Binary Cepheids

Insights from a simulation-based approach

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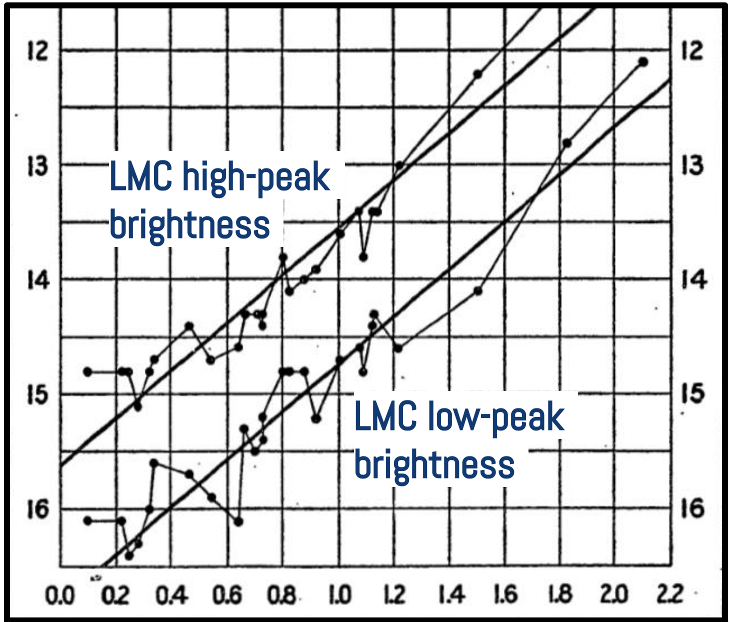
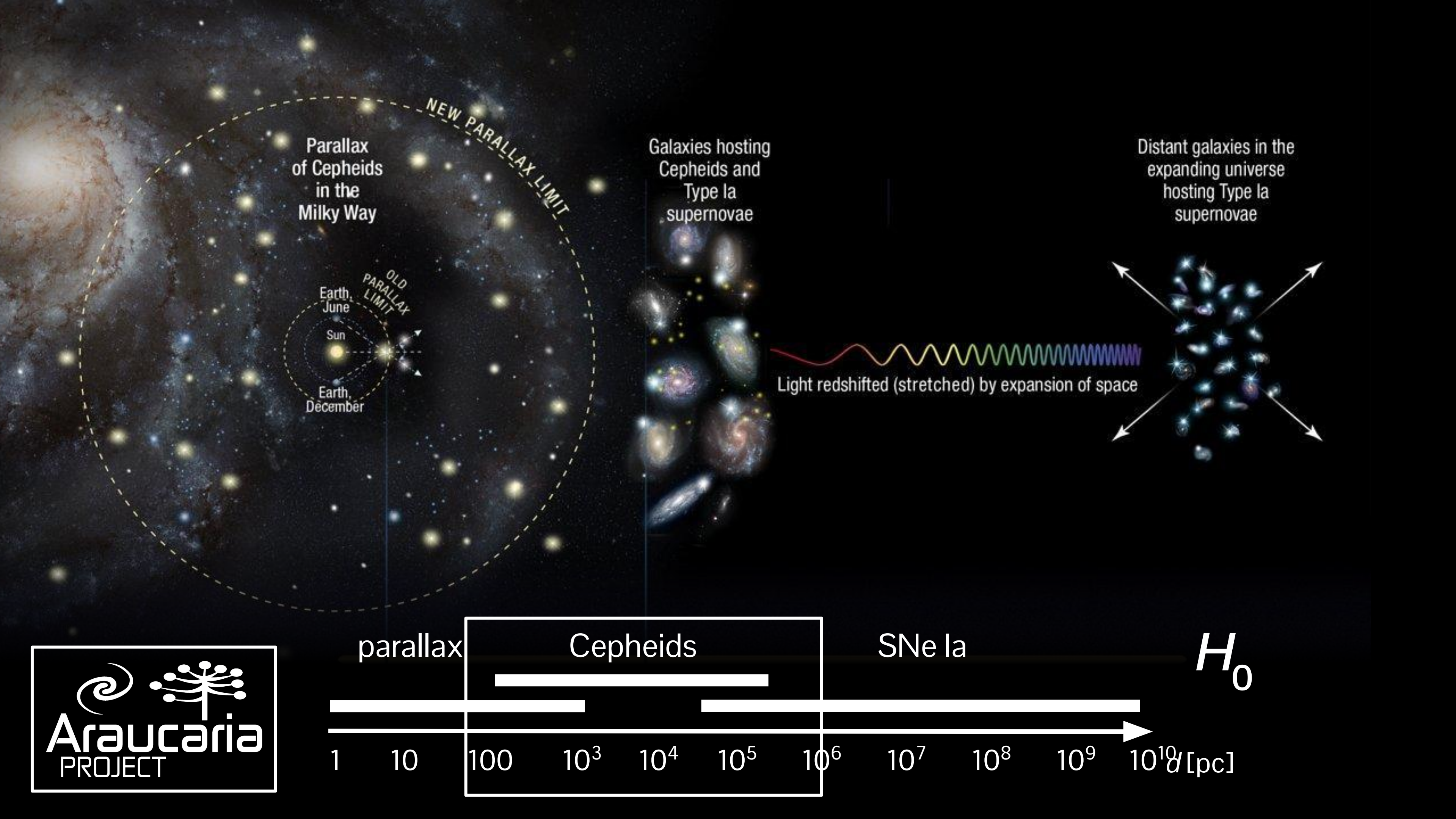
Araucaria PROJECT

Binary and Multiple Stars in the Era of Big Sky Surveys
Litomyšl, Sep 9-13, 2024

Leavitt Law (1912)



$$m - M = 5\log_{10}(d)$$



NEW PARALLAX LIMIT
Parallax of Cepheids in the Milky Way
OLD PARALLAX LIMIT
Earth, June
Sun
Earth, December
Galaxies hosting Cepheids and Type Ia supernovae
Light redshifted (stretched) by expansion of space
Distant galaxies in the expanding universe hosting Type Ia supernovae
parallax
Cepheids
SNe Ia
H_0
1
10
100
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
d [pc]
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Cepheid absolute / observed magnitude

- ✦ pulsation period
- ✦ metallicity (“metal-rich Cepheids are brighter”, Breuval+2022)
- ✦ overshooting & rotation
- ✦ reddening
- ✦ blending / crowding
- ✦ **binarity / multiplicity**
    - ✧ mass transfer / merger → metallicity, rotation, overshooting, age, evolutionary track…
    - ✧ companion’s contribution to the observed brightness

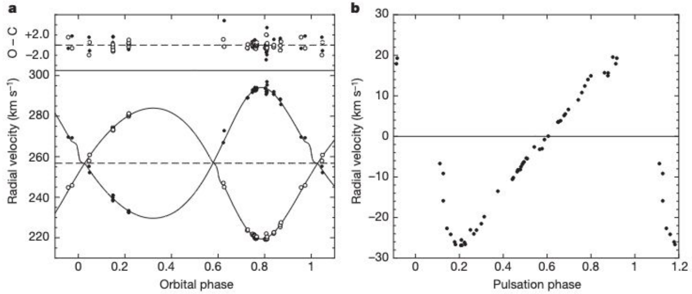
Binary Cepheids – perfect cosmic laboratory

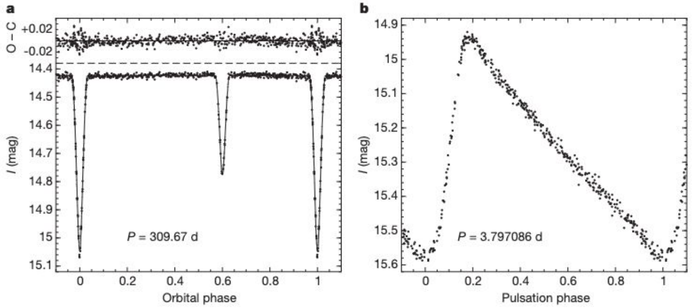
The dynamical mass of a classical Cepheid variable star in an eclipsing binary system

G. Pietrzyński[1,2], I. B. Thompson[3], W. Gieren[1], D. Graczyk[1], G. Bono[4,5], A. Udalski[2], I. Soszyński[2], D. Minniti[6] & B. Pilecki[1,2]

Abstract

Stellar pulsation theory provides a means of determining the masses of pulsating classical Cepheid supergiants—it is the pulsation that causes their luminosity to vary. Such pulsational masses are found to be smaller than the masses derived from stellar evolution theory: this is the Cepheid mass discrepancy problem[1,2], for which a solution is missing[3,4,5]. An independent, accurate dynamical mass determination for a classical Cepheid variable star (as opposed to type-II Cepheids, low-mass stars with a very different evolutionary history) in a binary system is needed in order to determine which is correct. The accuracy of previous efforts to establish a dynamical Cepheid mass from Galactic single-lined non-eclipsing binaries was typically about 15–30% (refs 6, 7), which is not good enough to resolve the mass discrepancy problem. In spite of many observational efforts[8,9], no firm detection of a classical Cepheid in an eclipsing double-lined binary has hitherto been reported. Here we report the discovery of a classical Cepheid in a well detached, double-lined eclipsing binary in the Large Magellanic Cloud. We determine the mass to a precision of 1% and show that it agrees with its pulsation mass, providing strong evidence that pulsation theory correctly and precisely predicts the masses of classical Cepheids.



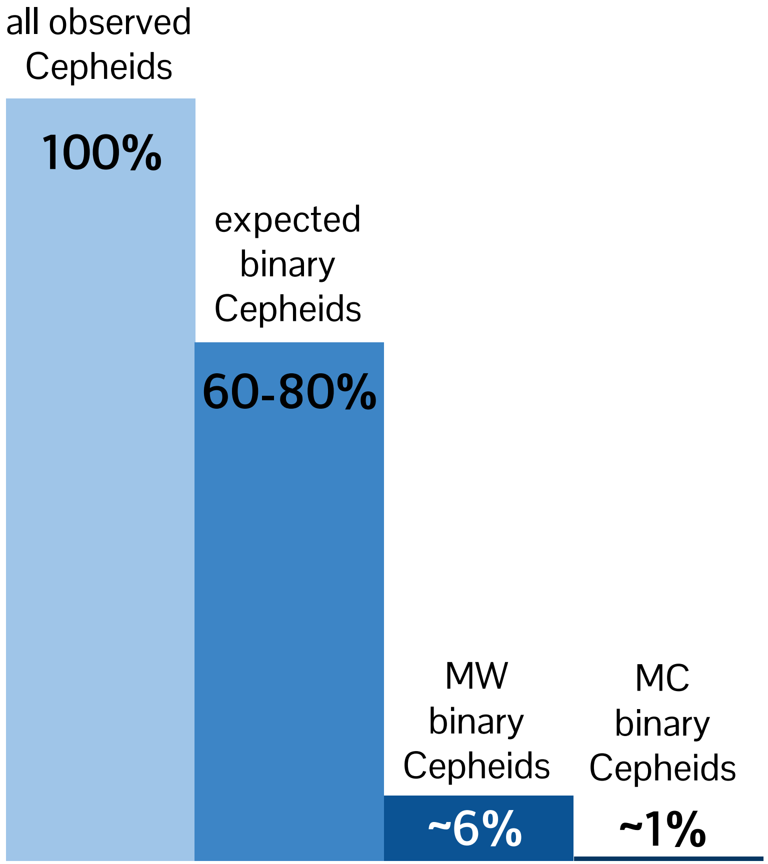


Gap between expected and observed binary Cepheids (BC)

60-80% Cepheids should have companions (Evans 1992, Kervella+2019)

MW: ~170 BC (Szabados 2003)

MC: ~80 BC (Szabados & Nehéz 2012, Pilecki+ 2018, 2021)



Synthetic population of binary Cepheids

- ✔ free from the selection and completeness biases
- ✔ the percentage of BCs is controlled by the *binarity parameter* $f_{\%}$
- ✔ fast & efficient: binary population synthesis method, *StarTrack*[1] code (Belczynski+2008)
- ✘ (too?) simplistic evolution of single and binary stars → statistical features
- ✘ no periods & magnitudes → calculated from external codes
- ✘ dependent on input parameters & processes → 16 variants of synthetic populations for 3 metallicities (SMC, LMC, MW), 200,000 systems each

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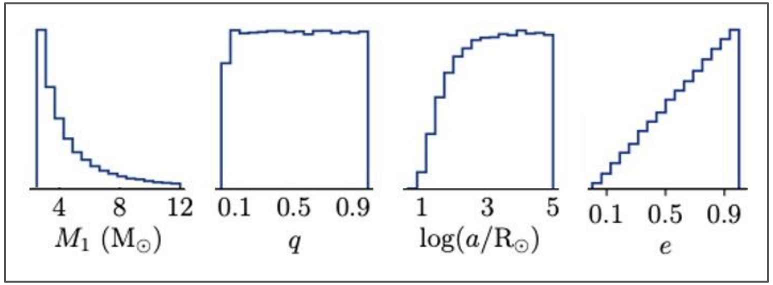
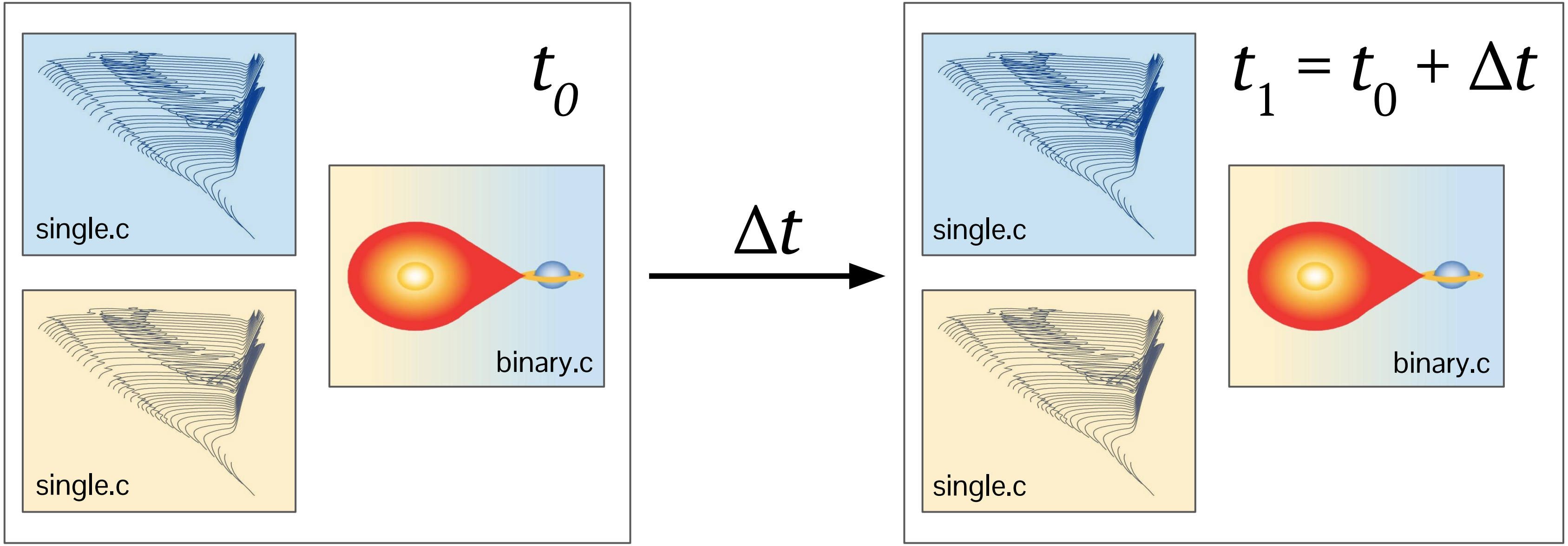
[1] "rapid" code (sub-second calculation of a full binary model), based on semi-analytical models based on pre-computed 1D stellar models (Hurley et al. 2002), alternatives: binary_c, SeBa (Toonen+2014)

Binary population synthesis method

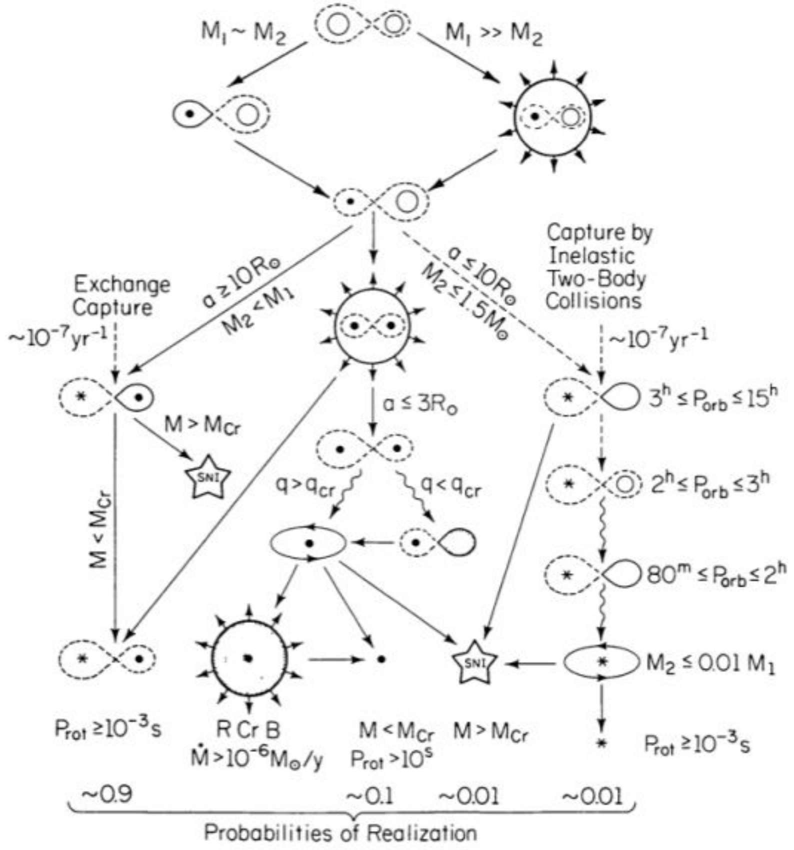


+

number of systems
max age
M_1 from … to …
Z



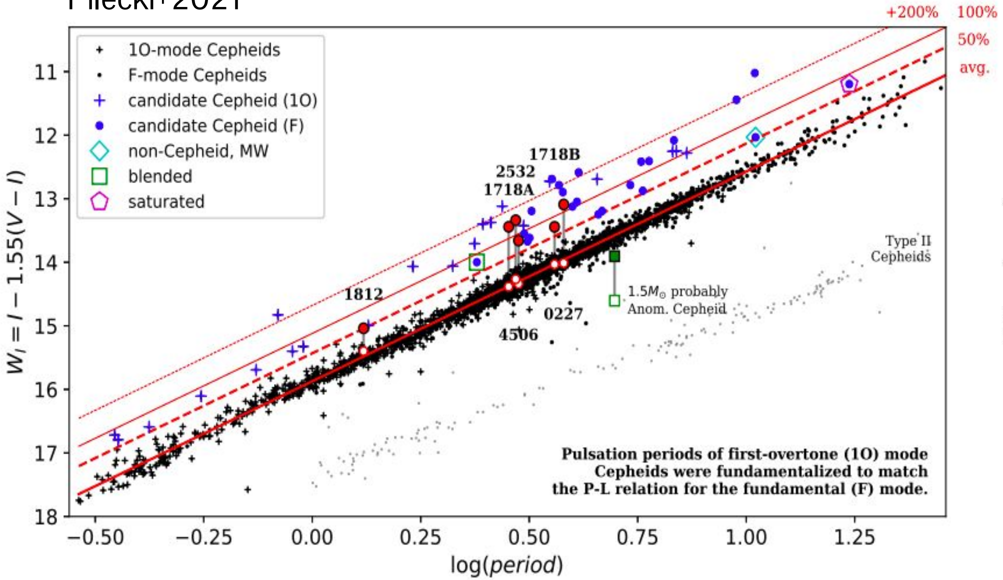
Binary interactions



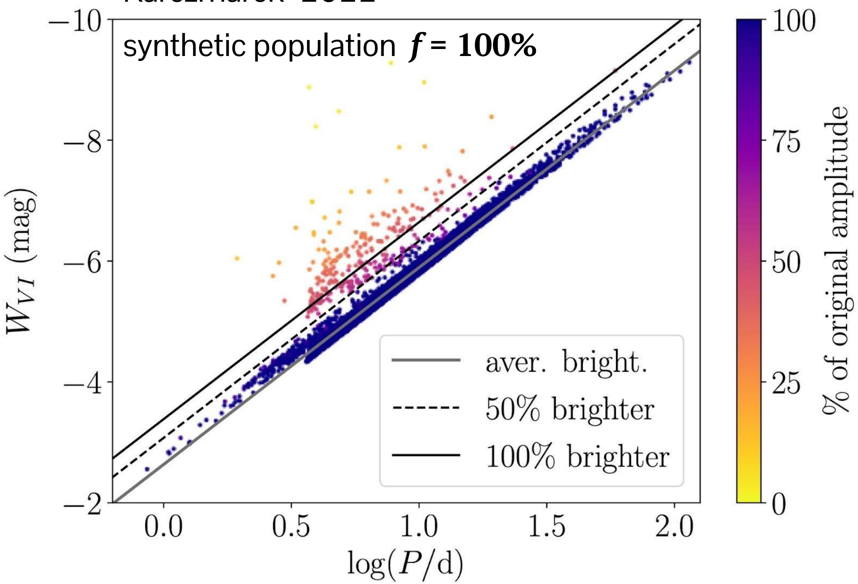
- stable vs unstable mass transfer
- mass transfer (regular, via winds, atmosphere)
- common envelope
- tidal interactions
- angular momentum loss
- gravitational radiation

Observed vs synthetic PLR

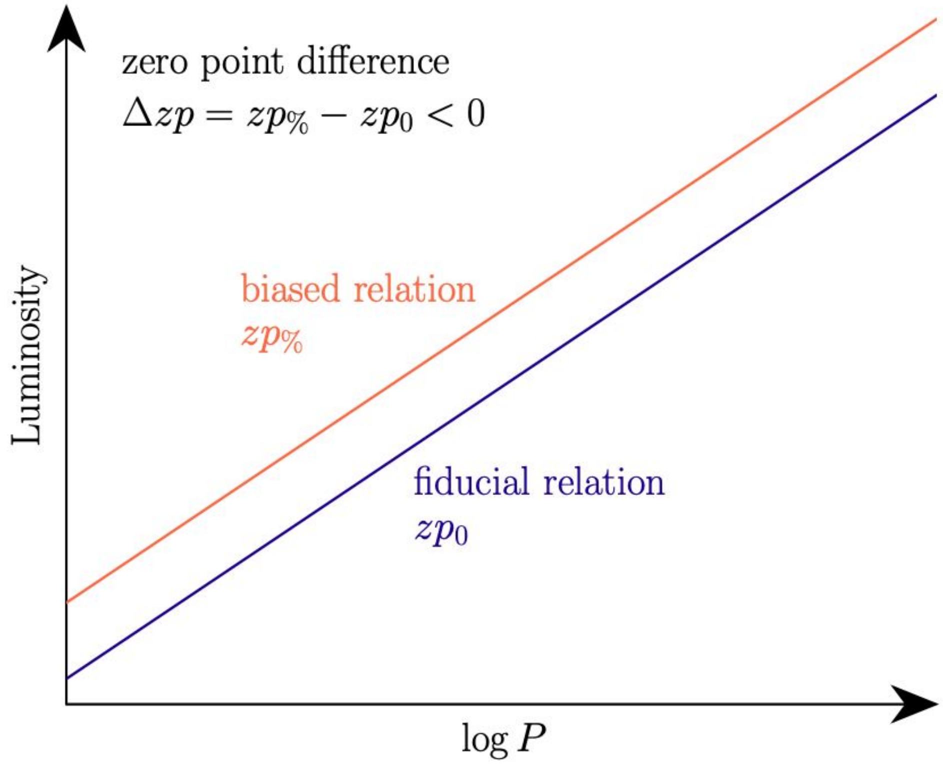
Pilecki+2021



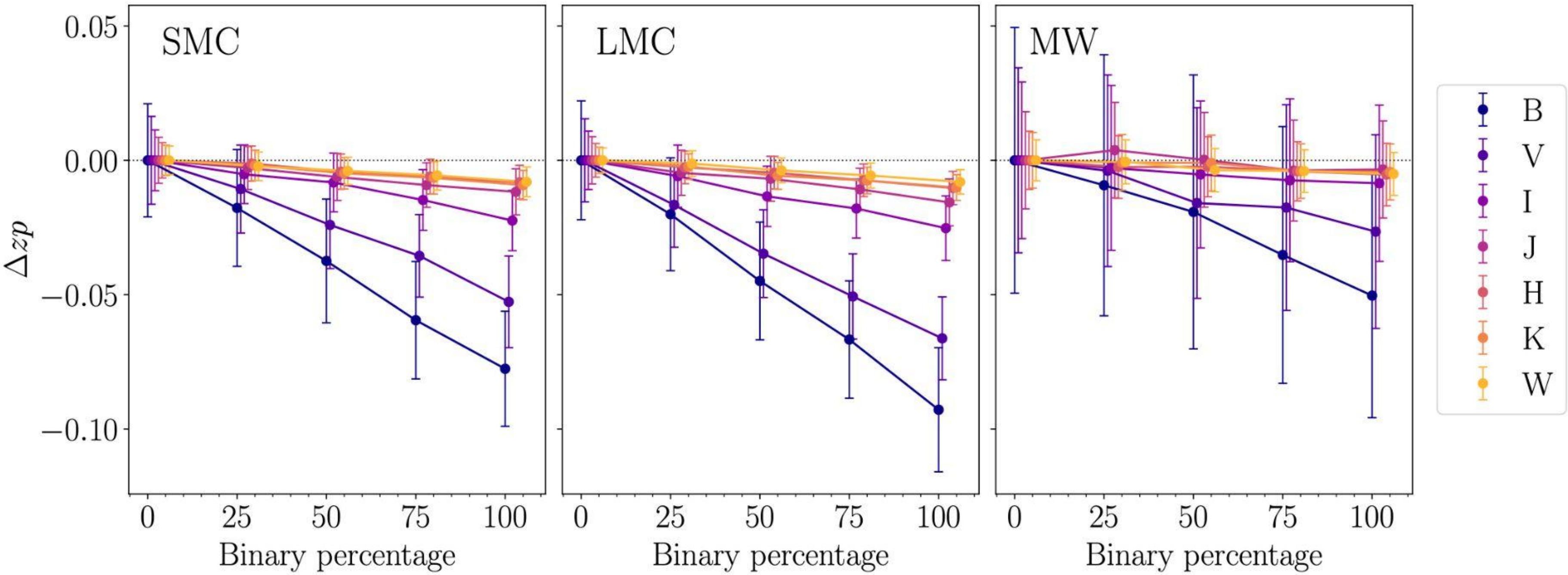
Karczmarek+2022



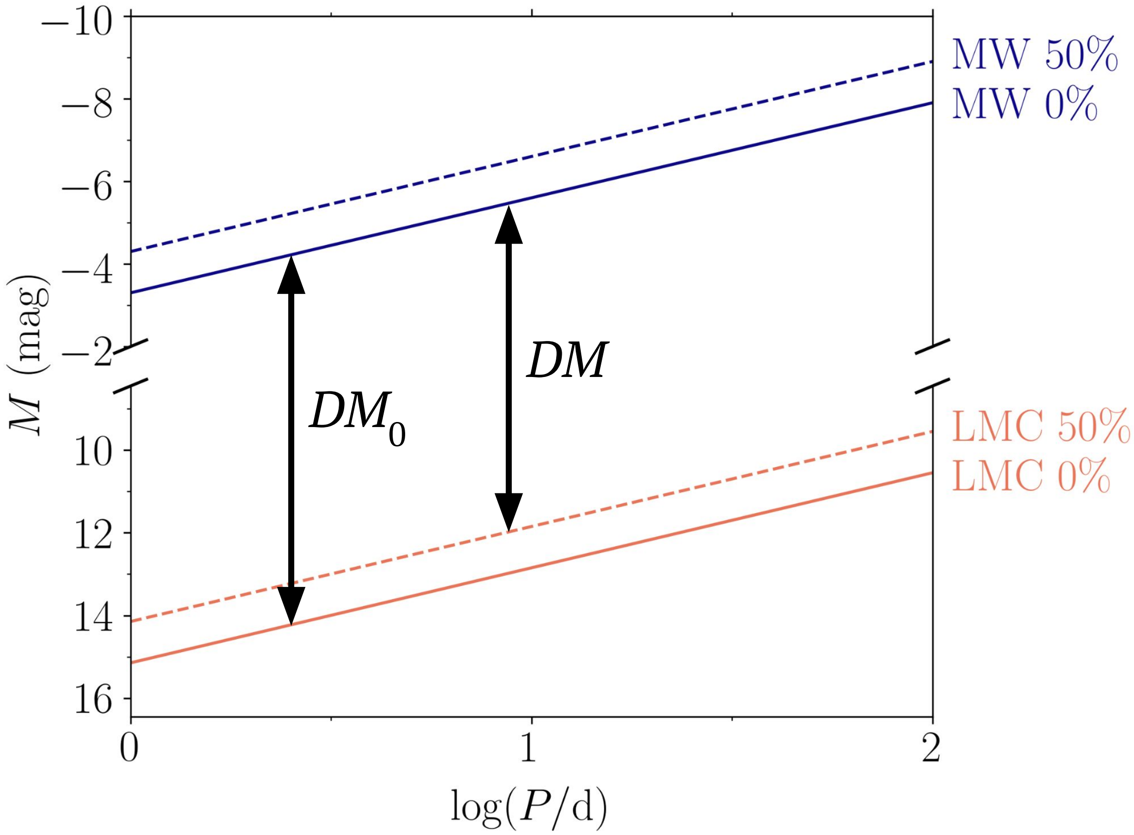
Zero point difference



PLR zero point difference Δzp



A shift in the distance modulus (DM)



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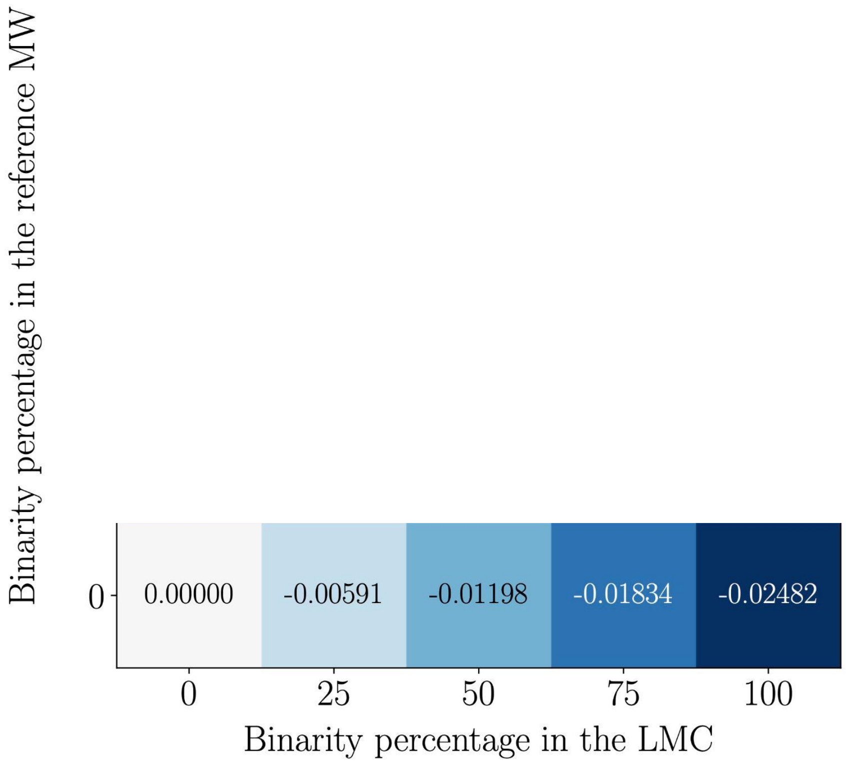

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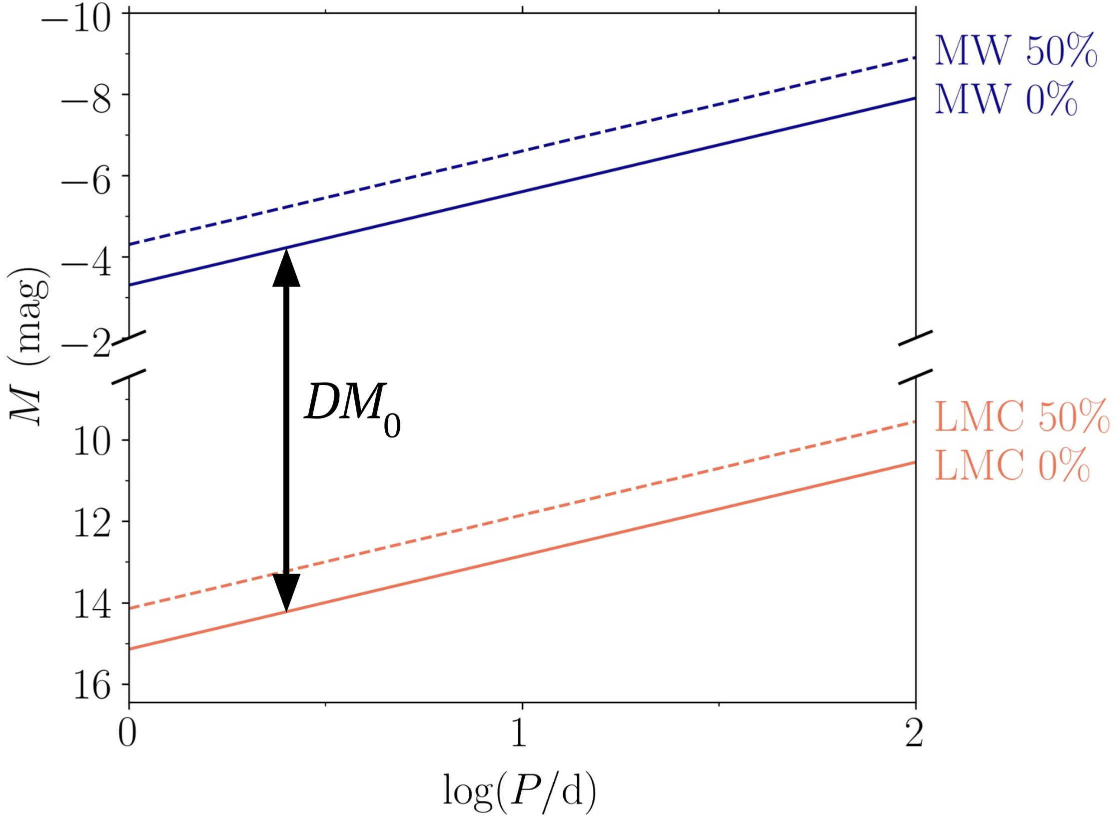

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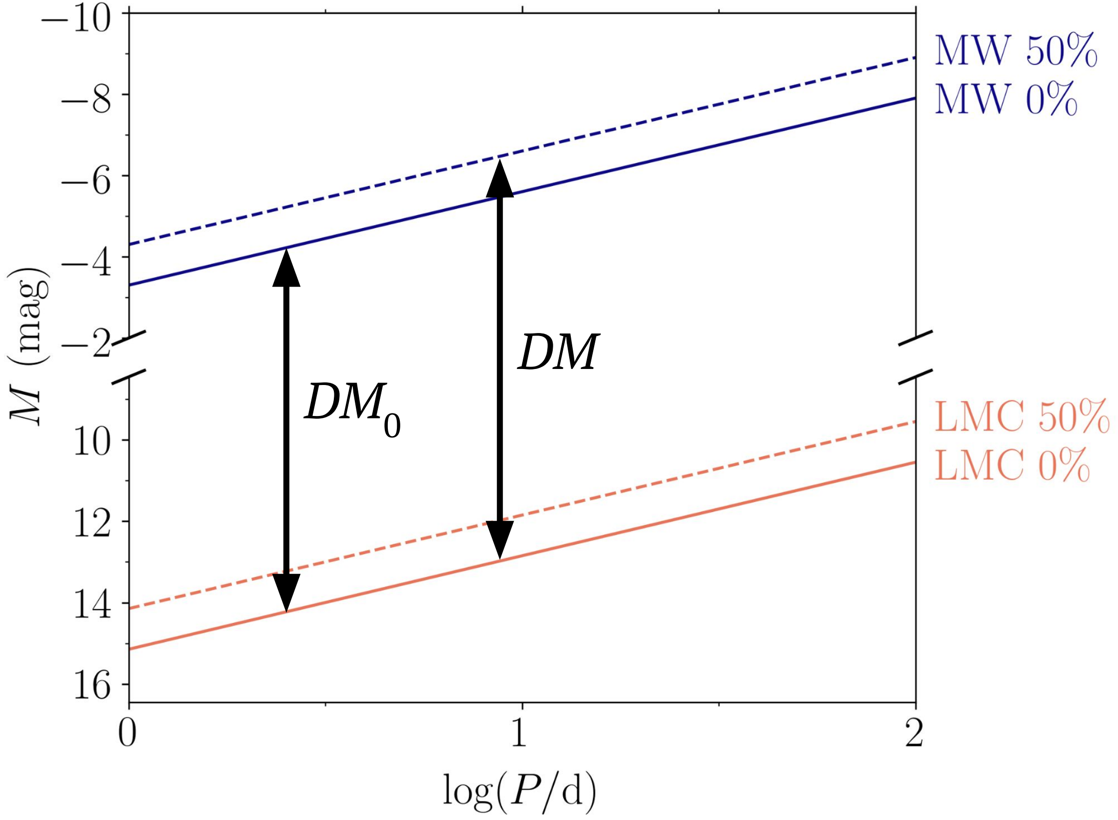

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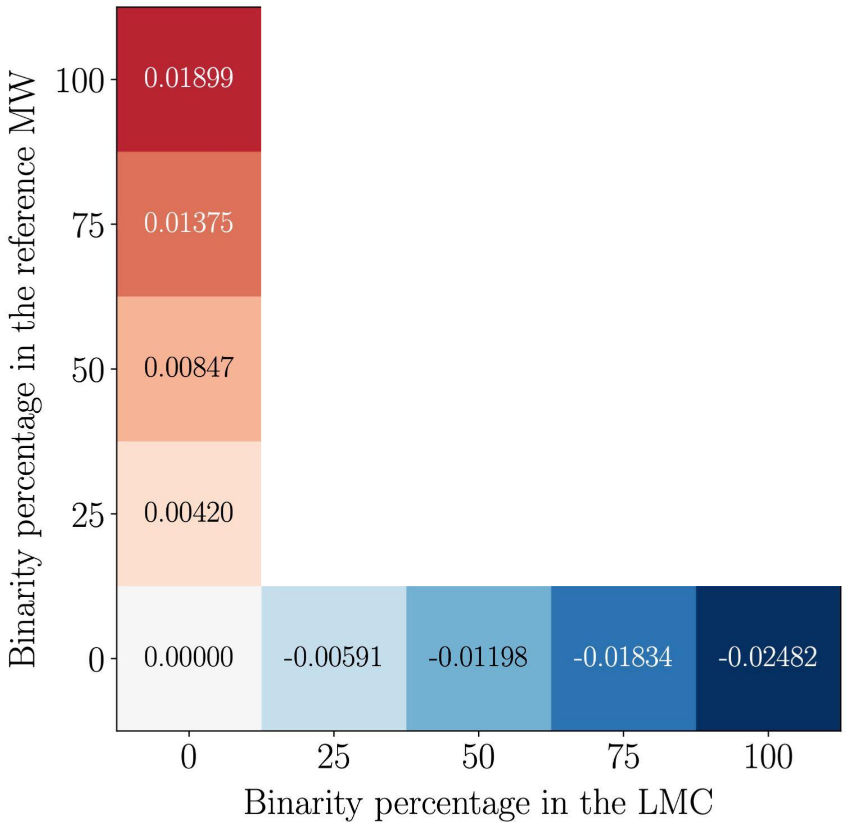
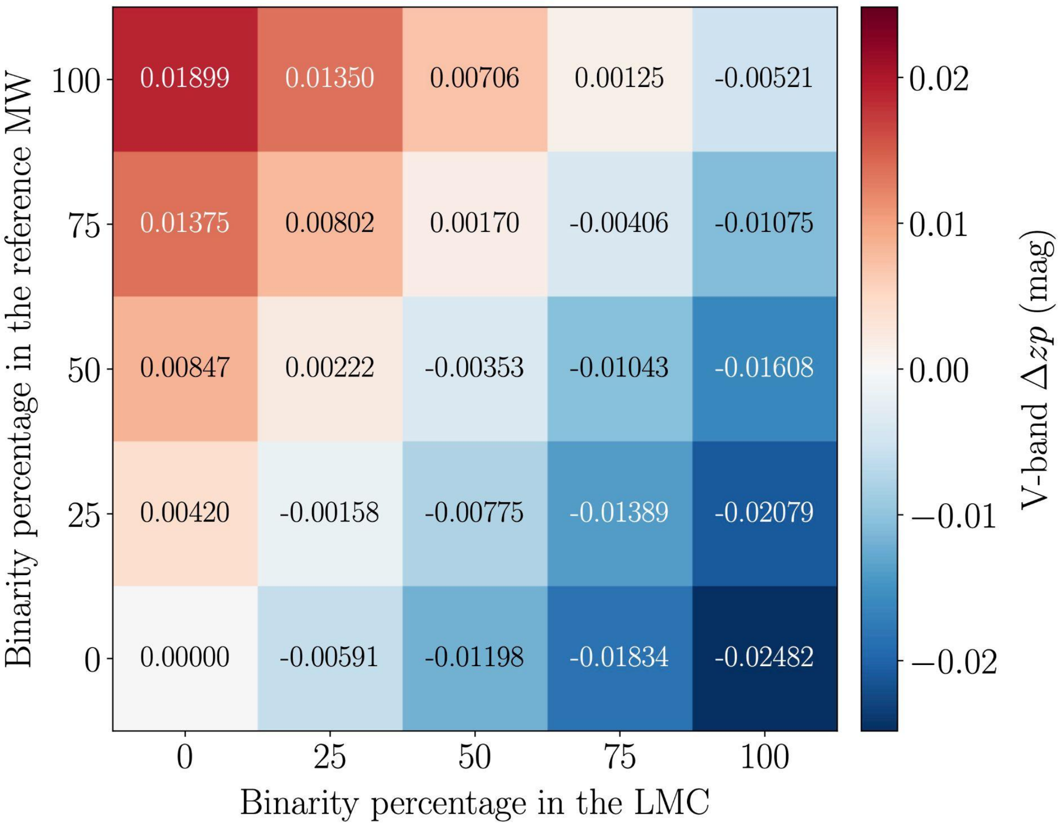
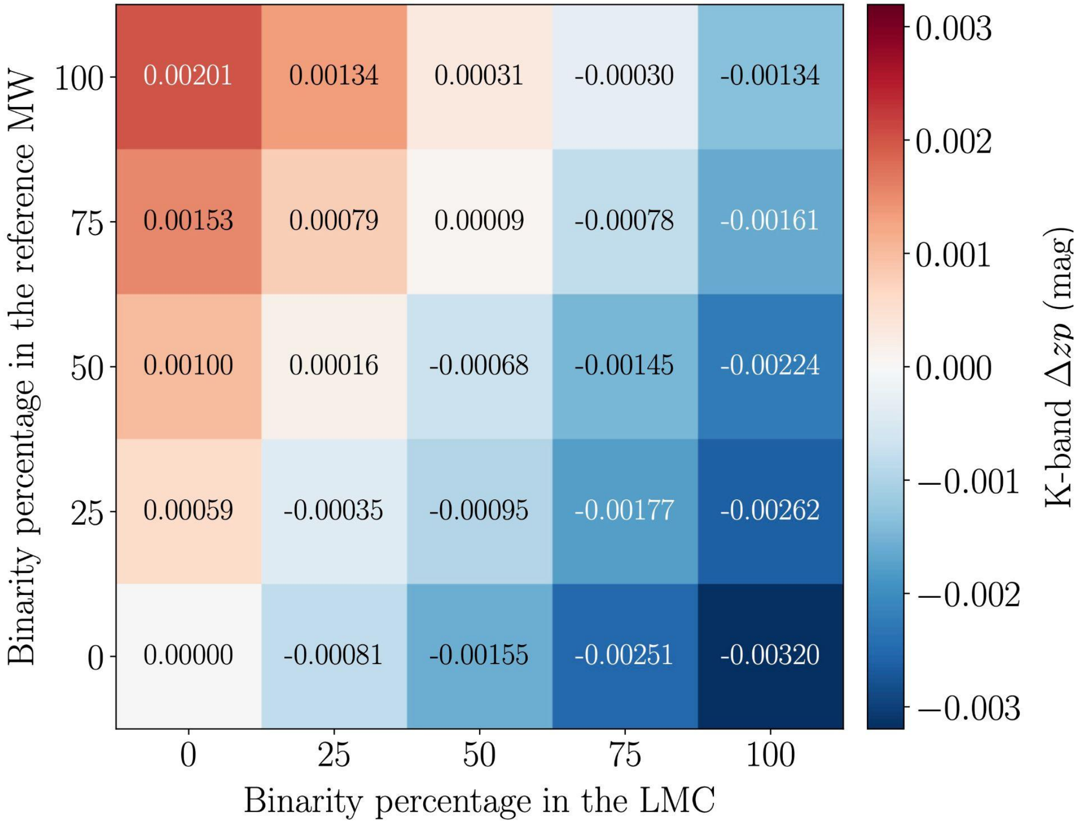


DM shift to the LMC, relative to the MW, V band



DM shift to the LMC, relative to the MW, K band



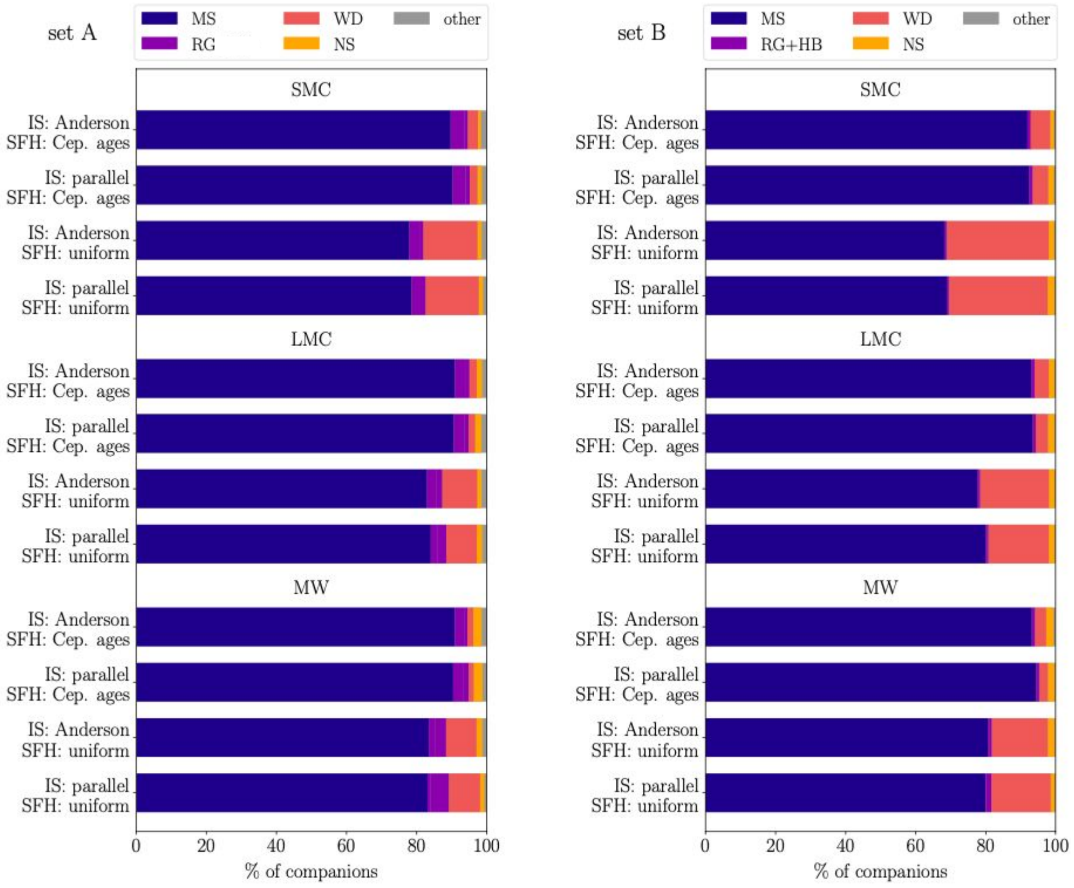
Conclusions

- ✦ results consistent with observations (outliers above the PLR)
- ✦ binaries are *baked* into the calibration
- ✦ ***DM shift*** depends on $\boldsymbol{f_{\mathrm{bin}}}$ **in reference and target galaxies**, wavelength, Z, and is the smallest in the near-infrared domain and Wesenheit: **±3-6 mmag at most** → **quantified!**

Karczmarek+2022 (ApJ 930, 65)
Karczmarek+2023 (ApJ 950, 182)

Insight in binary Cepheids

- **companions' evolutionary stages**
- companions' spectral types
- proportions of Cepheids on their 1st, 2nd, 3rd crossing



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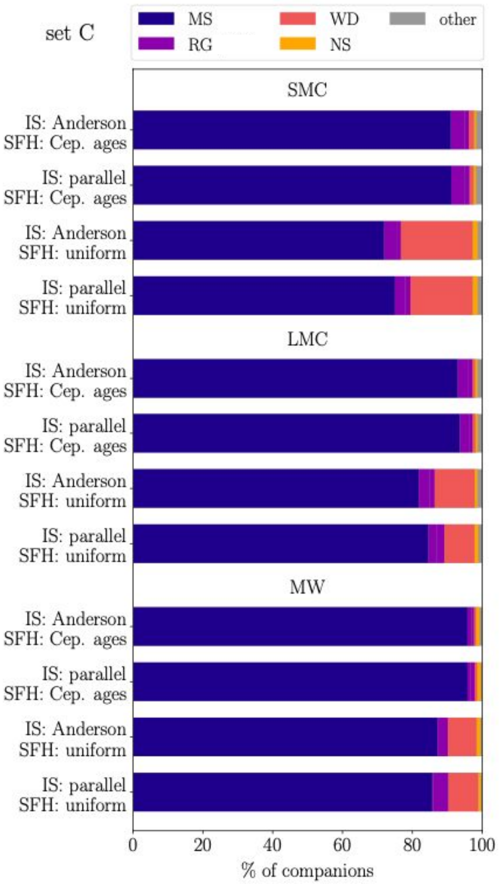

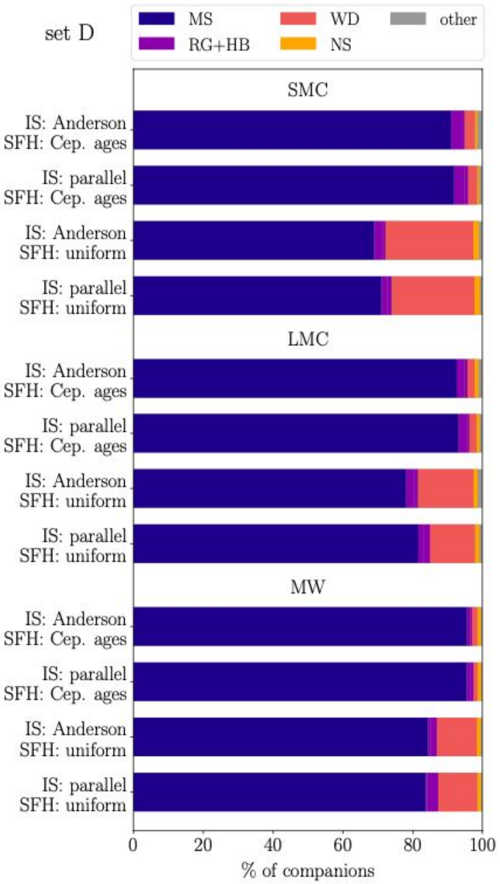

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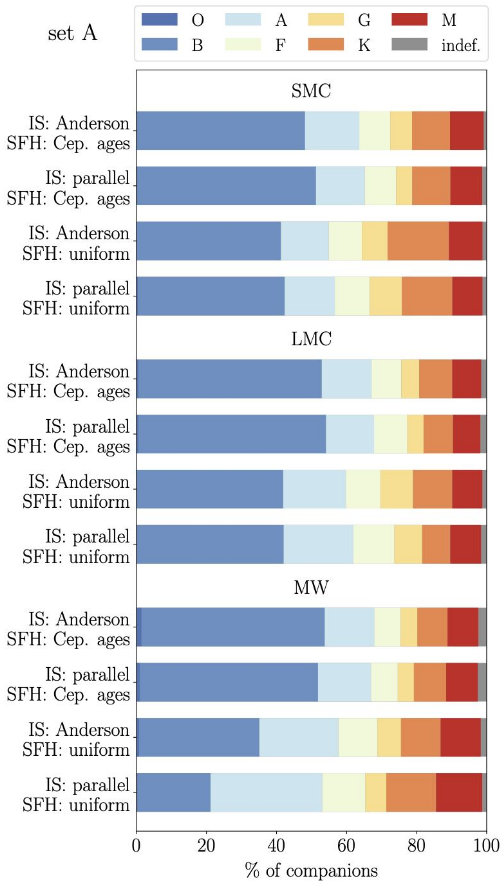

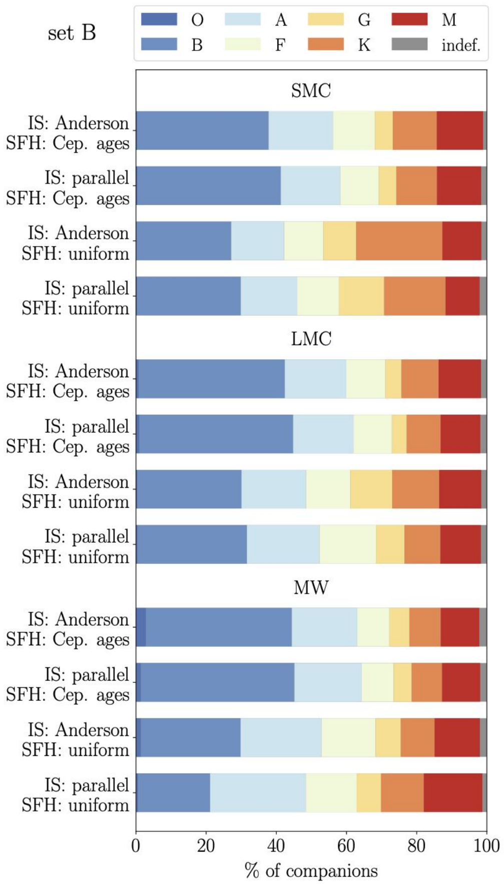

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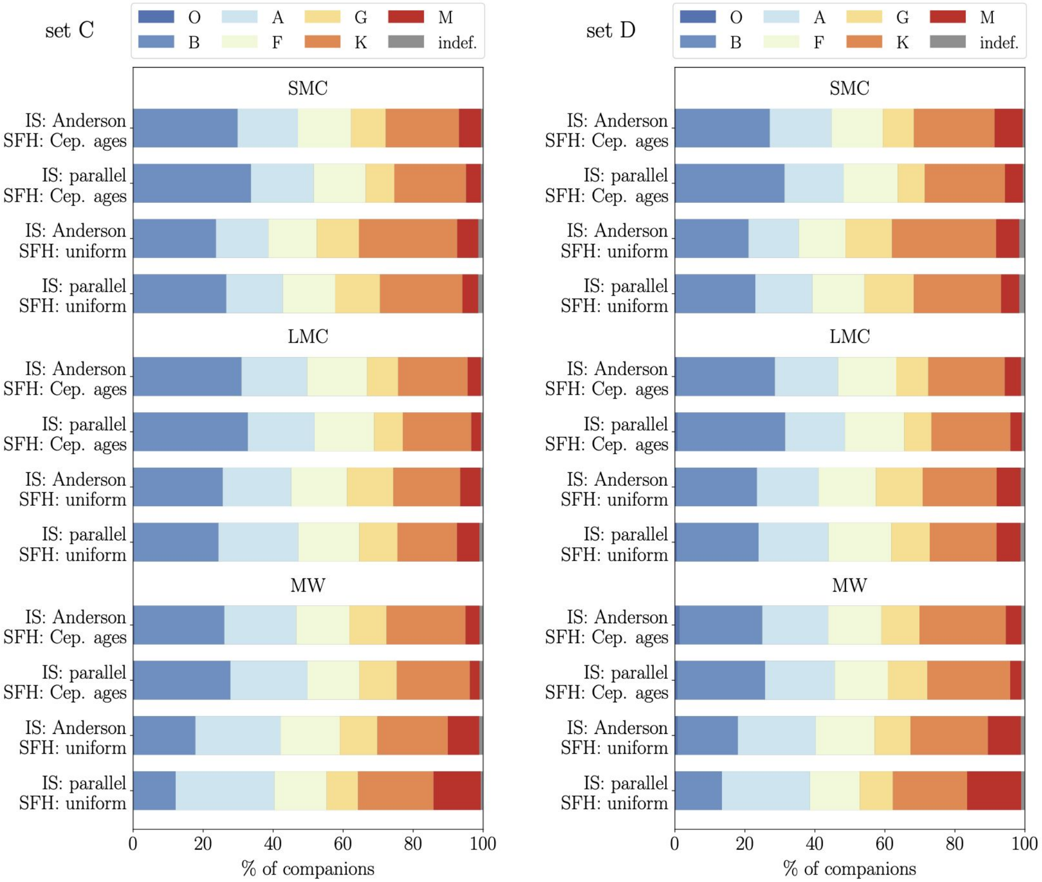

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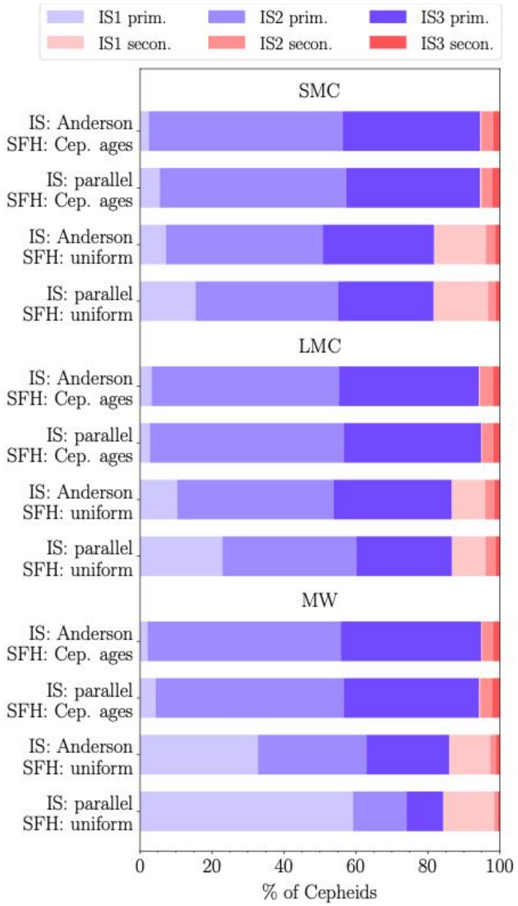
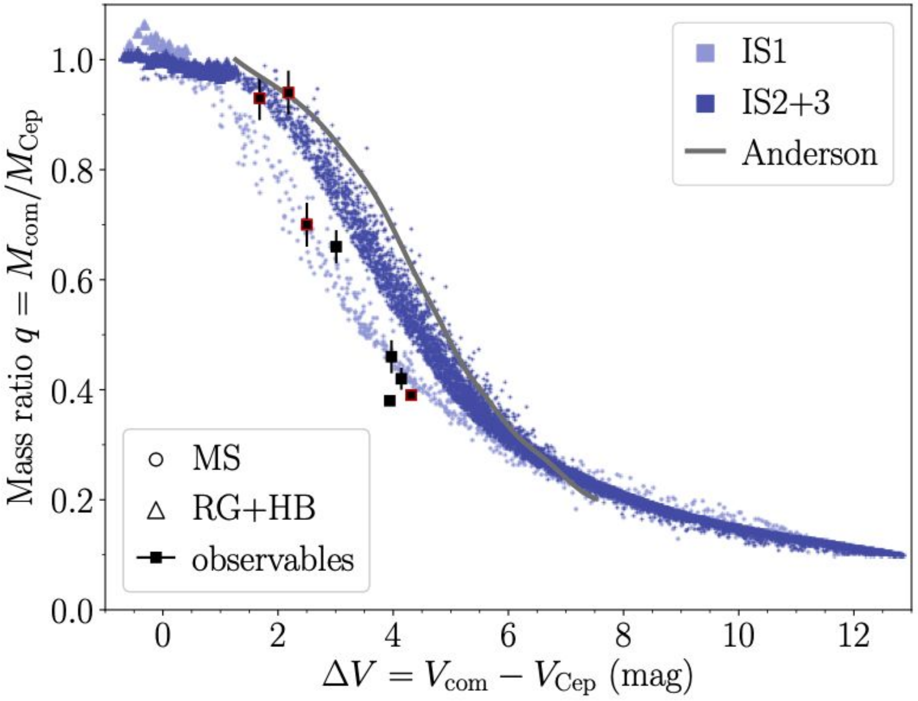
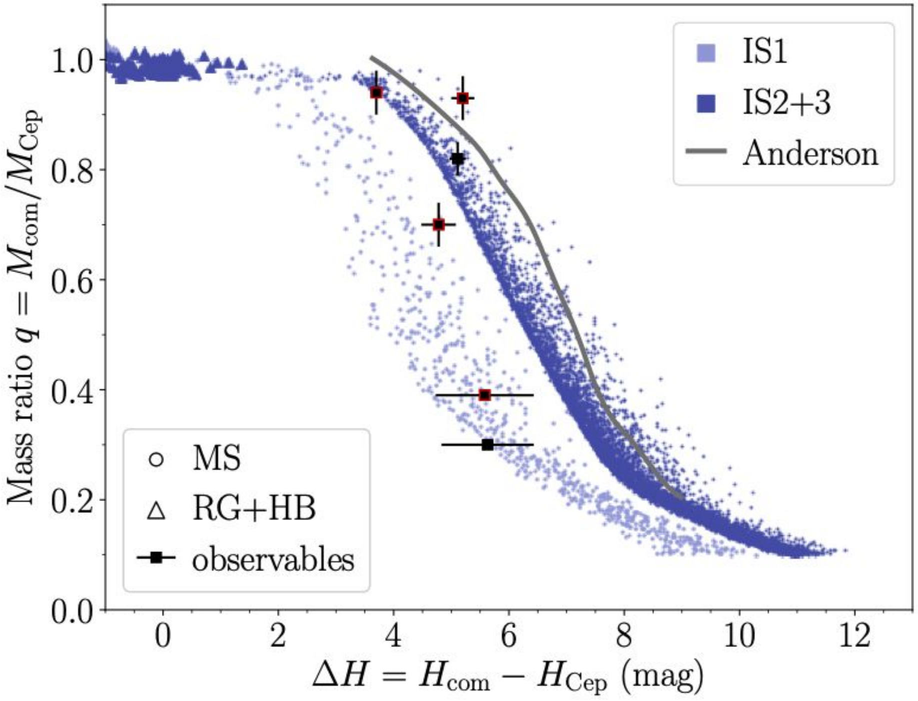
- ✦ companions' evolutionary stages
- ✦ companions' spectral types
- ✦ **proportions of Cepheids on their 1st, 2nd, 3rd crossing**



Mass ratio vs magnitude difference





Fraction of binary Cepheids in the LMC

Rough estimate!

- all eclipsing binaries with $i \geq 83°$ and $\log P < 4$ are known (6)
- for $i = [0,90]$ we expect 75 Cepheid binaries with $\log P < 4$
- from synt. pop. we have a fraction of Cepheids with giant companions and $\log P < 4$ (75)
- we calculate the entire population of Cepheids with giant companions
- giant companions constitute 3-5% of the population of binary Cepheids, so the entire population of binary Cepheids equals to...

Color-color diagram