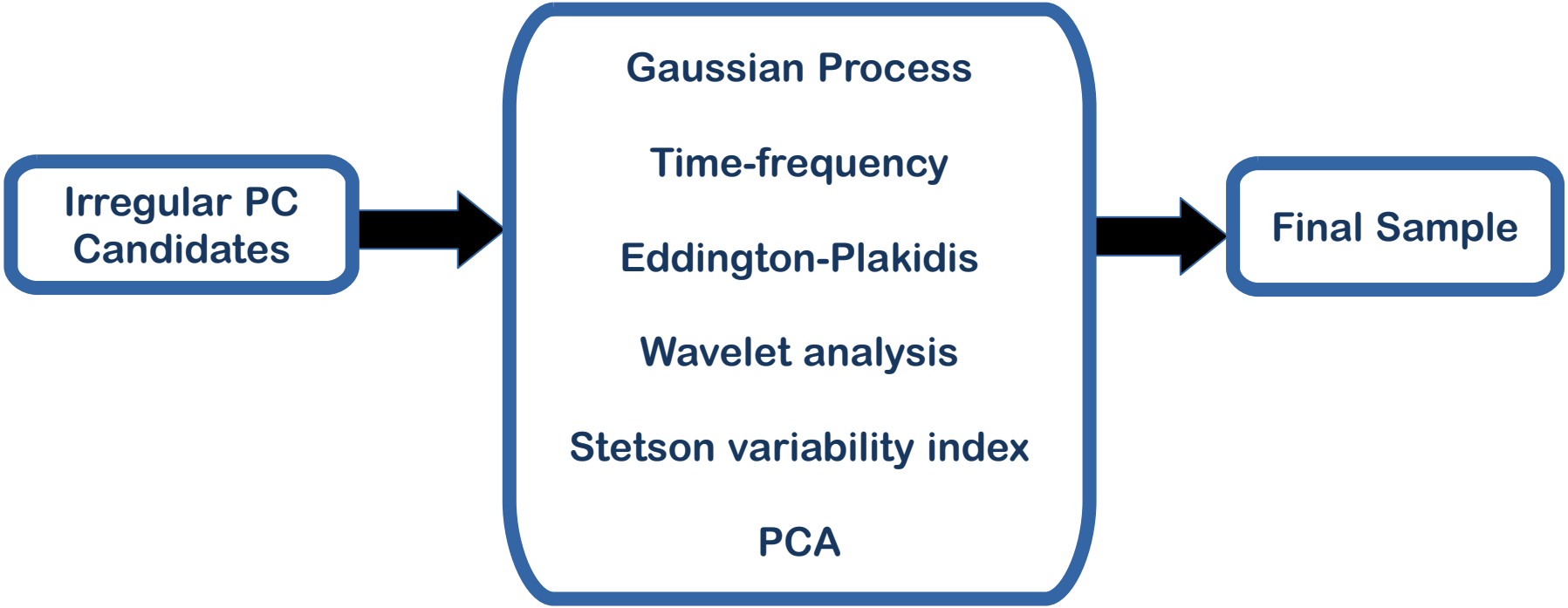
And many more!!





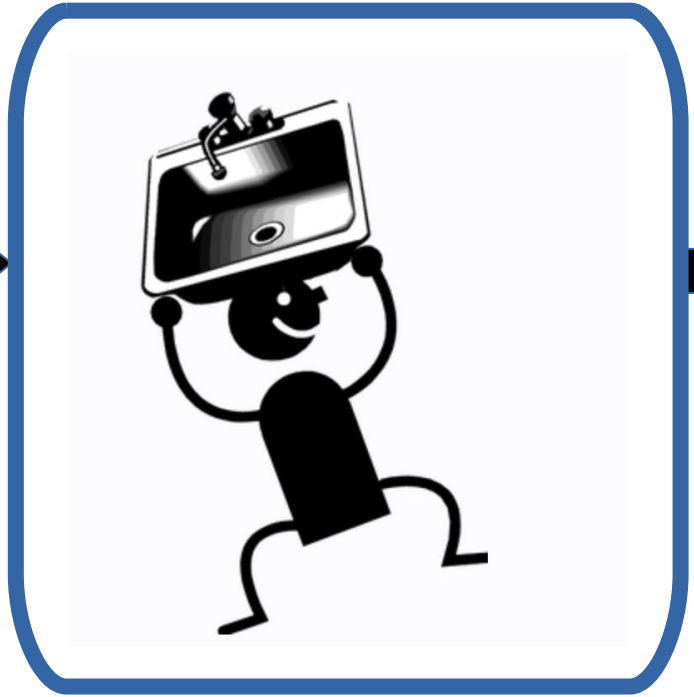


Absence of physical model



Absence of physical model

Irregular PC Candidates



Final Sample

PRELIMINARY FINDINGS

What is speculated

- Substantial fraction?
- More likely in overtone Cepheids (Poleski 2008)
- Metallicity effect (Deasy 1985)
- Fluctuations increase with pulsation period (Csörnyei et al. 2021)
- Uncorrelated with amplitude changes?

What is speculated What we see

- Substantial fraction? ~1600 Cepheids ✓
- More likely in overtone Cepheids (Poleski 2008) FO>FU ✓
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- Convection (Swigart and Renzini 1984)
- Mass-loss (Neilson et al. 2012)
- Magnetic field (Stothers et al. 1982)
- Combination? Other?

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Any valid mechanism should explain these effects!!

SUMMARY ++

PART 1

- ~5x boost to Magellanic binary Cepheid sample. Open for community to confirm spectroscopically.
- Two new SMC “overbright” Cepheids with likely giant companion!
- LTTE effect recovered in three LMC and two SMC eclipsing binaries.
- 21 candidate binary systems with very high mass-function, open to further investigation.
- Agreement with population synthesis predicted incidence rate ratio.

PART 2

- ~1000x boost to Magellanic nonlinear PC Cepheid sample.
- Key empirical constraints from a large sample of stars. Time to test underlying mechanism!
- 7 first crossing candidates!
- Next step: MESA
- Evolutionary models: Check Poster by Oliwia Ziółkowska
  Pulsation models: Computing. . . . . .