Insights from O-C study of 7000+ Magellanic Cepheids from OGLE survey: Census of irregular period changes and binary Cepheids candidates

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Based on Rathour et al. 2023(a, b) [in prep.]

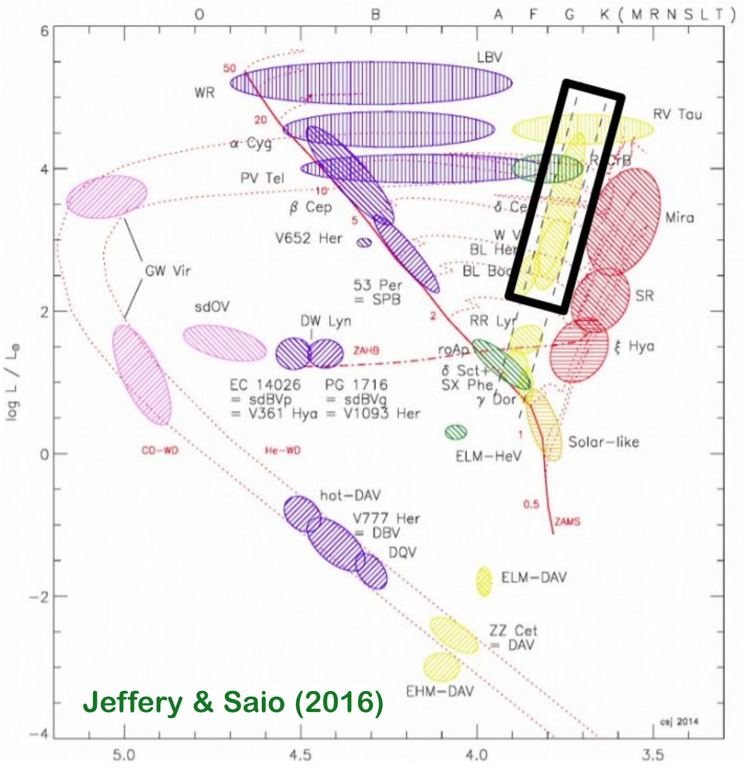
CEPHEIDS

CEPHEIDS

- Classical pulsators evolved from main-sequence
  Period: 1−100 days
  Mass: ~3−13 M⊙
  Mv: -0.2

- Excellent for extragalactic distance measurements

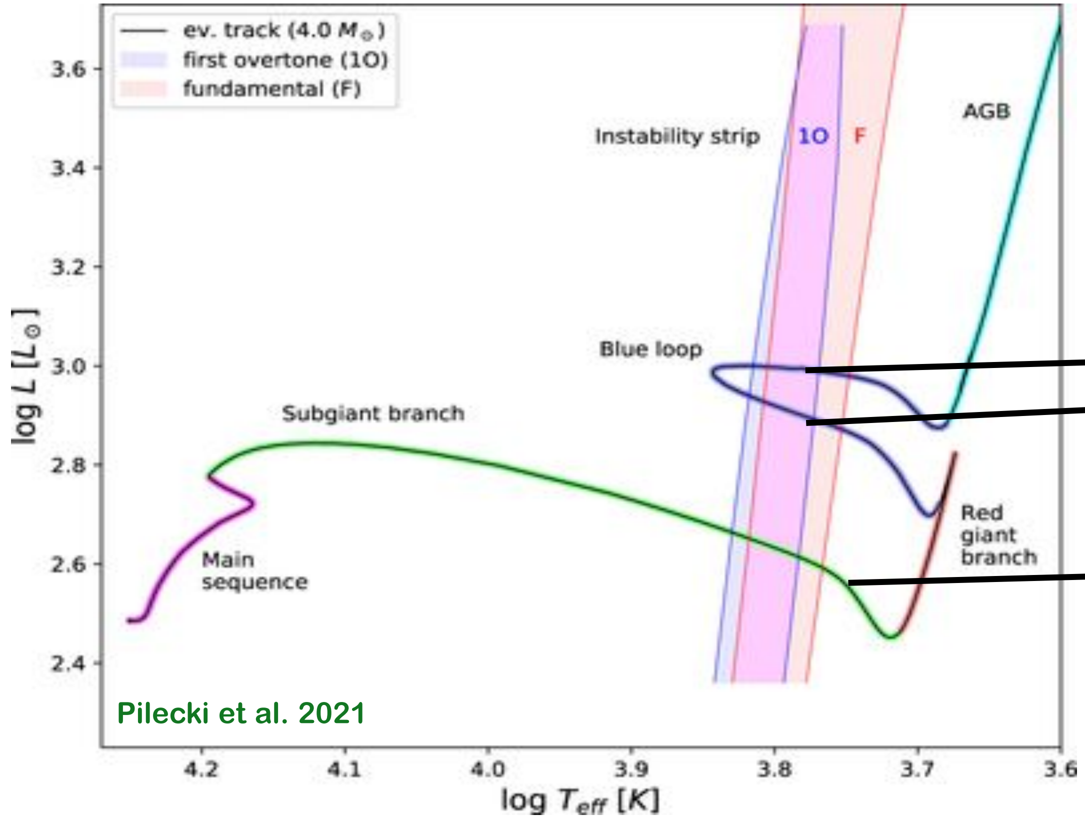
- Perfect for stellar evolution and pulsation studies



Jeffery & Saio (2016)

PERIOD CHANGES IN CEPHEIDS

Period change (PC) and Crossing Number



Period – Mean Density Relation: $\Pi \sim \sqrt{1/\bar{\rho}} \sim R^{3/2} M^{-1/2}$

Core Helium burning
(Slow)

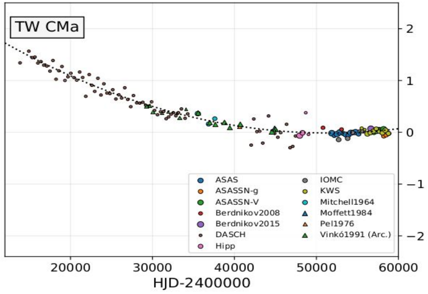
Hydrogen exhaustion at the core
Shell hydrogen burning
(Fast)

Taxonomy of PC

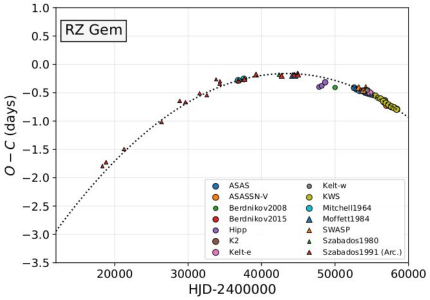
Evolutionary
(~10^4-10^7 yr)

Non-evolutionary
(~10^3 days)

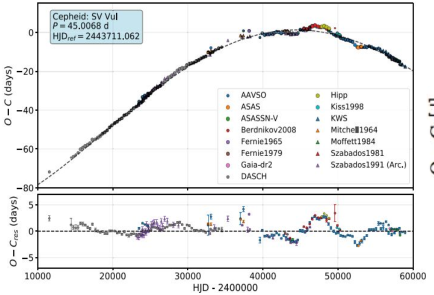
Positive



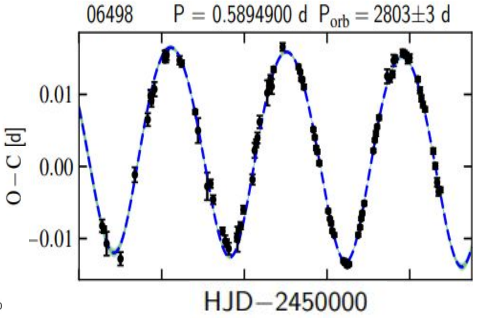
Negative



Irregular



LTTE



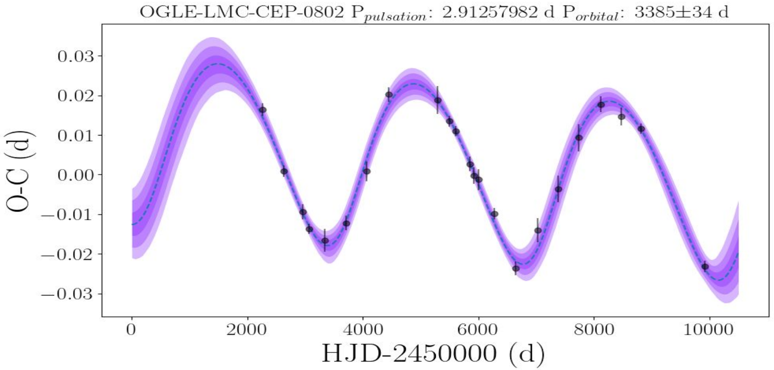
G. Csörnyei et al. (2021)

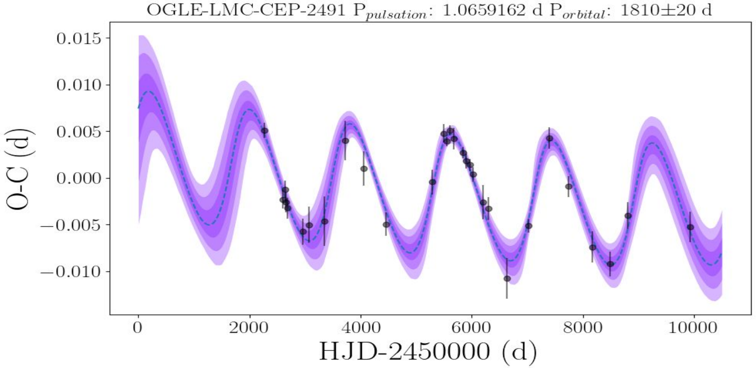
G. Hajdu et al. (2021)

FINDINGS I:
CEPHEIDS IN BINARY SYSTEMS

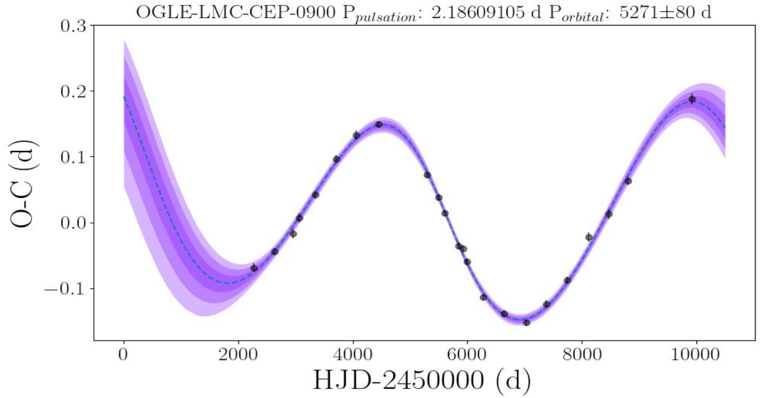
LMC Binary candidates

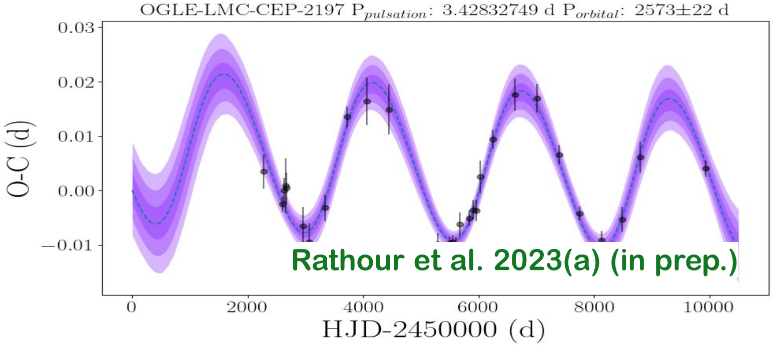
Fundamental





Overtone

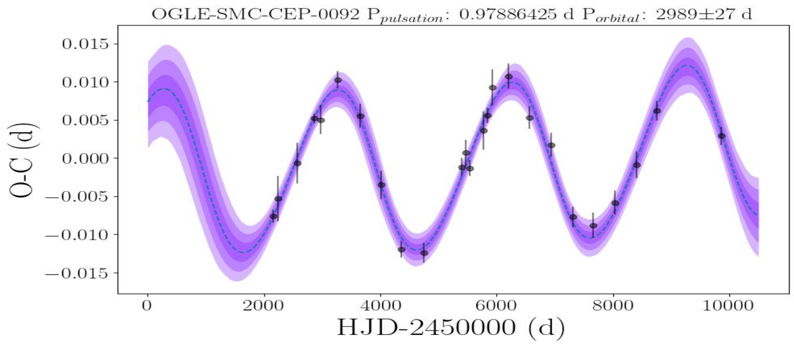


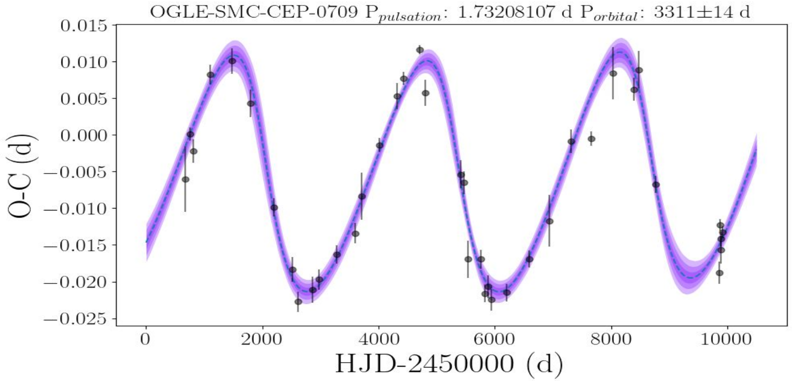


Rathour et al. 2023(a) (in prep.)

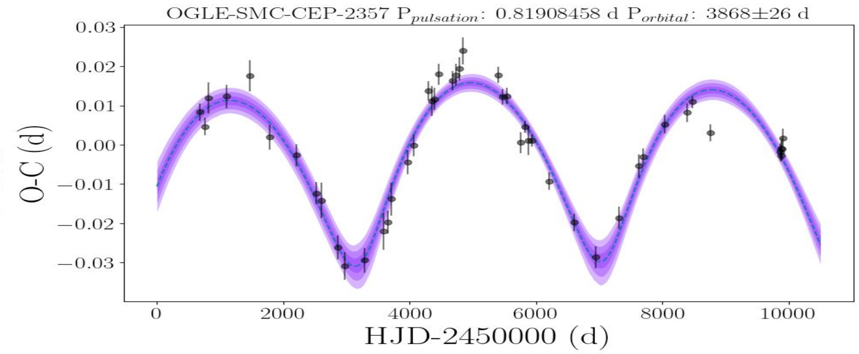
SMC Binary candidates

Fundamental

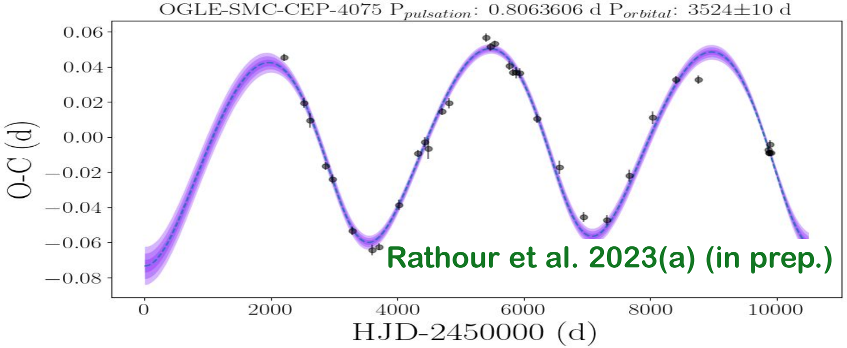




Overtone



HJD-2450000 (d)

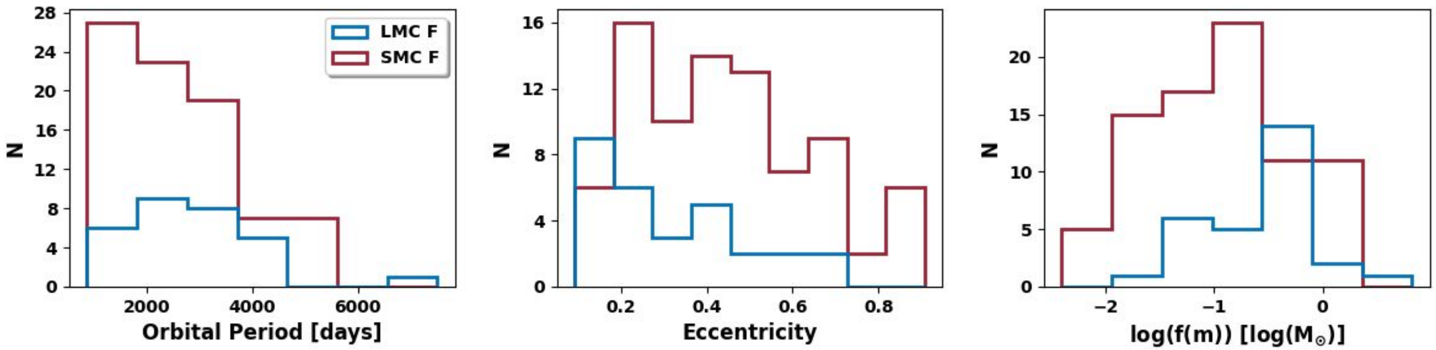


Rathour et al. 2023(a) (in prep.)

BINARY STATISTICS

	LMC F	LMC 1O	SMC F	SMC 1O
Starting sample:	1801	1238	2582	1617
O-C + visual inspection:	39	52	102	133
Binary parameters:	30	22	85	60
Fraction:	~1.67 %	~1.77 %	~3.29 %	~3.72 %

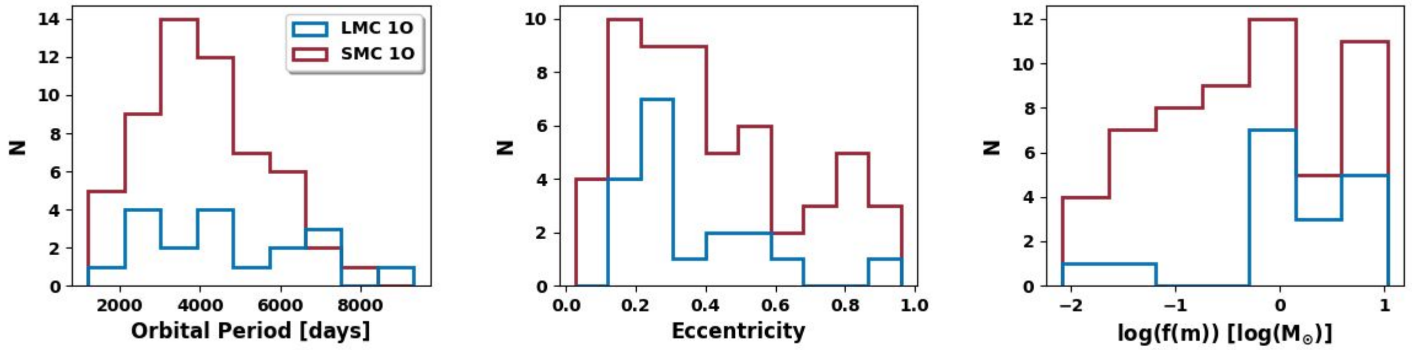
RESULTS: LMC vs SMC



Median companion mass: 1.38 $M_\odot$ LMC; 0.96 $M_\odot$ SMC

Rathour et al. 2023(a) (in prep.)

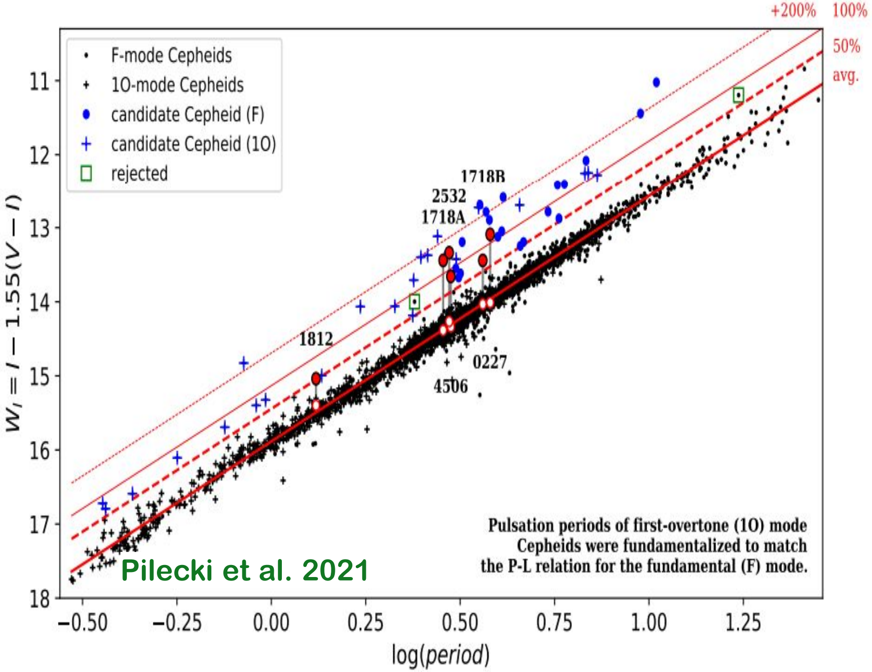
RESULTS: LMC vs SMC



Median companion mass: 2.71 $M_\odot$ LMC; 1.36 $M_\odot$ SMC

Rathour et al. 2023(a) (in prep.)

Finding companions with Period-Wesenheit relation?

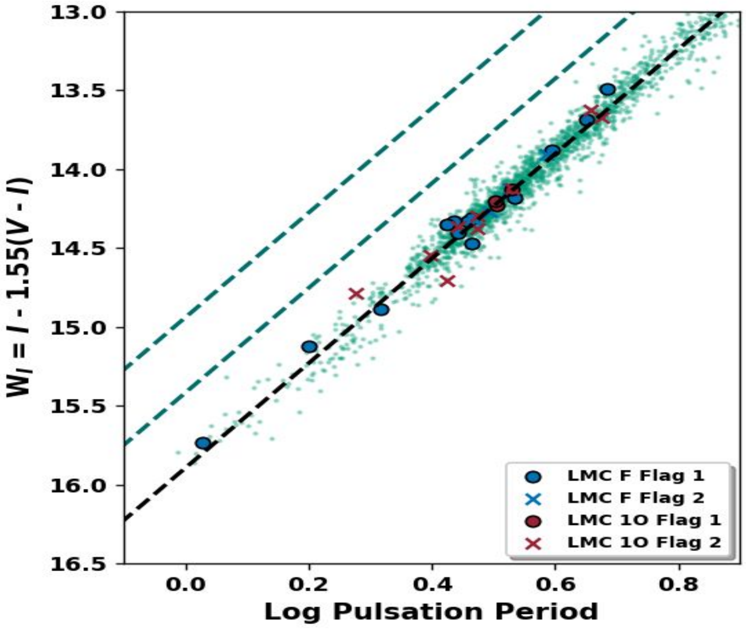


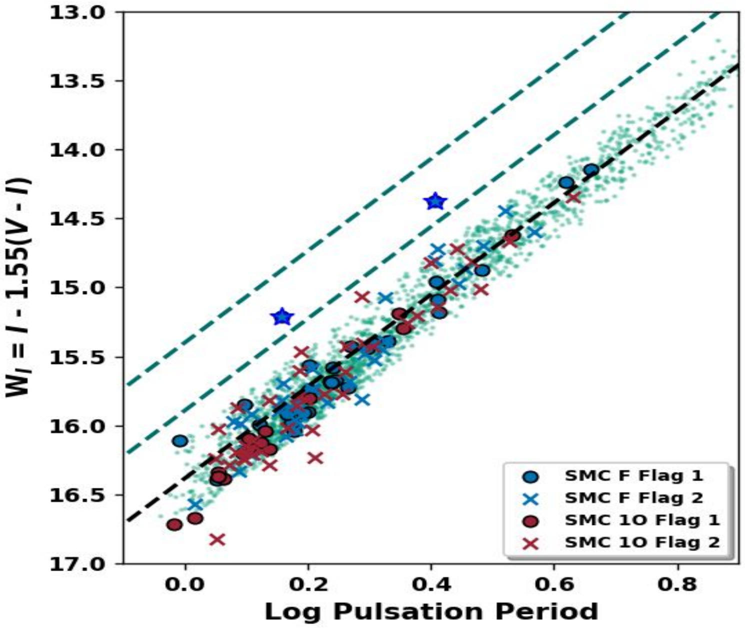
2. The Hypothesis

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).

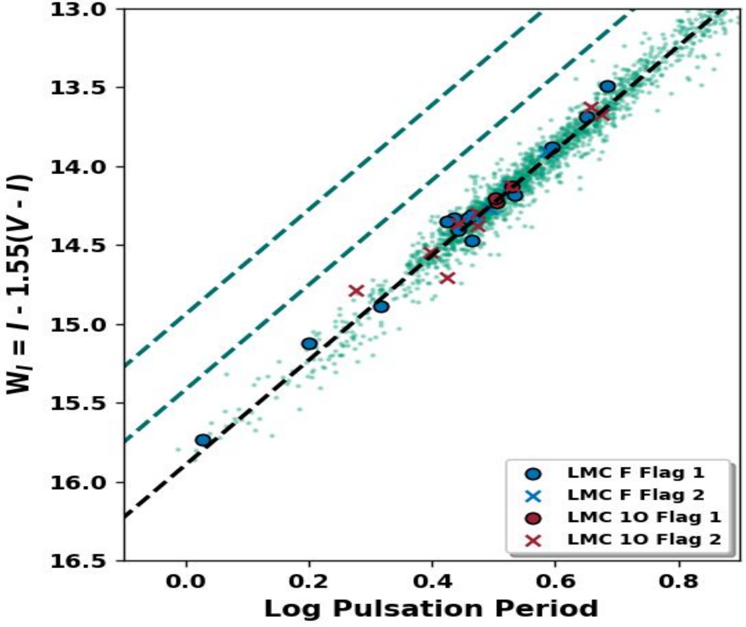
Finding companions with Period-Wesenheit relation?

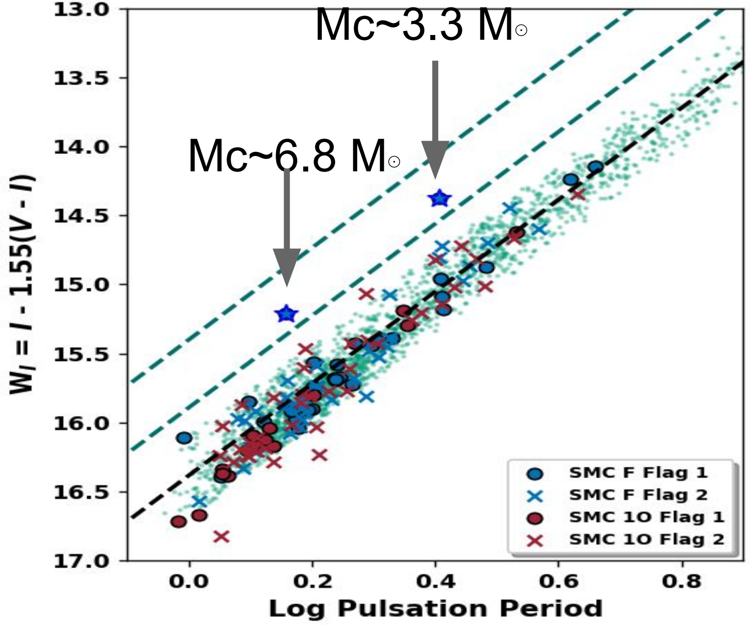




Rathour et al. 2023(a) (in prep.)

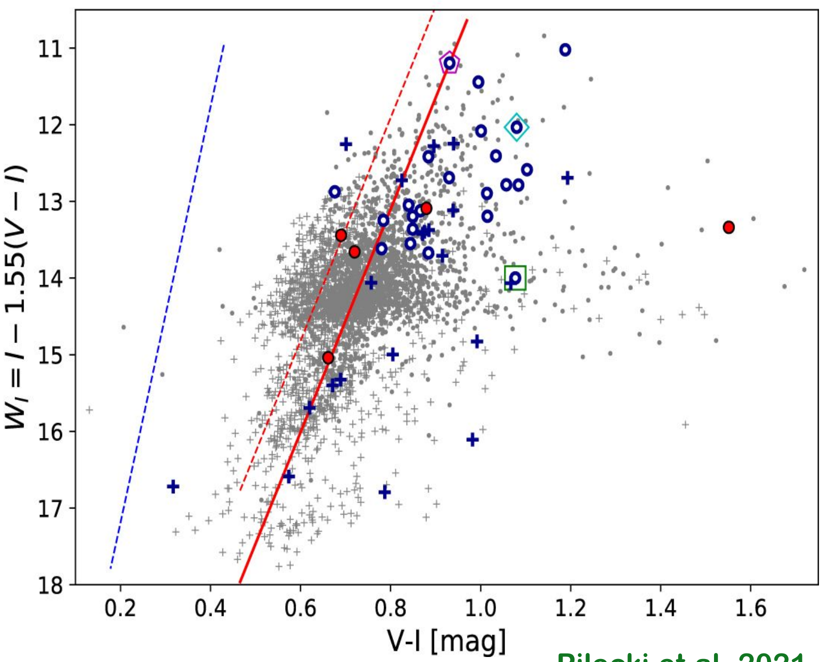
Finding companions with Period-Wesenheit relation?



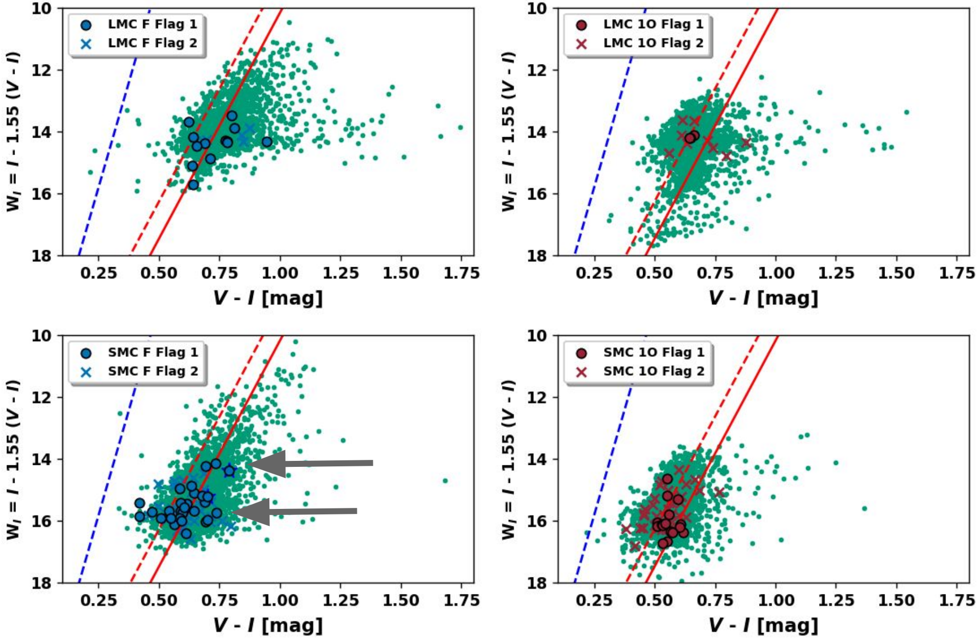


Rathour et al. 2023(a) (in prep.)

Color-Wesenheit Diagram



Pilecki et al. 2021

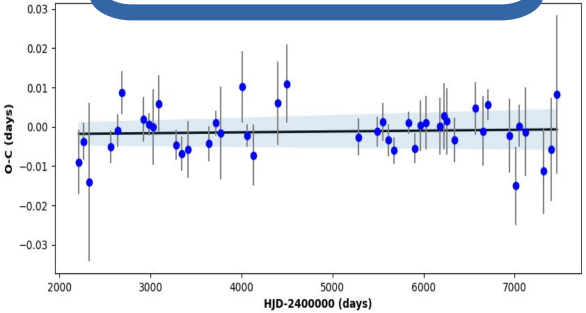


Rathour et al. 2023(a) (in prep.)

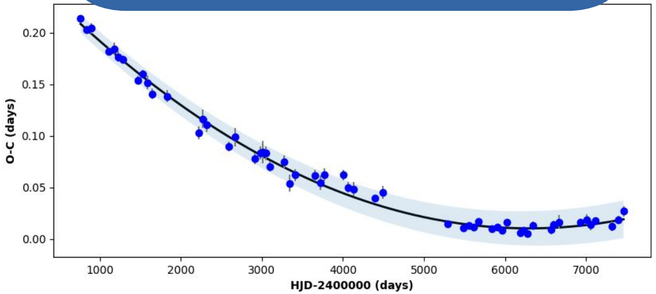
FINDINGS II:
CEPHEIDS WITH IRREGULAR PERIOD CHANGES

Classification

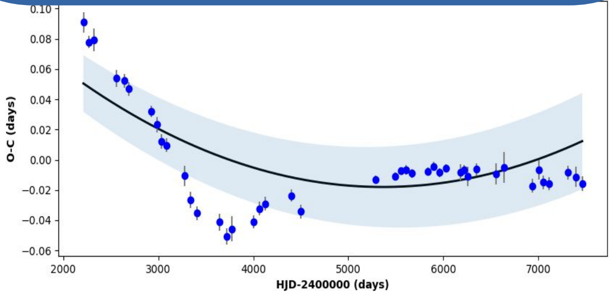
No period change



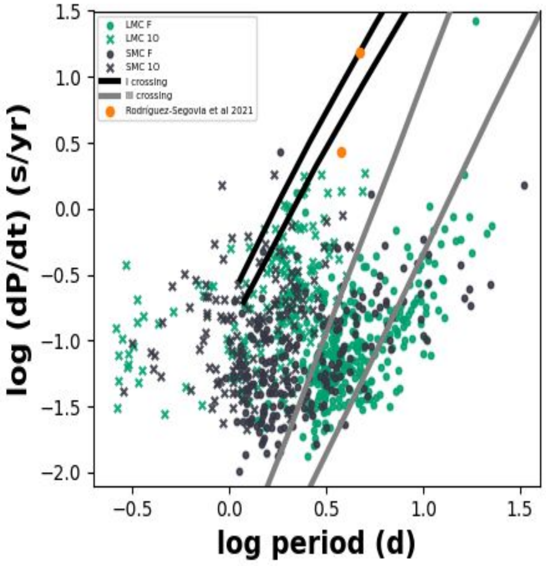
Linear period change

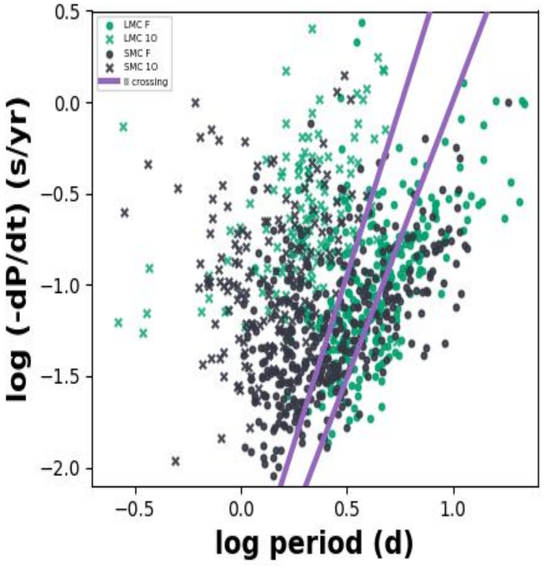


Non-Linear period change



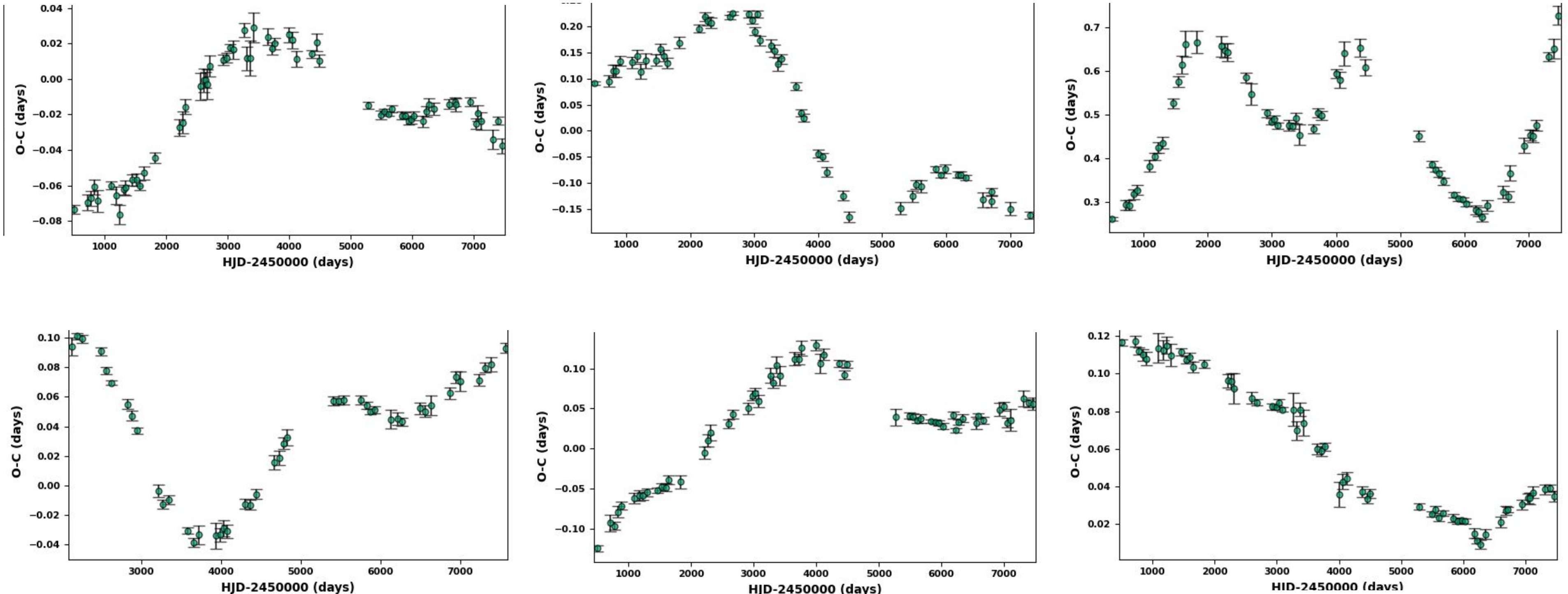
LINEAR PERIOD CHANGE CANDIDATES



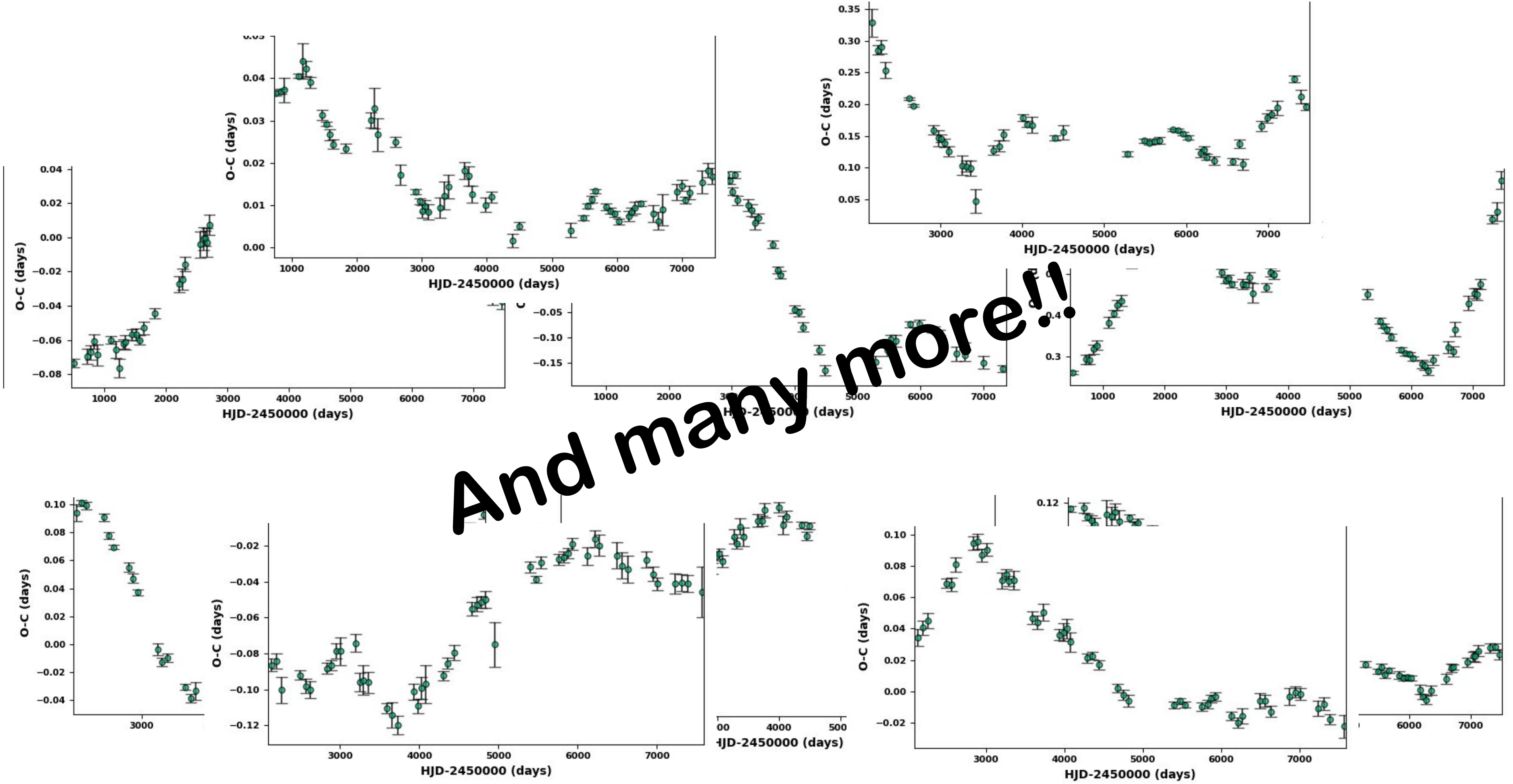


- **Crossing predictions** (Turner 2006)
- **Time base small to capture evolutionary period change rates**
- **However, could capture first crossing candidates.**
- **We have ~10 such candidates**

IRREGULAR PERIOD CHANGE CANDIDATES



Rathour et al. 2023(b) (in prep.)


And many more!!
O-C (days)
HJD-2450000 (days)

STATISTICS

	No PC	Linear PC	Non-Linear PC
LMC F	648	549	594
LMC 1O	113	289	802
SMC F	941	557	982
SMC 1O	105	297	1177
Fraction:	~25.5 %	~24.2 %	~50.3 %

- Irregular PC candidates are more in overtone Cepheids
- Lower metallicity seems to favour irregular PC

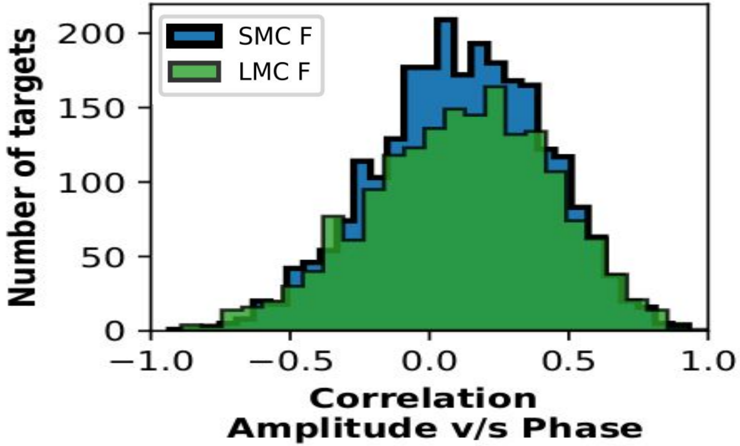
Sample retained

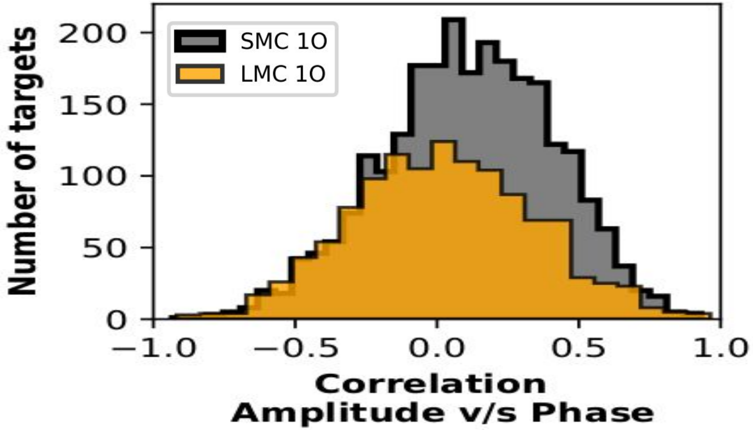
LMC: ~69% (F); ~89% (1O)

SMC: ~67% (F); ~94% (1O)

IrPC Fraction: ~41 %

Effects on Period change





Rathour et al. 2023(b) (in prep.)

Large fraction of the sample has no correlation between amplitude and phase changes

CONCLUSIONS & FUTURE WORK

Conclusions

- Successfully search 7200+ OGLE Magellanic Cepheids for (i) binarity and (ii) irregular period change candidates

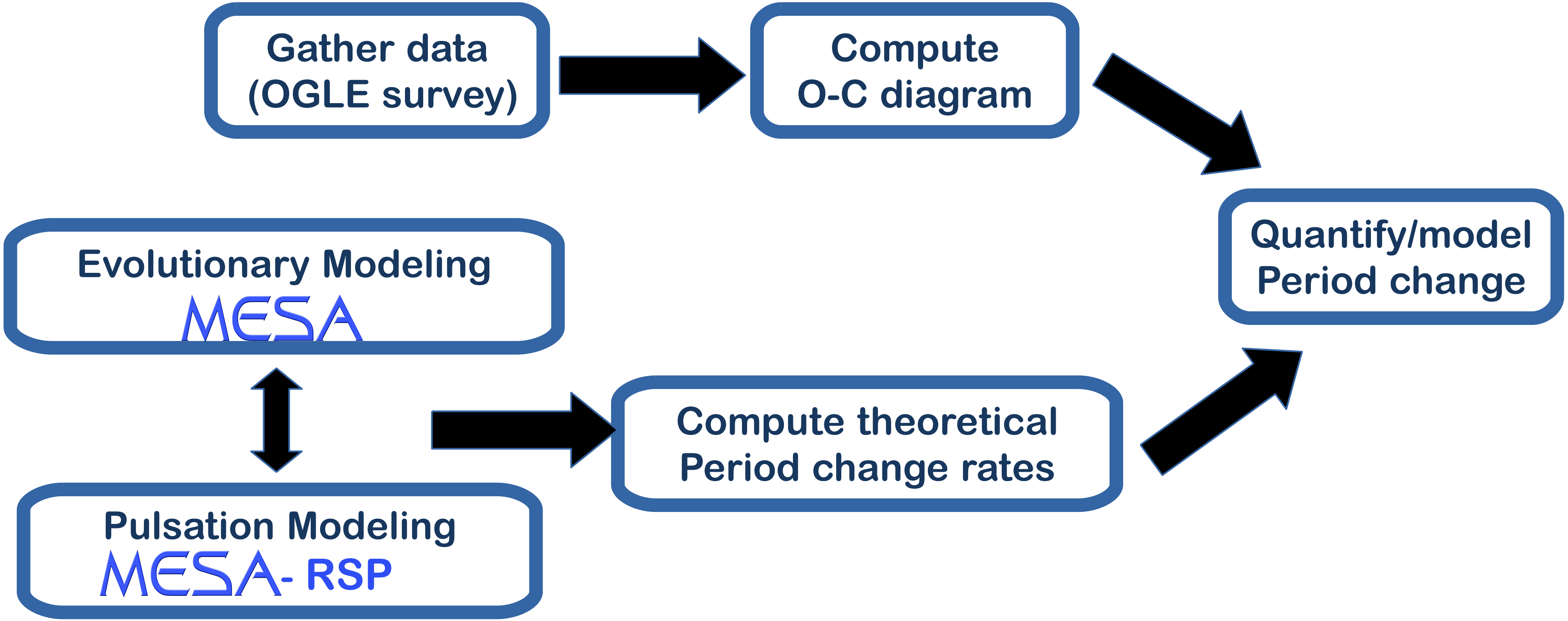
- We find 197 Cepheid binary candidates available for the community to confirm spectroscopically. 2 SMC Cepheids with likely giant companion!

- Irregular period change: substantial fraction (upto ~40%), more likely in overtone Cepheids (Poleski 2008), and SMC (Deasy 1985), uncorrelated with amplitude changes. Fluctuations increase with period (Csörnyei et al. 2021)

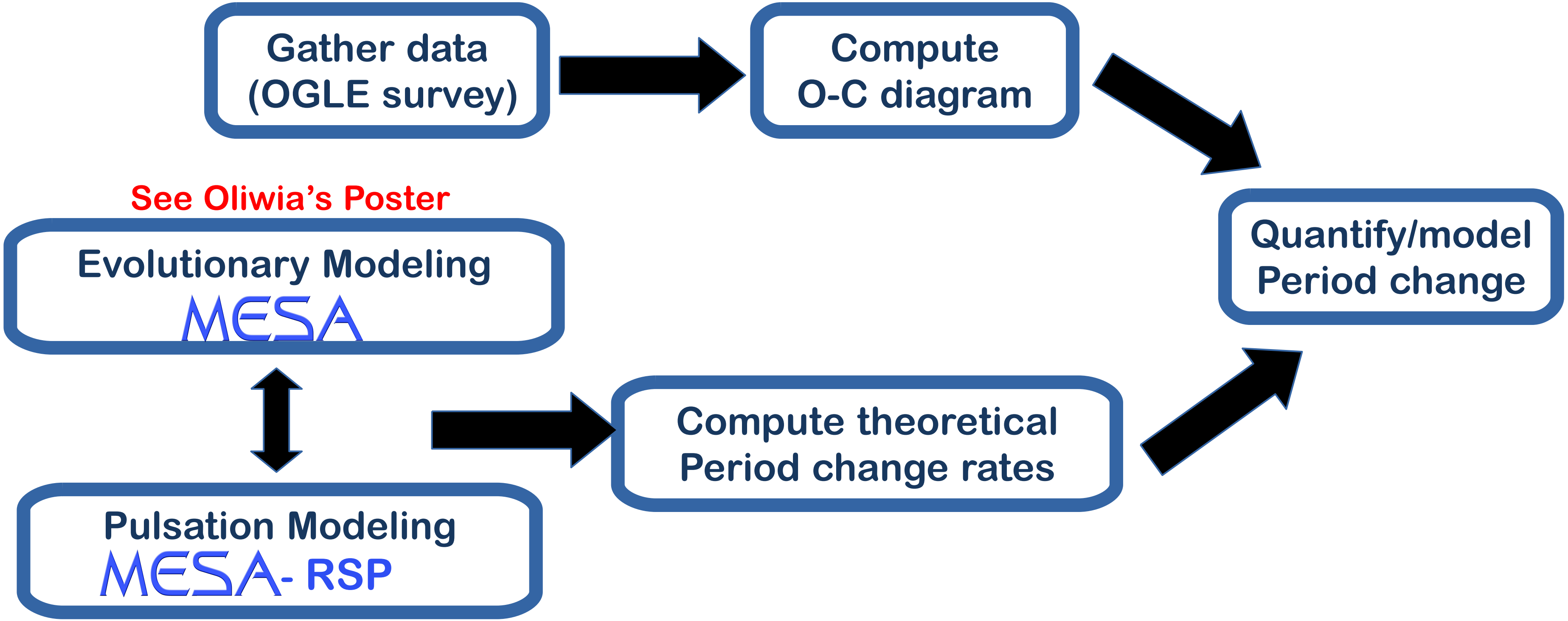
- PC (evo+non-evo) are essential to understand full picture of Cepheid evolution.

- Modelling survey (MESA+RSP) with above empirical constraints.

Future/On-going work



Future/On-going work



Thank you for your attention!

Dziękuję za uwagę!

APPENDIX

What is O-C diagram?

Observed-Calculated

$$T_{\max} = T_0 + PE$$

$$T_m = T_0 + P_0 E + \frac{1}{2}\frac{dP}{dt}\bar{P}E^2$$

$$O - C = \frac{1}{2}\frac{dP}{dt}\bar{P}E^2$$

What does it do?

Measures period changes rate (PCR)

Why is it important?

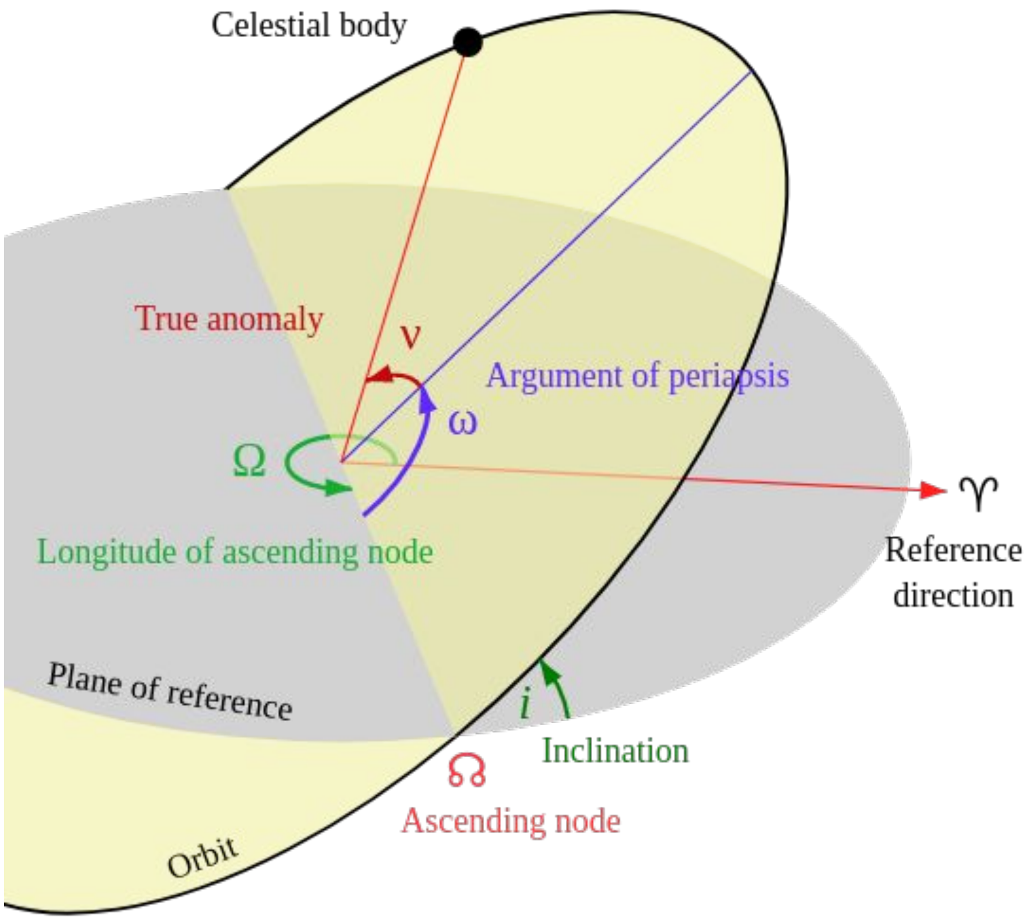
Can be a direct measure of Cepheid evolutionary and non-evolutionary processes

$$z(t) = a_1 \sin i \frac{1 - e^2}{1 + e\cos(\nu)} \sin(\nu + \omega),$$

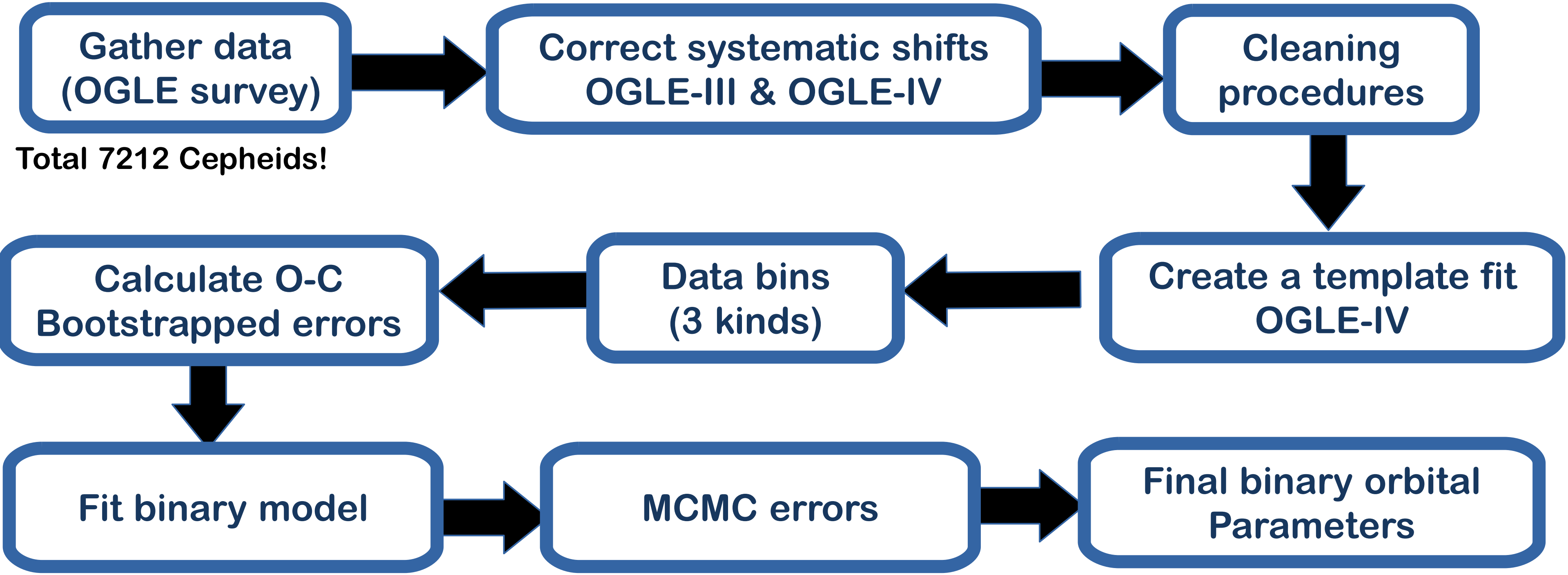
$$(O - C)(t) = z(t) + c_0 + c_1 t + c_2 t^2,$$

$$f(m) = \frac{a_1^3 \sin^3 i}{P_{\mathrm{orb}} \sqrt{1 - e^2}},$$

$$f(m) = \frac{m_S^3 \sin^3 i}{(m_{\mathrm{RR}} + m_S)^2},$$

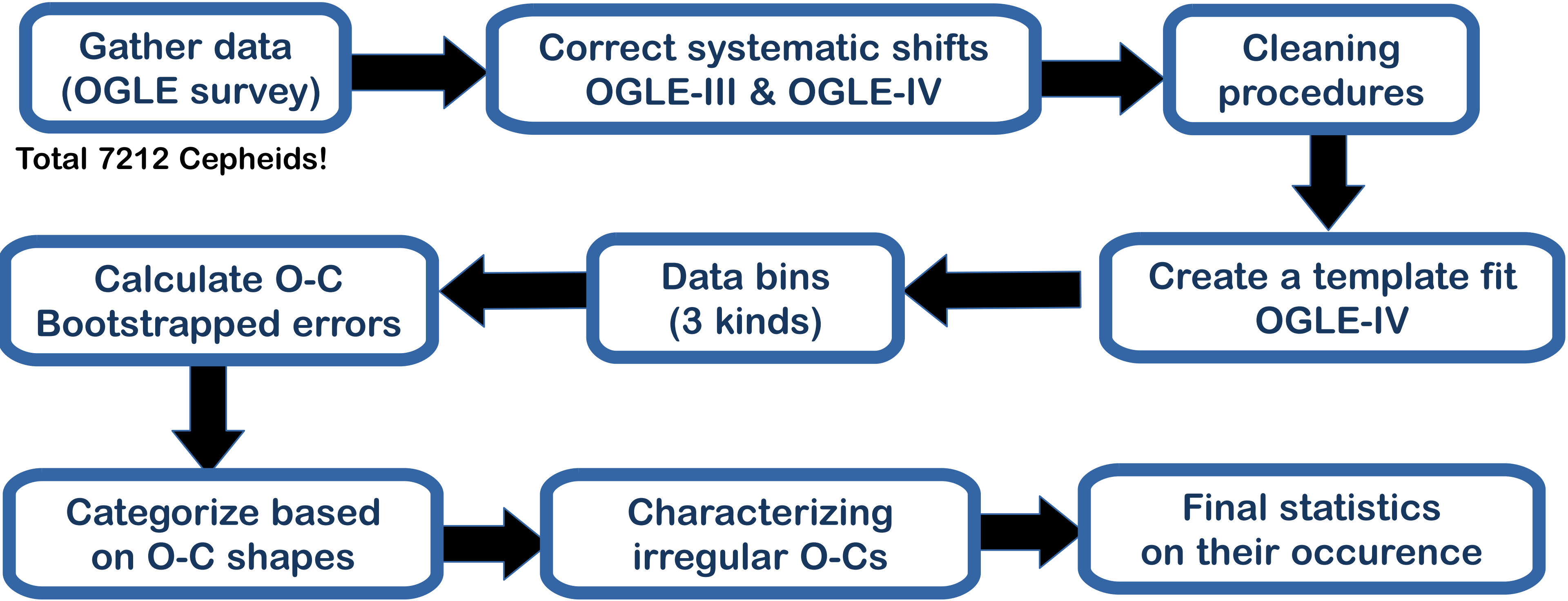


Work flow



Code routines adapted from rrl_binaries_1: G. Hajdu et al. (2021)

Work flow


Gather data (OGLE survey)
Total 7212 Cepheids!
Correct systematic shifts OGLE-III & OGLE-IV
Cleaning procedures
Create a template fit OGLE-IV
Data bins (3 kinds)
Calculate O-C Bootstrapped errors
Categorize based on O-C shapes
Characterizing irregular O-Cs
Final statistics on their occurence

FACTORS AFFECTING!

Sample was composed for Cepheids with data in both OGLE-III & OGLE-IV

Some candidates were rejected due to not enough LTTE O-C cycles to be convincing

Low amplitude noisy O-C curves were rejected

METHODOLOGY: SEARCHING THE SURVEY

The Optical Gravitational Lensing Experiment (OGLE)

- Largest database for variable stars!
- 1.3 m telescope, Las Campanas, Chile
- Mosaic CCD camera; FOV 1.4 square degrees
- Optical and Infra-red bands
- More than 20 years of photomotry data
- OGLE-III:2001-2009 & OGLE-IV:2010-present
- Technical upgrades from OGLE-III to OGLE-IV

OGLE SURVEY

Magellanic Cloud (MC) observed by OGLE

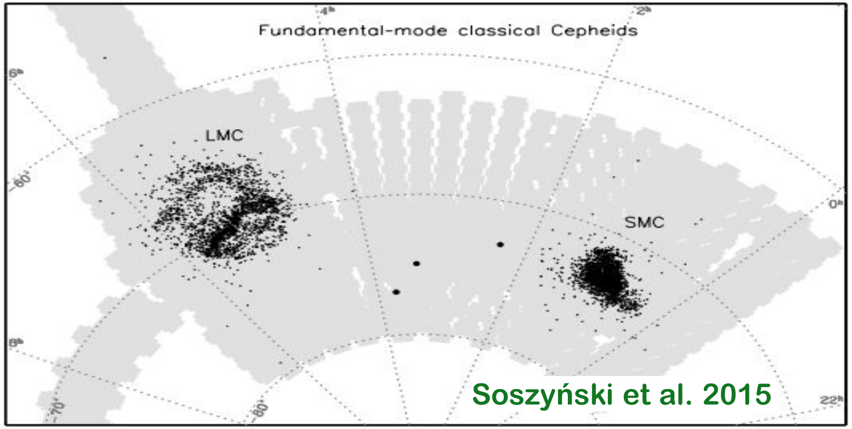
Completeness near 100% (Soszyński et al. 2017)

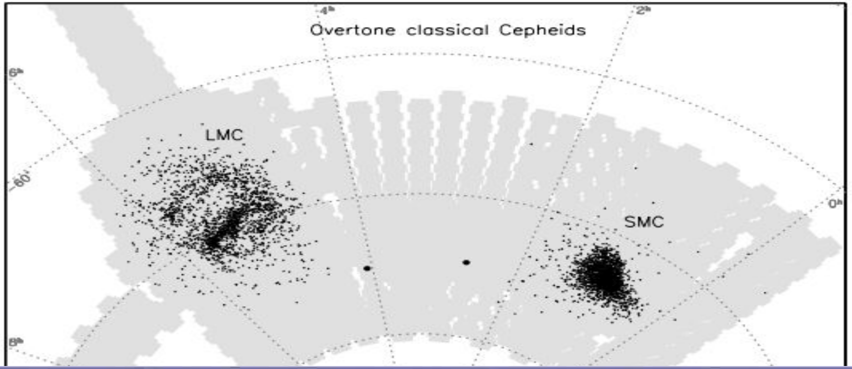
Our starting sample was 9649 Cepheids

Total working sample was 7212!

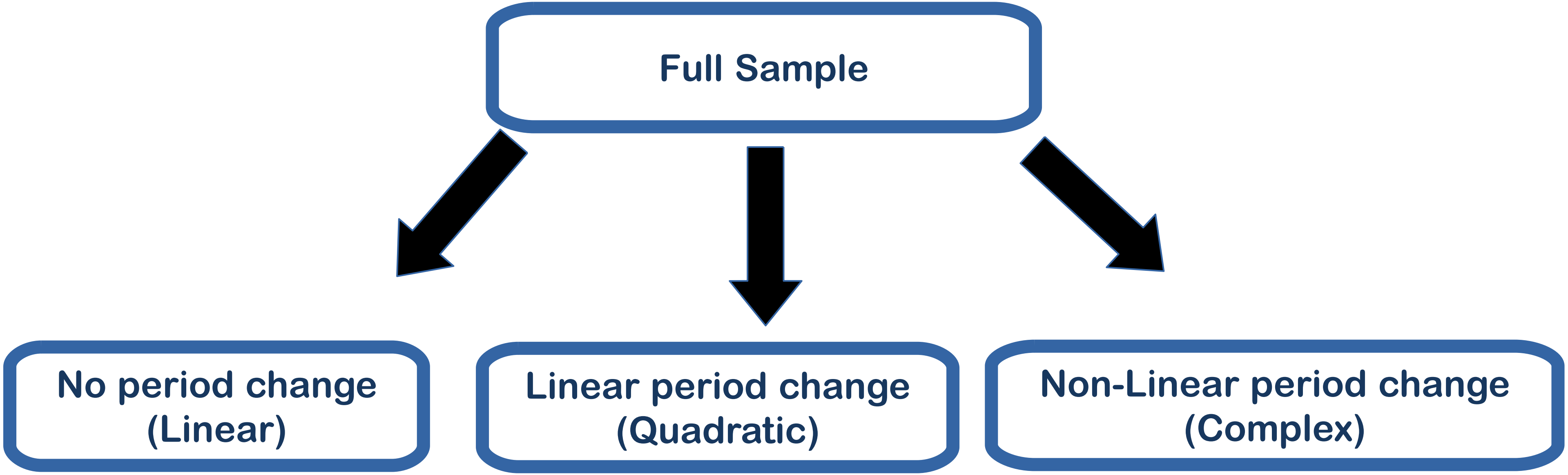
Typically OGLE-III & OGLE-IV cominbed has 14 seasons of data

For some promising candidates, OGLE team provided extended data on request





Filtering Process



Data flag tests: AIC, BIC, Jurcsik test, reduced Chi square

Residual flag tests: Ljung–Box, Anderson–Darling

Filtering Process

Field	Pulsation	OGLE-III	OGLE-IV	OGLE-III+IV
SMC	F mode	2626	2739	2582
	1O mode	1644	1790	1617
LMC	F mode	1818	2430	1801
	1O mode	1238	1769	1212

No period change (Linear)

Linear period change (Quadratic)

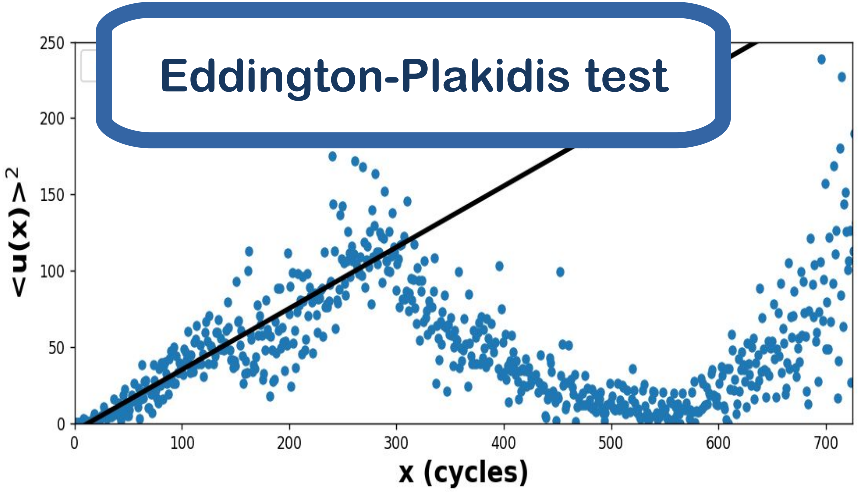
Non-Linear period change (Complex)

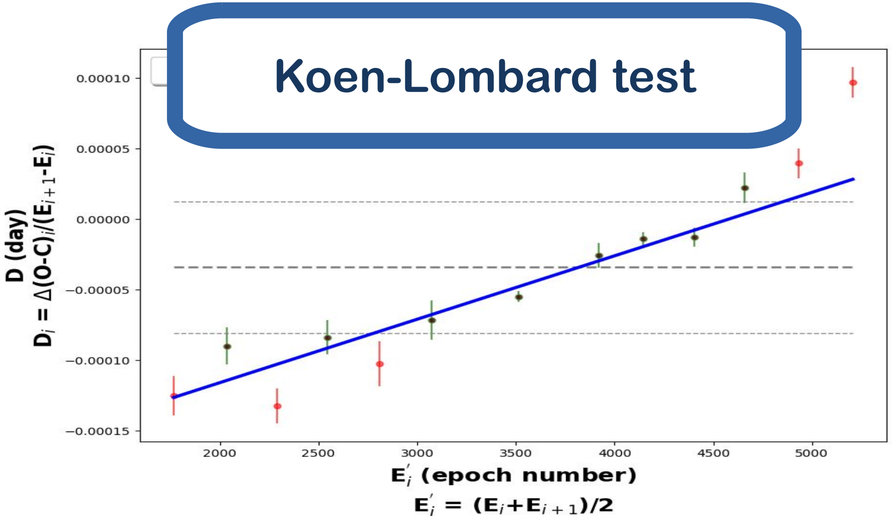
Data flag tests: AIC, BIC, Jurcsik test, reduced Chi square

Residual flag tests: Ljung–Box, Anderson–Darling

Validating Period changes with fluctuation tests

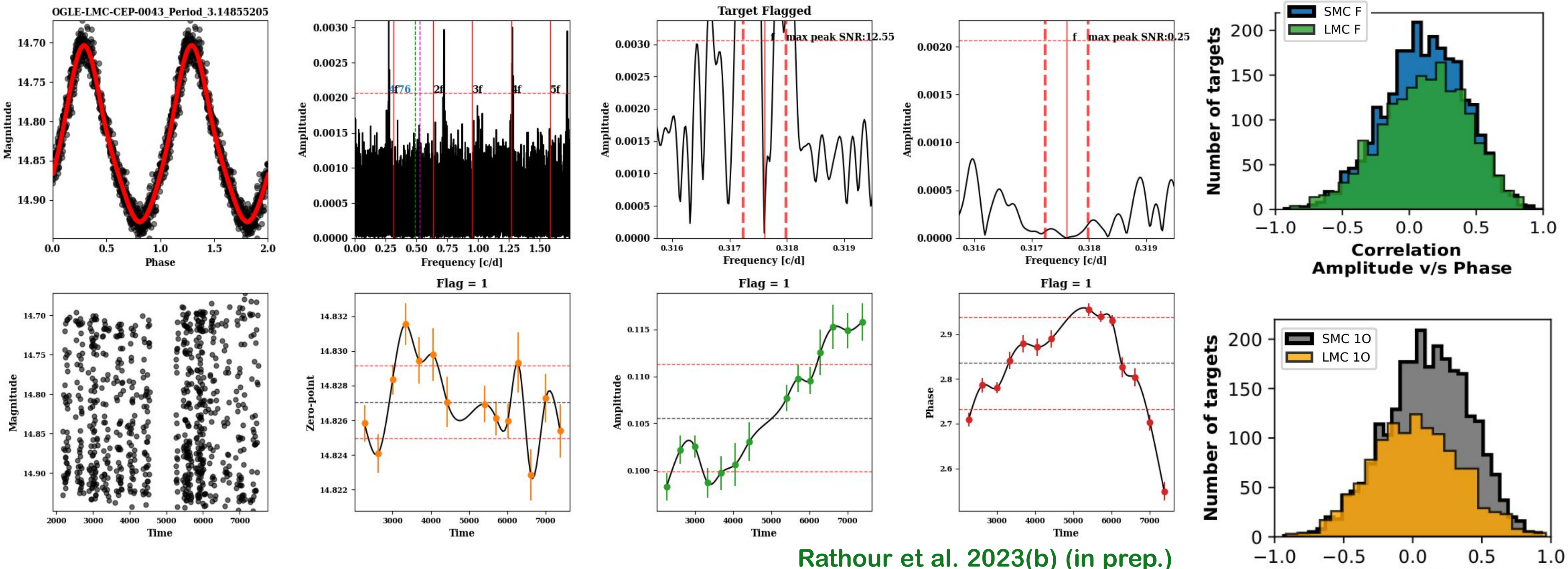
Sample retained
LMC: ~69% (F); ~89% (1O)
SMC: ~67% (F); ~94% (1O)





Rathour et al. 2023(b) (in prep.)

Other effects on Period change



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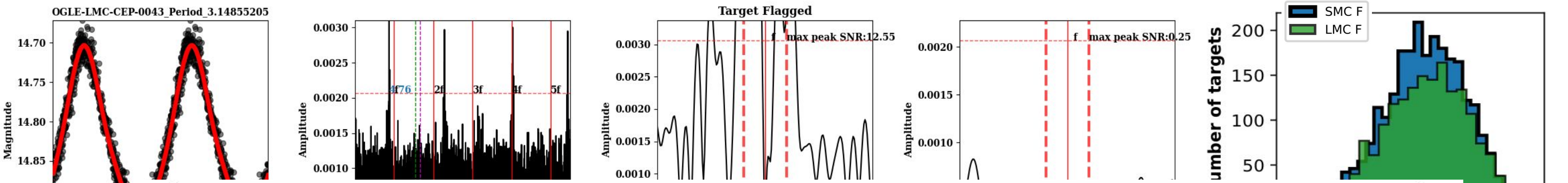
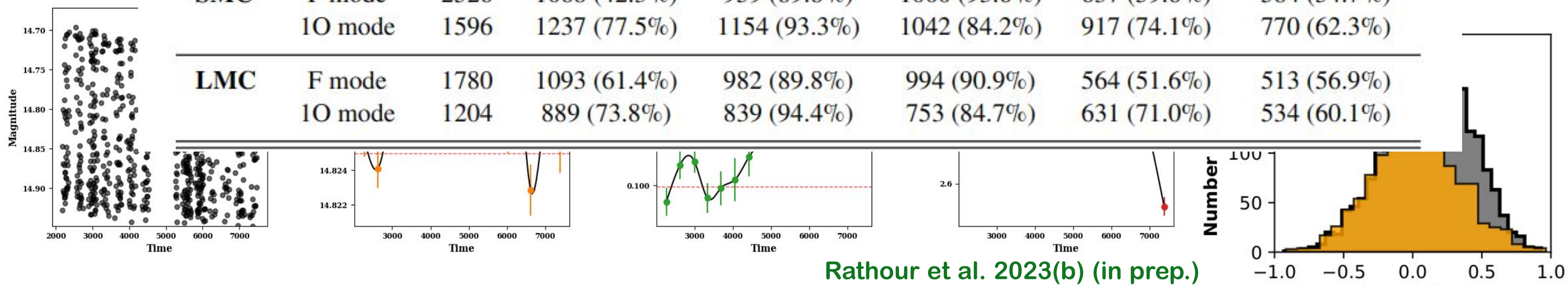
Other effects on Period change

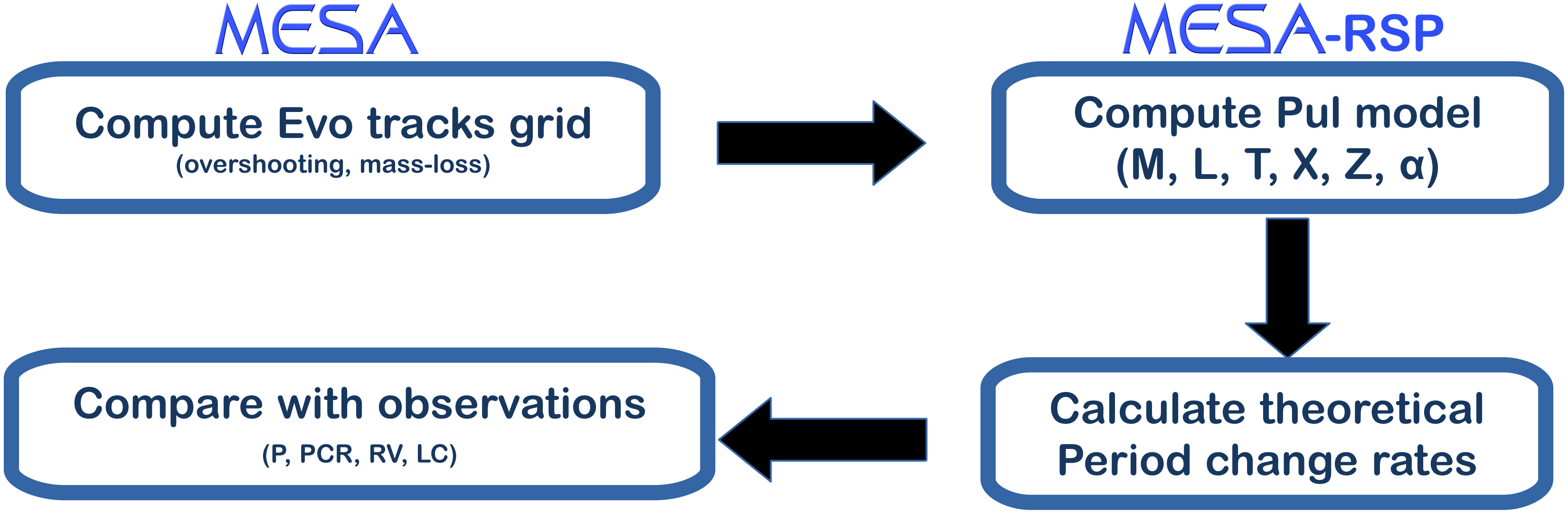


Field	Pulsation	Total	Flag 1	Zero-point	Amplitude	Phase	Simultaneous
SMC	F mode	2526	1068 (42.3%)	959 (89.8%)	1000 (93.6%)	637 (59.6%)	584 (54.7%)
	1O mode	1596	1237 (77.5%)	1154 (93.3%)	1042 (84.2%)	917 (74.1%)	770 (62.3%)
LMC	F mode	1780	1093 (61.4%)	982 (89.8%)	994 (90.9%)	564 (51.6%)	513 (56.9%)
	1O mode	1204	889 (73.8%)	839 (94.4%)	753 (84.7%)	631 (71.0%)	534 (60.1%)



Rathour et al. 2023(b) (in prep.)

Modeling Work Plan



(Un)Knowns about evolutionary PCR

- 67% inc. and 33% dec. PCR (Turner 2006)
- Overtone pulsation less stable (Poleski 2008)
- Reasonable agreement with theoretical models yet cannot satisfactorily reproduce PCR distribution

(Un)knowns about non-evolutionary PCR

- Least in galactic field; More likely to be in SMC (Deasy 1985) (Perhaps, a metallicity trend ?)
- Lack of systematic search and mechanism.

Validating Period changes with fluctuation tests

Sample retained

LMC: ~69% (F); ~89% (1O)

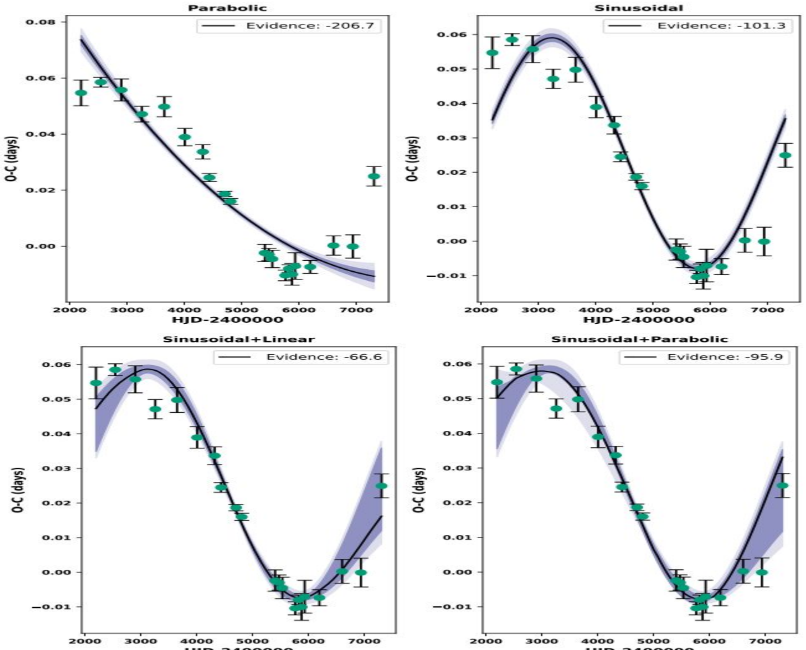
SMC: ~67% (F); ~94% (1O)

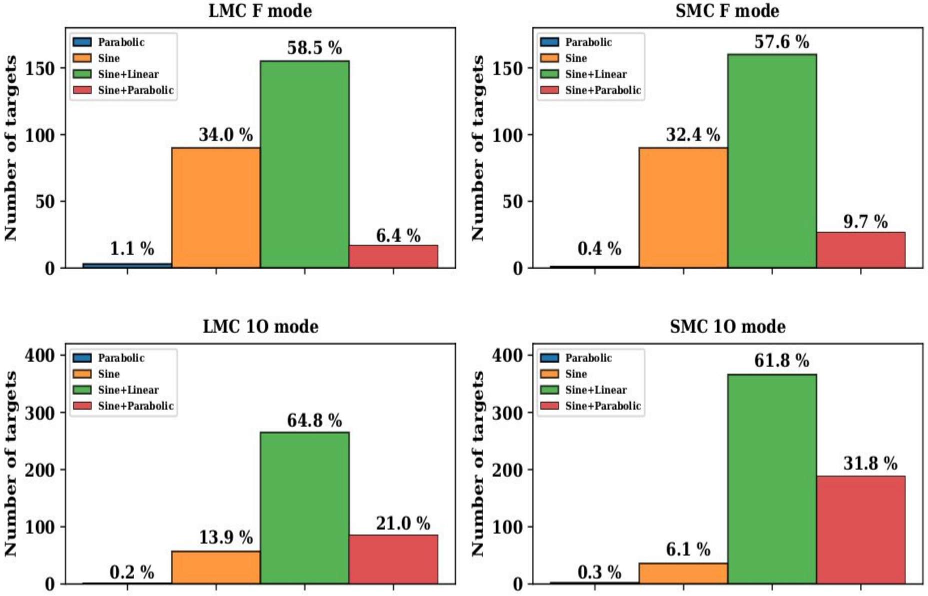
Occurance rate:

LMC: ~10.3% (F); ~58.8% (1O)

SMC: ~14.4% (F); ~68.4% (1O)

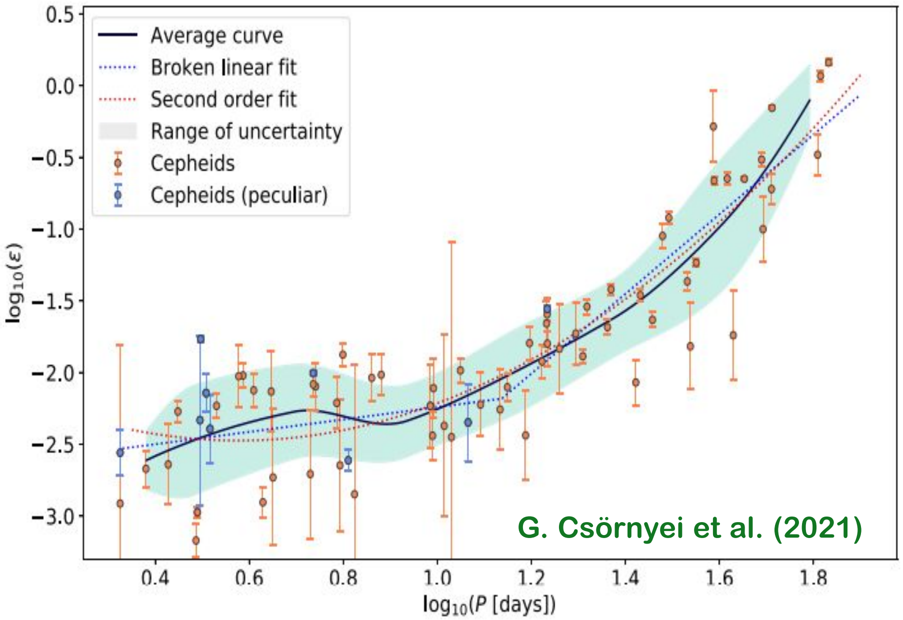
Field	Pulsation	OGLE-III	OGLE-IV	OGLE-III+IV
SMC	F mode	2626	2739	2582
	1O mode	1644	1790	1617
LMC	F mode	1818	2430	1801
	1O mode	1238	1769	1212





Rathour et al. 2023(b) (in prep.)

Validating Period changes with fluctuation tests

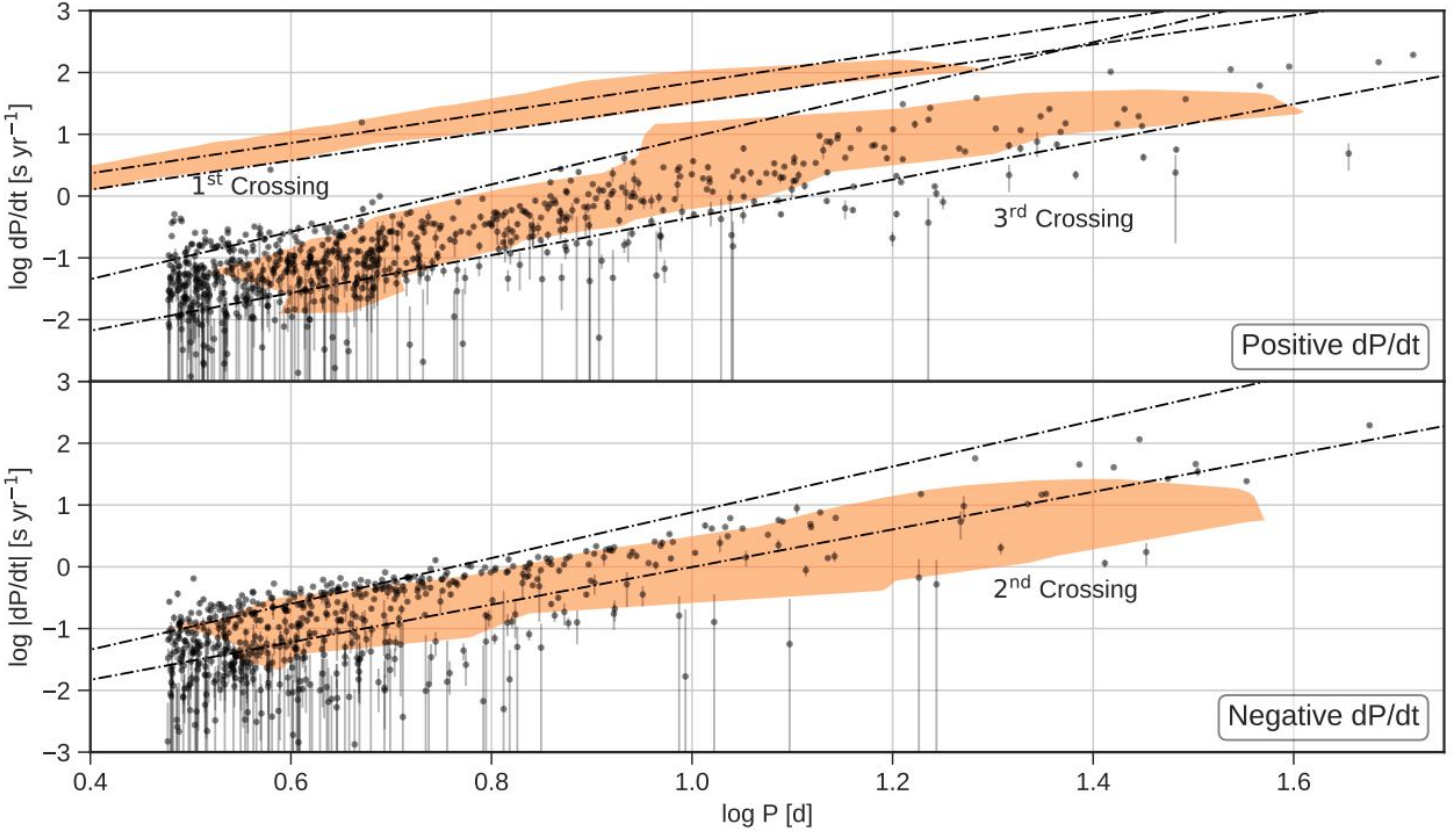


Sample retained

LMC: ~69% (F); ~89% (1O)

SMC: ~67% (F); ~94% (1O)

IrPC Fraction: ~41 %



N. Rodriguez-Segovia et al. (2021)