The multiplicity fraction in 202 open clusters from *Gaia*

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MW-GAIA WG2 Workshop – Stellar Variability, Stellar Multiplicity: Periodicity in Time & Motion

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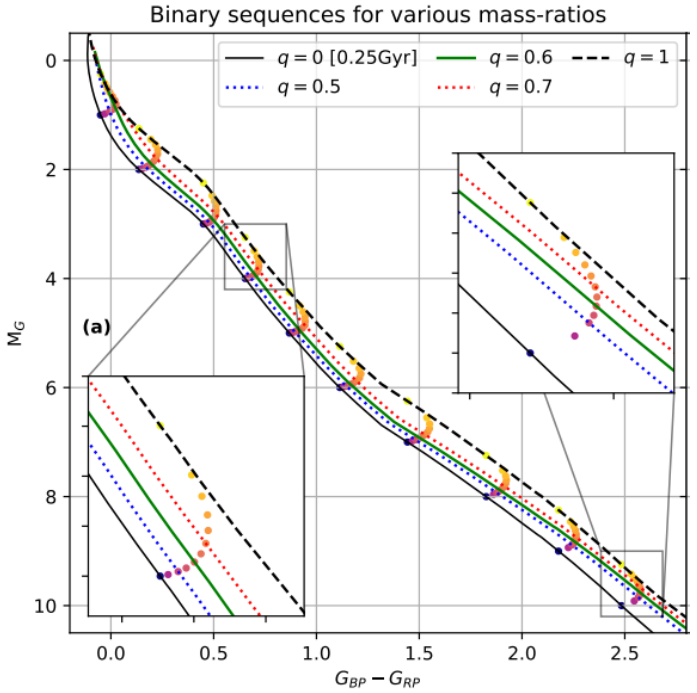
Donada, J., Anders, F., Jordi, C., et al., *The multiplicity fraction in 202 open clusters from Gaia*, **2023**, *Astronomy & Astrophysics* (accepted for publication on 25th April 2023, now in press). arXiv:2301.11061.

Multiplicity fraction: $f_b = \frac{B + T + \ldots}{S + B + T + \ldots}$ Binary system mass ratio: $q = M_2/M_1$ $(0 < q \leq 1)$

Multiple stellar systems in open clusters (OCs)

Most multiple systems are spatially unresolved, being located in the colour-magnitude diagram (CMD) above (and towards redder colours for $q < 1$) with respect to the main-sequence position of the primary component, by an amount which depends on q and M_1.



—— $q = 0$ locus: single-star sequence

– – – $q = 1$ locus: equal-mass binary sequence (0.753 mag brighter than the equivalent single star)

Jadhav, Vikrant V. et al., *High Mass-Ratio Binary Population in Open Clusters: Segregation of Early Type Binaries and an Increasing Binary Fraction with Mass*, **2021**, *AJ*, 162.6, p. 264.

Selection of the sample of OCs and their main-sequence members

OCs' membership lists

Membership determinations of OCs in the extended solar neighbourhood (**closer than 1.5 kpc** from the Sun) from the *Gaia*-derived catalogues:

- **Tarricq et al. 2022** (**T22**, EDR3-based), age > 50 Myr

  Tarricq, Y. et al., *Structural parameters of 389 local open clusters*, **2022**, *A&A*, 659, A59. arXiv: 2111.05291.

- **Cantat-Gaudin et al. 2020** (**CGa20**, DR2-based), selecting those of age < 50 Myr

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Both are limited to $G < 18$, we further select those members with membership probability $\geq 70\%$.

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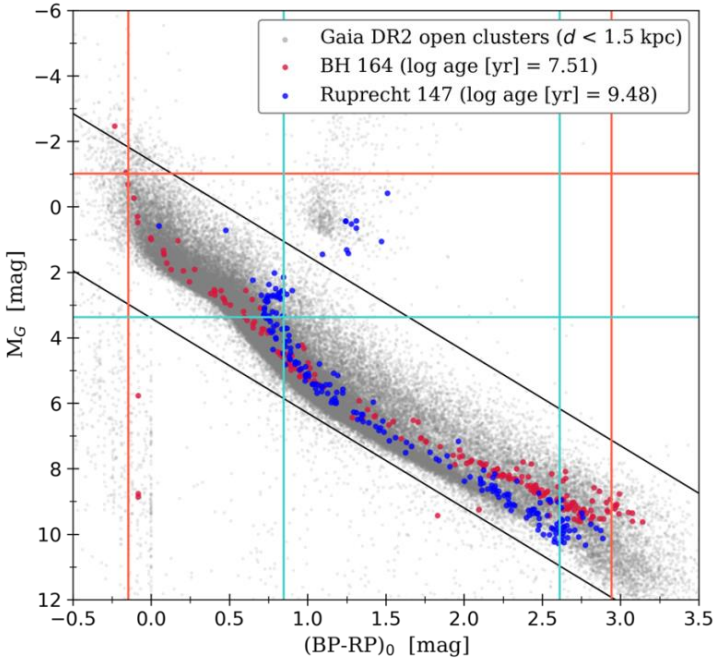
OC's physical parameters: from CGa20.

Selection of OC's main-sequence (MS) members

We retain only those OCs having:

- at least 30 MS members
- $(BP - RP)_0$ range of at least 1 mag

and obtain 377 OCs.



Two examples of the homogeneous selection of the main sequence members of the OCs.

Mixture model for the observed OC's *Gaia* CMD

The observed G vs. (BP-RP) *Gaia* CMD of selected MS members is modelled as a mixture distribution

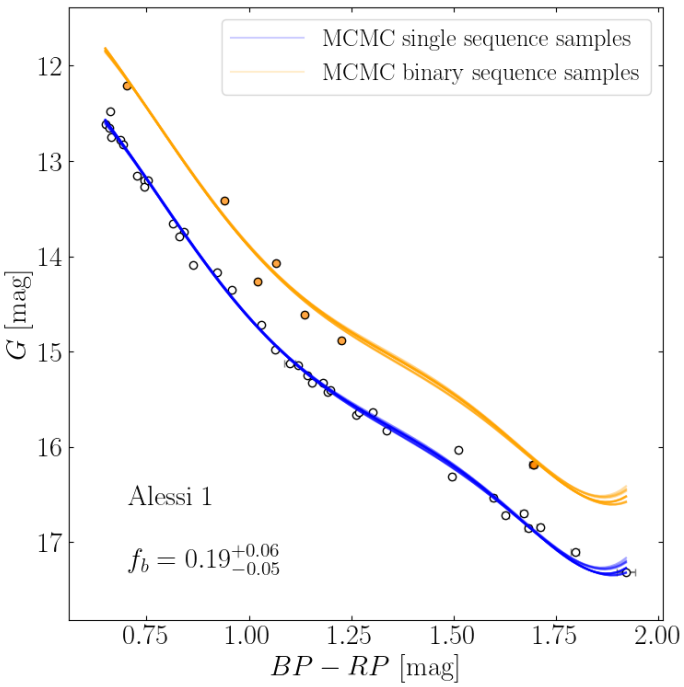
of { single stars / unresolved binaries } arising from 2 Gaussian distributions: { $\mathcal{N}(G;\ G_{SS}(M_1), \sigma_{SS})$ (weight: w_{SS}) / $\mathcal{N}(G;\ G_{BS}(M_1), \sigma_{BS})$ (weight: w_{BS}) }

Likelihood function ($\mathcal{L}$) depending on:

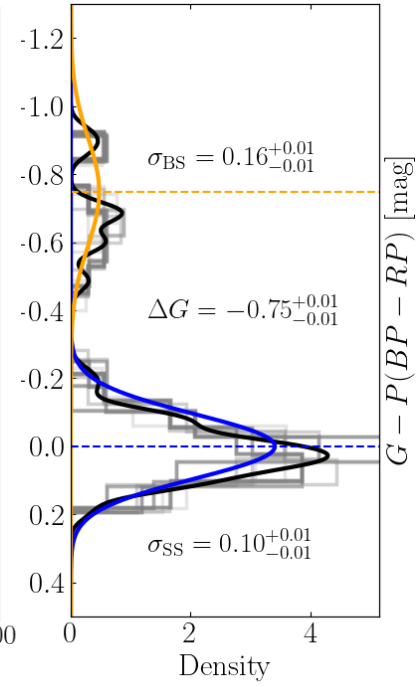
- p+1 parameters of p_{SS} polynomial (p=6)
- $\Delta G = G_{BS} - G_{SS}$
- σ_{SS} (SS comprises $q \in [0,\ q_{\mathrm{lim}}(M_1))$)
- σ_{BS} (BS comprises $q \in (q_{\mathrm{lim}}(M_1), 1]$)
- $\boldsymbol{f_b(q > q_{\mathrm{lim}}) = \frac{w_{BS}}{w_{SS} + w_{BS}} = w_{BS}}$

  Multiplicity fraction of high-q unresolved systems integrated over the OC's MS mass range.

`emcee` is used for the MCMC sampling of the posterior probability distribution.



Fit of the single sequence ridge and the binary sequence in the observed *Gaia* CMD.



Residuals with respect to the polynomial fit and Gaussian mixture fit.

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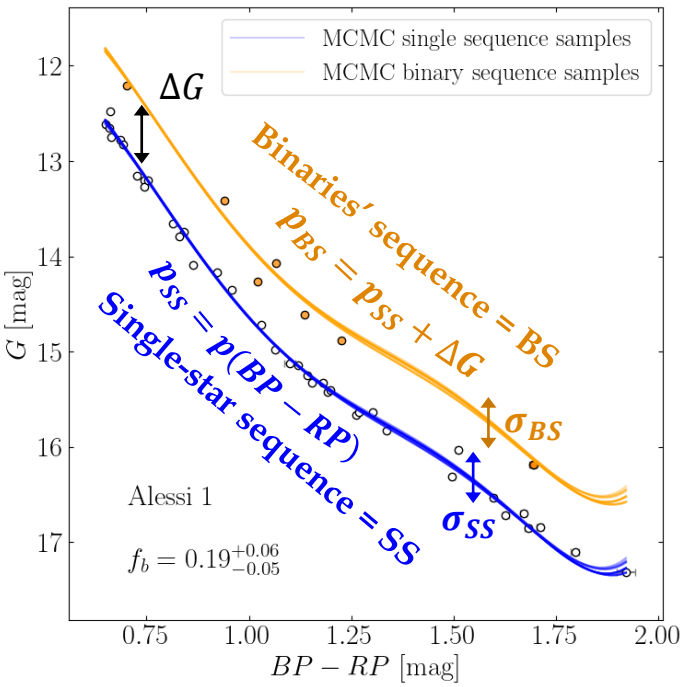

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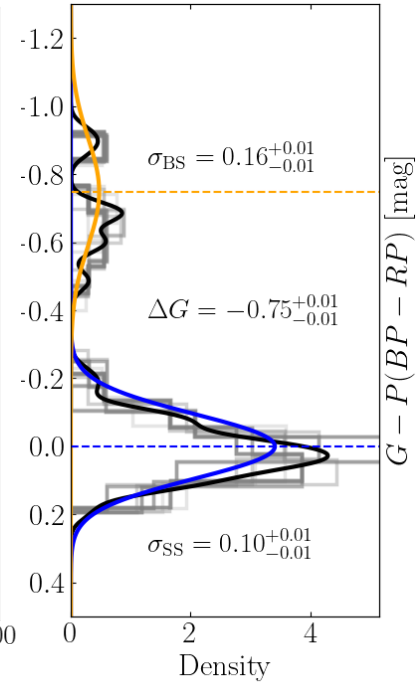


Residuals with respect to the polynomial fit and Gaussian mixture fit.

Selection of OCs with an accurate CMD fit

We only retain the OCs having:

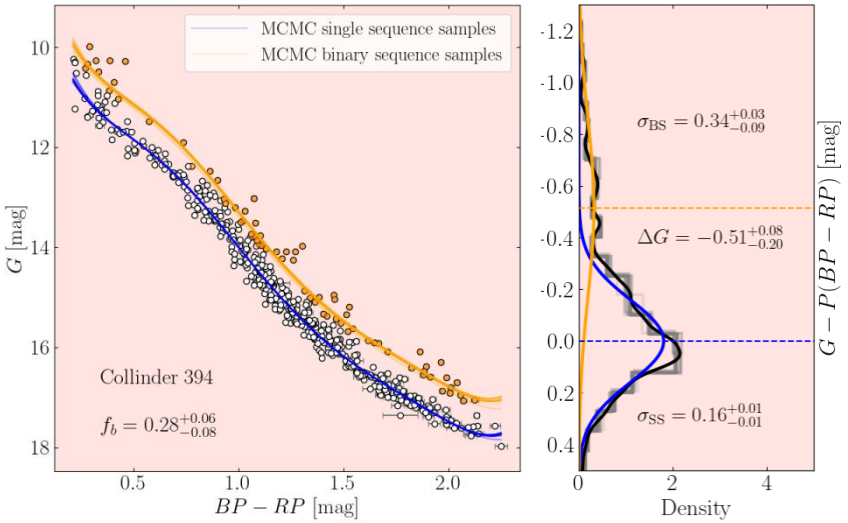
1. $\sigma_{SS} \leq 0.2$
2. $\sigma_{BS} \leq 0.25$
3. $|\Delta G + 0.75| \leq 0.05$
4. $\sigma_{f_b} \leq 0.25$
5. Well-fit CMD (visual inspection)

We obtain a final sample of **202 OCs**:

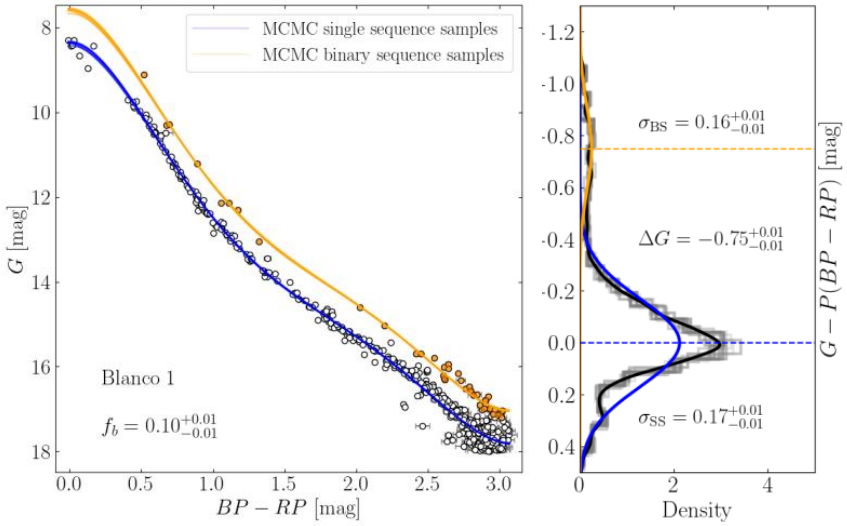
146 from T22 (~ 72%)

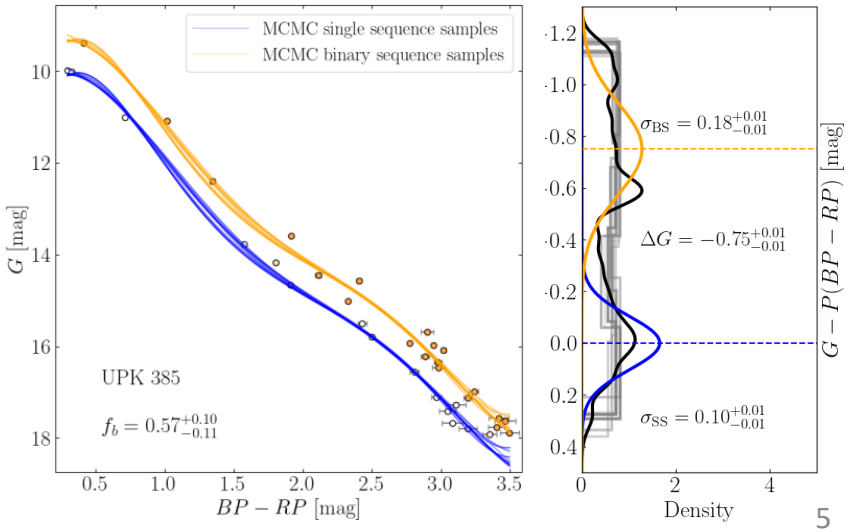
56 from CGa20 (~ 28%)

Example of a discarded OC:



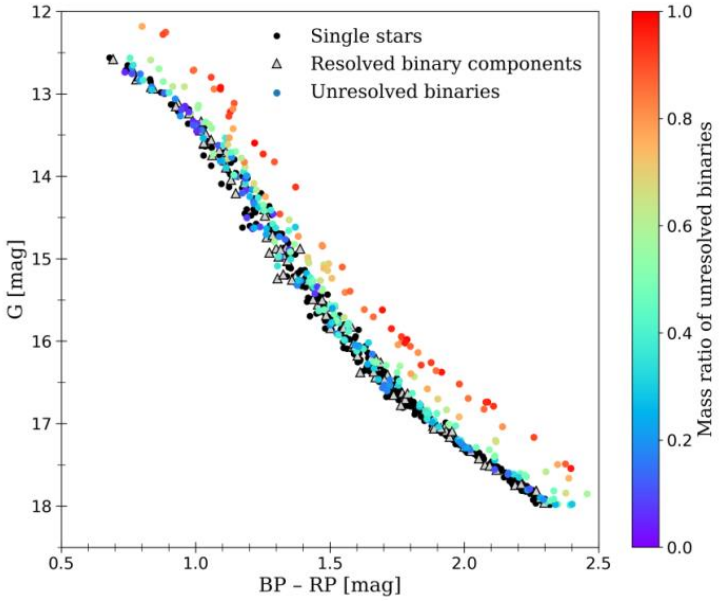
Examples of selected OCs:

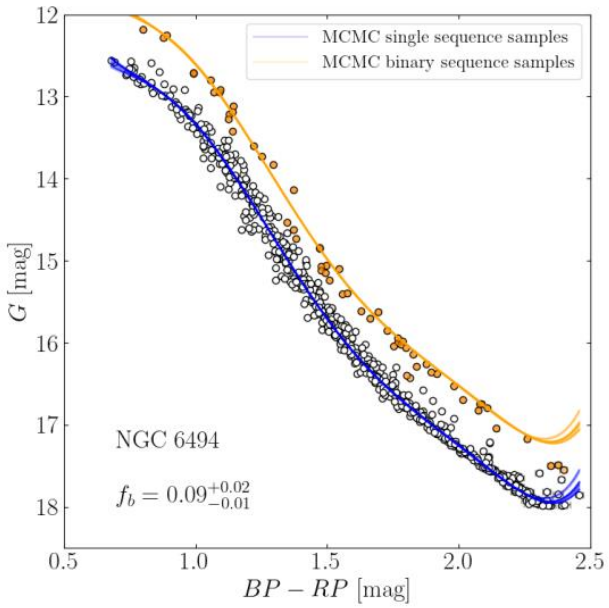




Simulated *Gaia*-like OCs

Gaia Object Generator (GOG; Luri, X., et al. **2014**, A&A, 566, A119) + Multiple-star module (Arenou, F. **2011**, in American Institute of Physics Conference Series, Vol. 1346, 107–121) of the Gaia Universe Model simulations (Robin, A. C., et al. **2012**, A&A, 543, A100)





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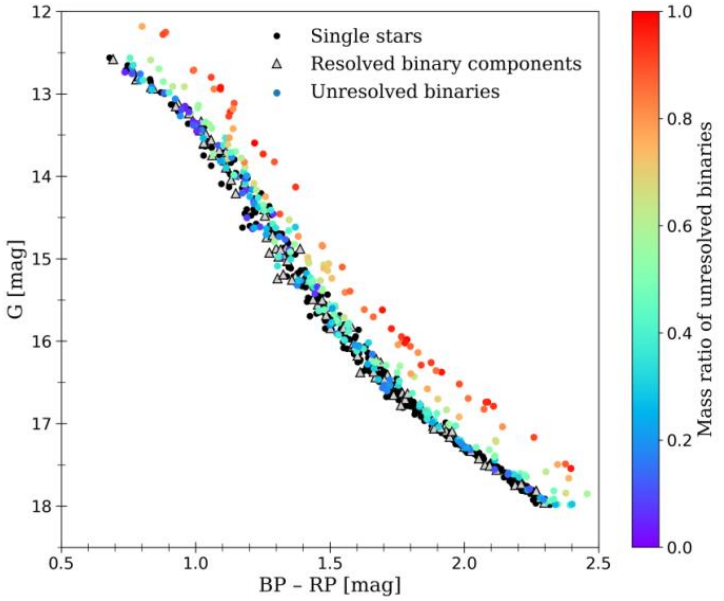
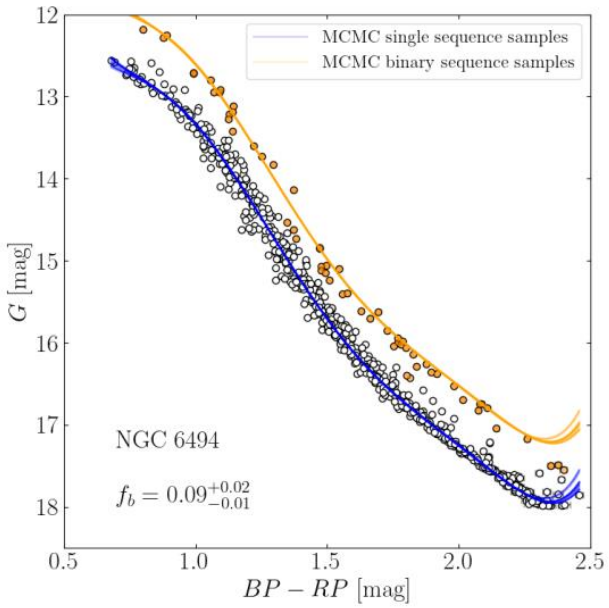




A sample of **219 simulated OCs,** and **10 different CMD realisations each**, is used to:

1) Estimate the $\boldsymbol{q_{\mathrm{lim}}}$ which the unresolved multiplicity fraction $f_b(q > q_{\mathrm{lim}})$ takes into account

$\boldsymbol{q_{\mathrm{lim}}}$ is assumed to be the q_{min} for which $\overline{f_b{}^{sim,\,theo}}(q > q_{min})$ is the closest possible to $\overline{f_b{}^{sim}}$

$q_{min} \in [0.2, 0.7]$ in steps of 0.05

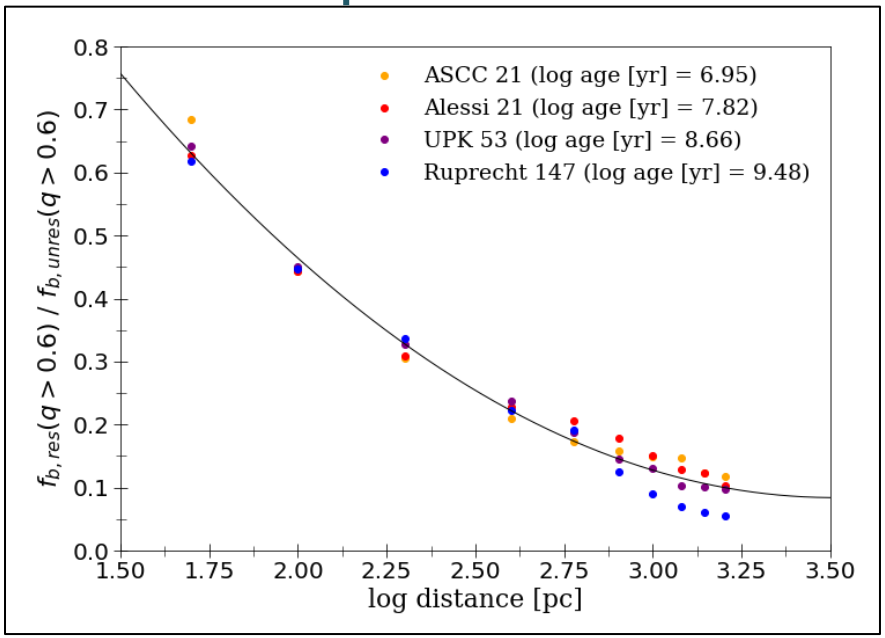
from MCMC fit to the CMD

We find: $\boldsymbol{q_{\mathrm{lim}} = 0.6^{+0.05}_{-0.15}}$

Simulated *Gaia*-like OCs

2) Use simulated OCs to estimate the OC's **total multiplicity fraction**

$$f_b^{tot}\left(q > q_{\lim} = 0.6^{+0.05}_{-0.15}\right) = \underbrace{f_{b,\,unres}^{MCMC}\left(q > q_{\lim}\right)}_{\text{From MCMC fit in the observed } Gaia \text{ CMD}} \cdot \left[1 + \underbrace{\frac{f_{b,\,res}^{sim,theo}\left(q>q_{\lim}\,;\,d\right)}{f_{b,\,unres}^{sim,theo}\left(q>q_{\lim}\,;\,d\right)}}_{\text{Estimated through a fit as a function of the OC's distance}}\right]$$



Results and discussion

Homogeneous catalogue accessible via CDS containing the estimated **unresolved and total multiplicity fractions** of main-sequence systems of $q > 0.6^{+0.05}_{-0.15}$ for 202 OCs closer than 1.5 kpc, having ages between 6.6 Myr and 3.0 Gyr.

$f_b \in [5, 67]\%$, median: 15%.

$f_b^{tot} \in [6, 80]\%$, median: 18%. For 89% of the OCs, $f_b^{tot} - f_b < 5\%$.

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1) Comparison to other studies

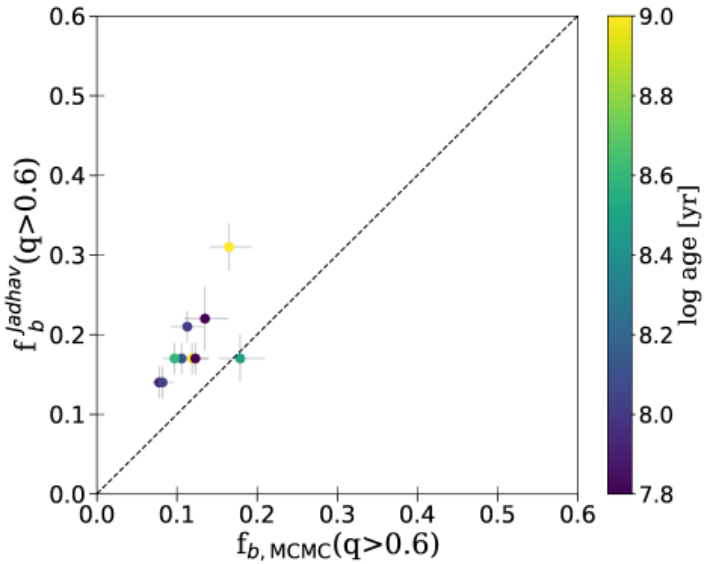
Large homogeneous studies are still rare.

Results of different studies are very seldom directly comparable:

- Different mass range of the OC is covered
- Different q_{lim}
- Dependence on the applied model's assumptions
- Different OC membership determinations

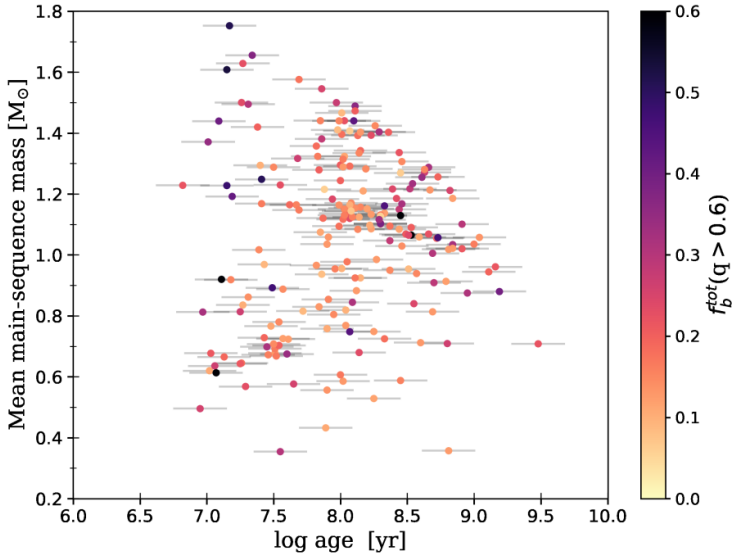
Recent studies of multiplicity fraction in OCs:

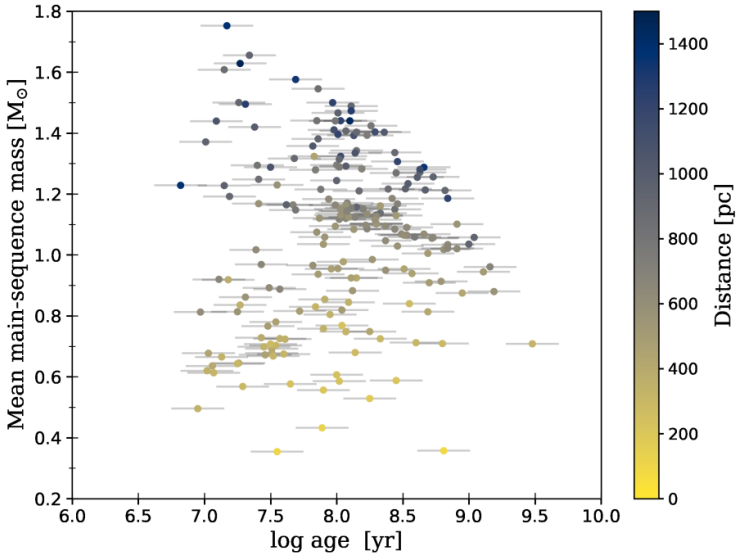
- Li, L., Shao, Z., Li, Z.-Z., et al. **2020**, ApJ, 901, 49
- Niu, H., Wang, J., & Fu, J. **2020**, ApJ, 903, 93
- Jadhav, V. V., Roy, K., Joshi, N., & Subramaniam, A. **2021**, AJ, 162, 264
- Li, L. & Shao, Z. **2022**, ApJ, 930, 44

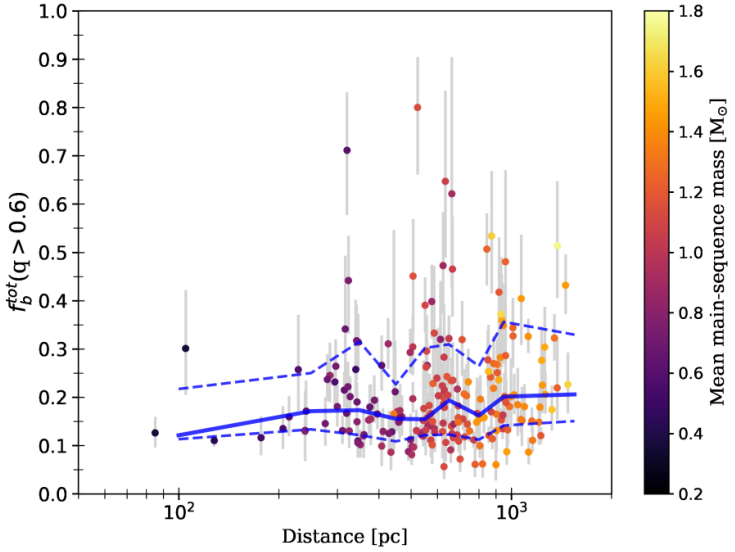


Comparison of the unresolved multiplicity fraction values for the 10 OCs our study has in common with Jadhav, V. V. et al. 2021.

2) Dependence of the multiplicity fraction on the distance and stellar mass







The OC's parameters of age, distance, and mean sampled mass are heavily entangled: **complex selection effects**.

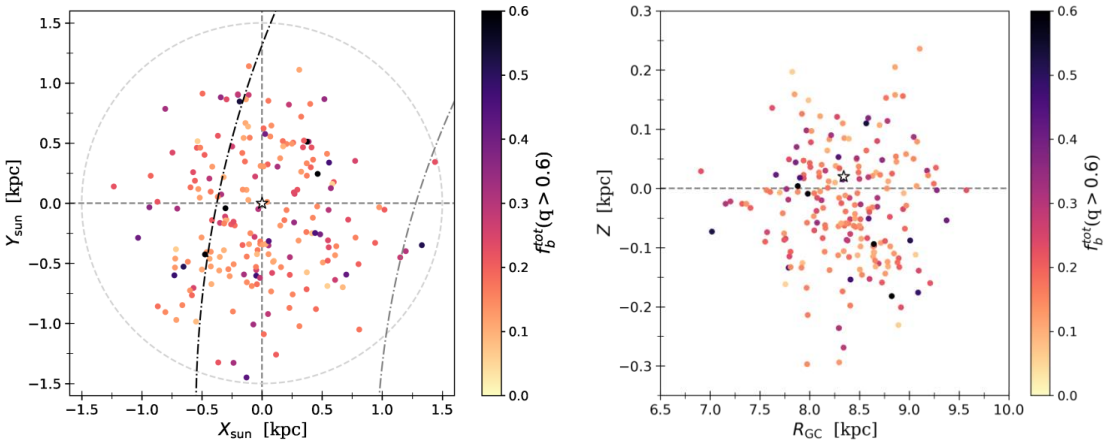
f_b^{tot} increases with distance because for more distant OCs we tend to see only the upper ends of their MSs, which have more massive stars.

⇓

f_b^{tot} increases with the mass of the primary star, in agreement with observational evidence from field stars and OCs (Bouvier, J., et al. **1997**, A&A, 323, 139 and Deacon, N. R. & Kraus, A. L. **2020**, MNRAS, 496, 5176).

Results and discussion

3) Dependence of the multiplicity fraction on position



There is no apparent correlation between f_b^{tot} and the position in or perpendicular to the Galactic plane.

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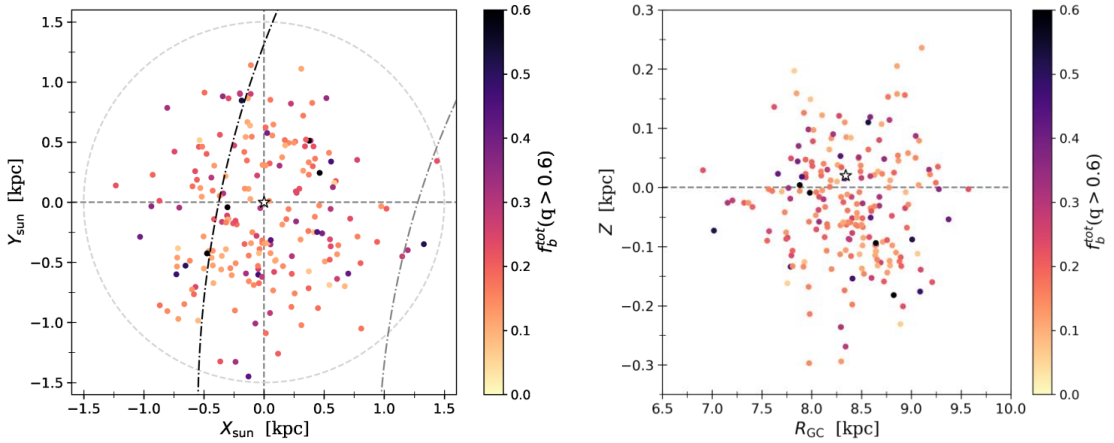

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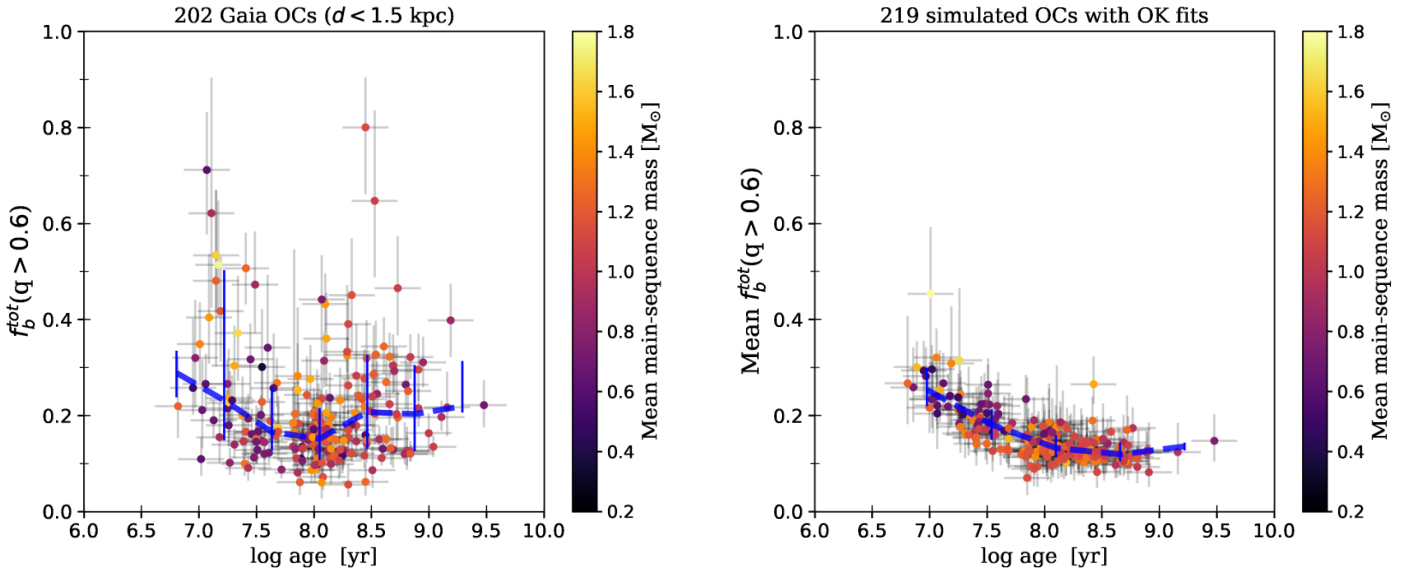
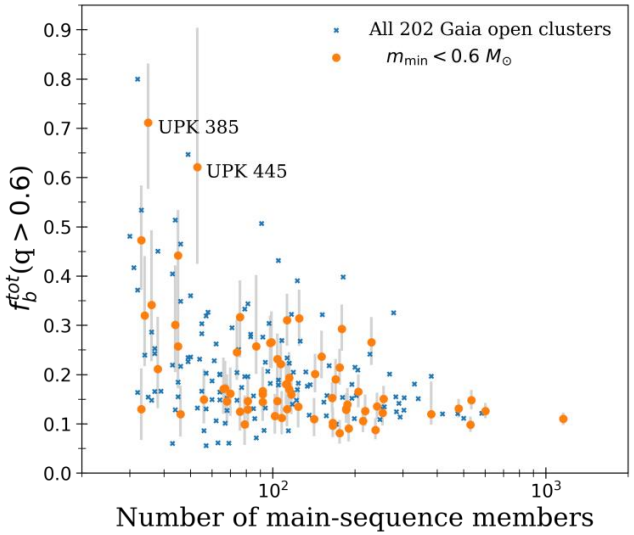
4) Dependence of the multiplicity fraction on the OC's age



Dividing the sample into four bins of mean main-sequence mass ⟨m⟩ this age trend persists.

f_b^{tot} running median trend (decrease with age until ~ 100 Myr, and slight increase for older OCs) is reproduced by simulated OCs ⇒ mainly caused by the sample's complex selection effects.

5) Dependence of the multiplicity fraction on the number of cluster members



OCs with

- $m_{min} < 0.6\ M_\odot$ and
- highly elevated multiplicity fractions

could be candidates for being close to dissolution, in line with simulations (e.g. Hurley, J. R., Aarseth, S. J., & Shara, M. M. **2007**, ApJ, 665, 707).

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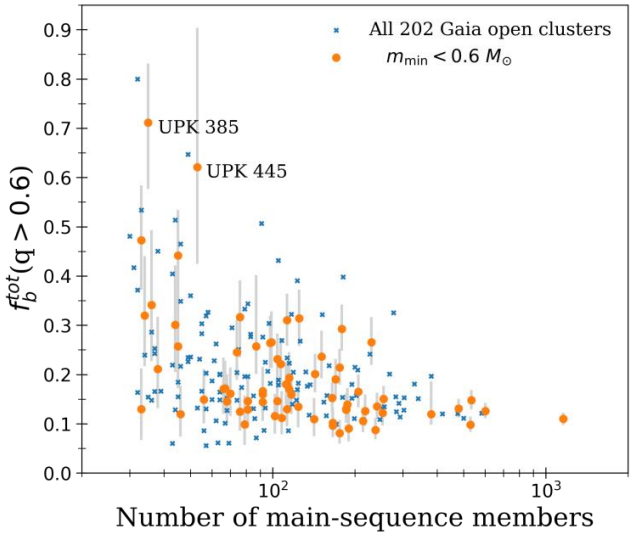

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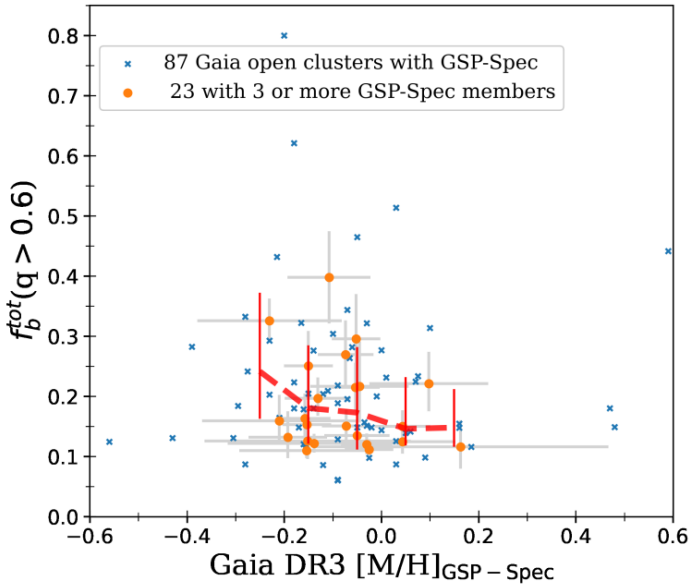
6) Dependence of the multiplicity fraction on metallicity



Gaia DR3 GSP-Spec catalogue metallicities (Recio-Blanco, A., et al. 2022, A&A, in press, arXiv:2206.05541).

The **multiplicity fraction decreases with metallicity**, in line with recent studies using close binaries in the field (e.g. El-Badry, K. & Rix, H.-W. **2019**, MNRAS, 482, L139 and Moe, M., Kratter, K. M., & Badenes, C. **2019**, ApJ, 875, 61).

The same trend is found using Netopil, M., et al. **2022**, MNRSS, Volume 509, Issue 1, pp.421-439, but for much less OCs.

Conclusions

- ✓ CMD is a fundamental diagnostic tool for OCs.
- ✓ The multiplicity fraction estimation depends inevitably to some degree on **modelling**.
- ✓ Our approach does not rely on fitting theoretical isochrones to the CMD, nor it depends on any stellar model.

  The mixture model fitting is performed directly in *Gaia*'s observed CMD.

  Synthetic CMDs are only used to characterise the q range that f_b takes into account and to estimate the total multiplicity fraction.

  Our f_b is integrated over the main-sequence mass range of the OC: the OC's q distribution is not determined.

Future work

Corroborate our results with revised and more complete membership lists:

Apply our method to the recent *Gaia* DR3 OC catalogue from Hunt, E. L. & Reffert, S., **2023**, A&A, Volume 673, id.A114, 31 pp.