Towards Open cluster masses with Gaia

Friedrich Anders
Andrija Zupic, Alfred Castro-Ginard (Leiden),
Duarte Almeida (Lisboa), Judit Donada, Sandro Moreira (Lisboa), Carme Jordi,
André Moitinho (Lisboa), Tristan Cantat-Gaudin (MPIA), Mark Gieles, Irene Quadrino,
Lola Balaguer-Núñez, Laia Casamiquela (Obs Paris-Meudon), Eduard Masana, the GaiaUB group

$$M\left(\quad\right) = (1.4 +\text{-}\ 0.2) \cdot 10^3\ \text{kg}$$

ICCUB Institute of Cosmos Sciences

EXCELENCIA MARÍA DE MAEZTU

UNIVERSITAT DE BARCELONA

UB Gaia

Cantat-Gaudin+2020:
Open cluster parameters with an ANN

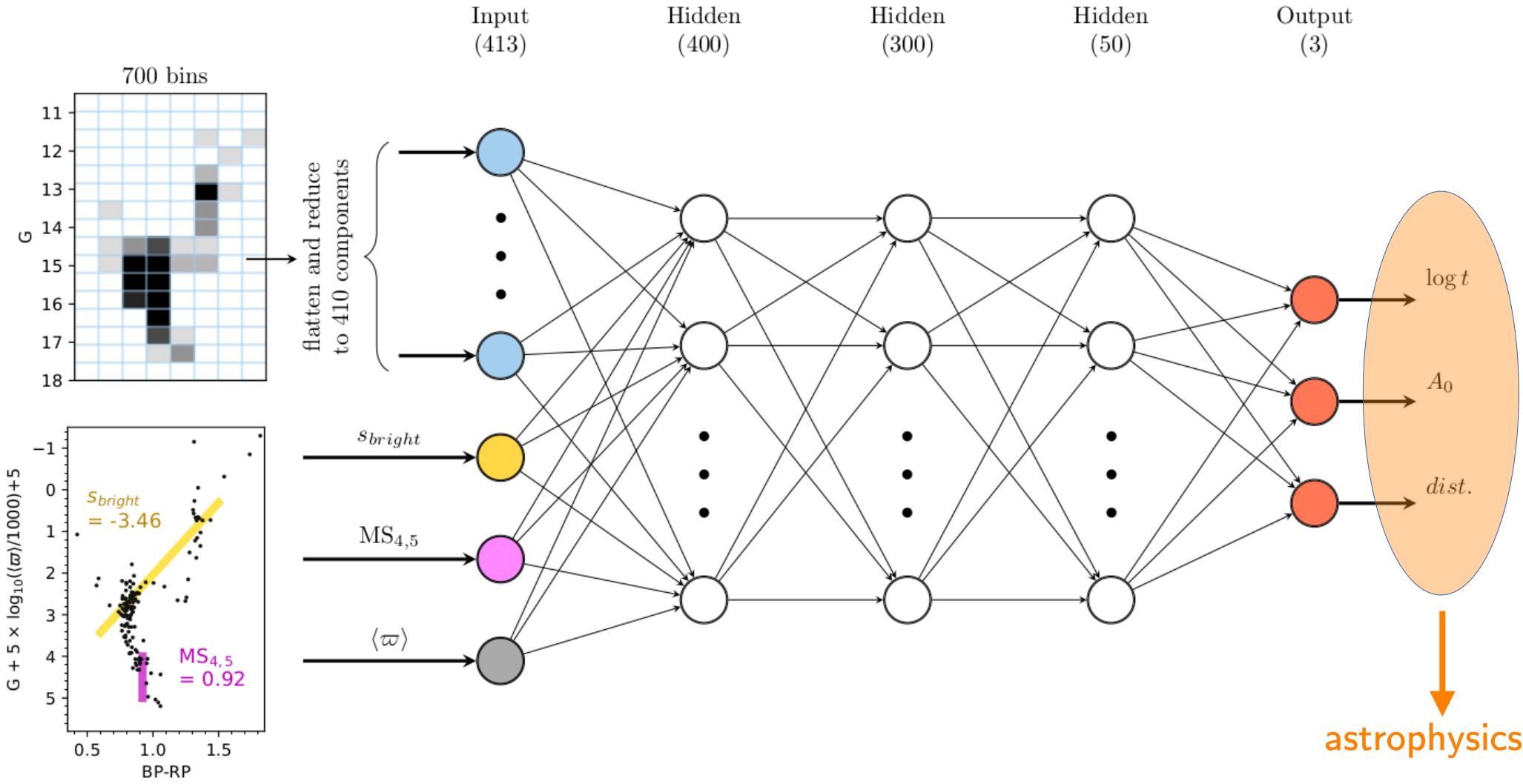


Fig. 2. Architecture of our artificial neural network, indicating the width (number of nodes) of each layer. The example cluster is Haffner 22. The input quantities are described in Sect. 3.1.

What kind of astrophysics?

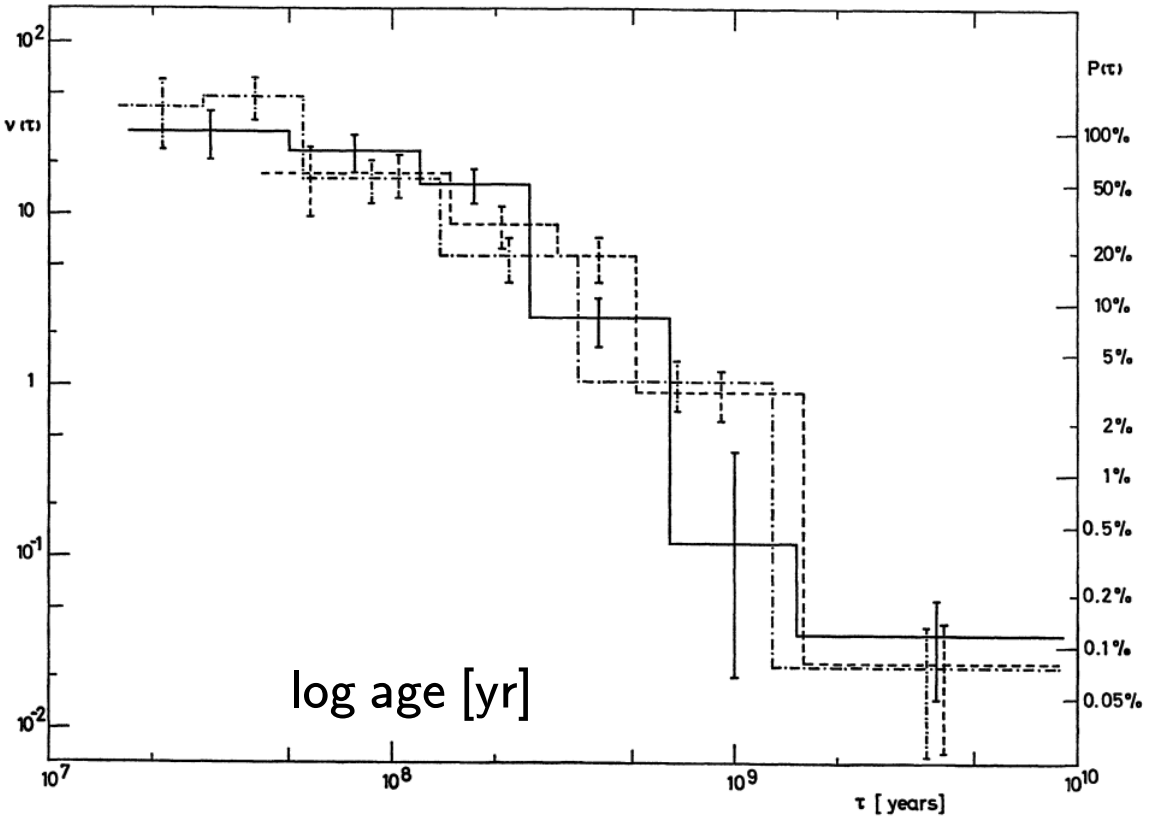
Cluster demographics (births & deaths)!

The Age Distribution and Total Lifetimes of Galactic Clusters

R. WIELEN
Astronomisches Rechen-Institut, Heidelberg

Received April 27, 1971

Clusters within 1 kpc / Myr



Survival rate

Fig. 2. Age distribution of galactic clusters within $r_p \leqq 1000$ pc. The age frequency $\nu(\tau)$ of clusters per age interval of 10^8 years is given as a function of age τ. The scale at the right-hand side shows the fraction P of surviving clusters discussed in Section 6. Becker's and Fenkart's catalogue: ———. Lindoff's catalogue: ------- (Age calibration: Lindoff) and -------- (Age calibration: Barbaro *et al.*)

Cluster demographics (births & deaths)!

The Age Distribution and Total Lifetimes of Galactic Clusters

R. WIELEN
Astronomisches Rechen-Institut, Heidelberg

Received April 27, 1971

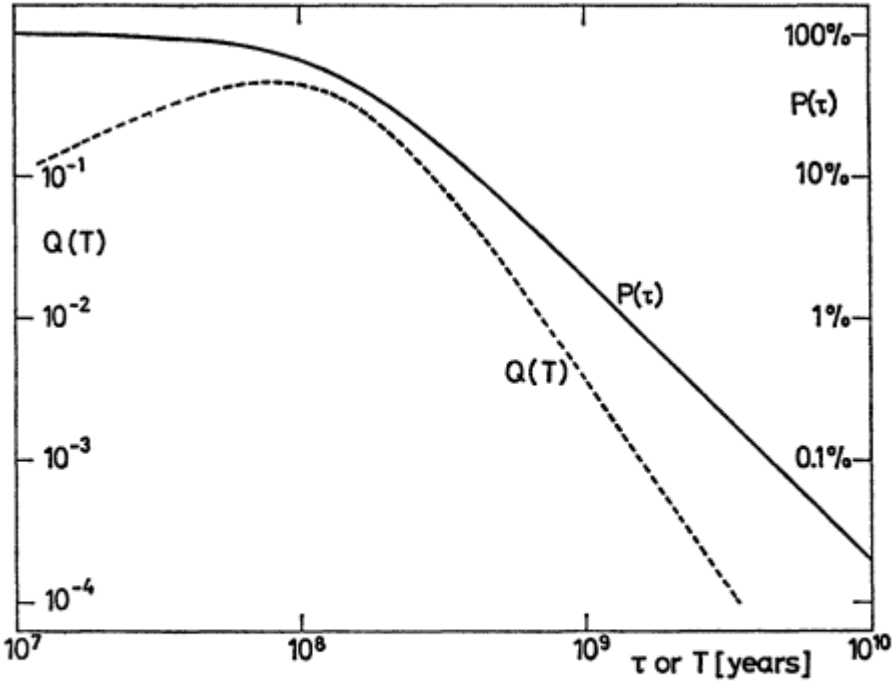


Fig. 5. Schematic representation of the fraction $P(\tau)$ of surviving clusters as a function of age τ (———), and the corresponding distribution function $Q(T)$ of total lifetimes T (---------)

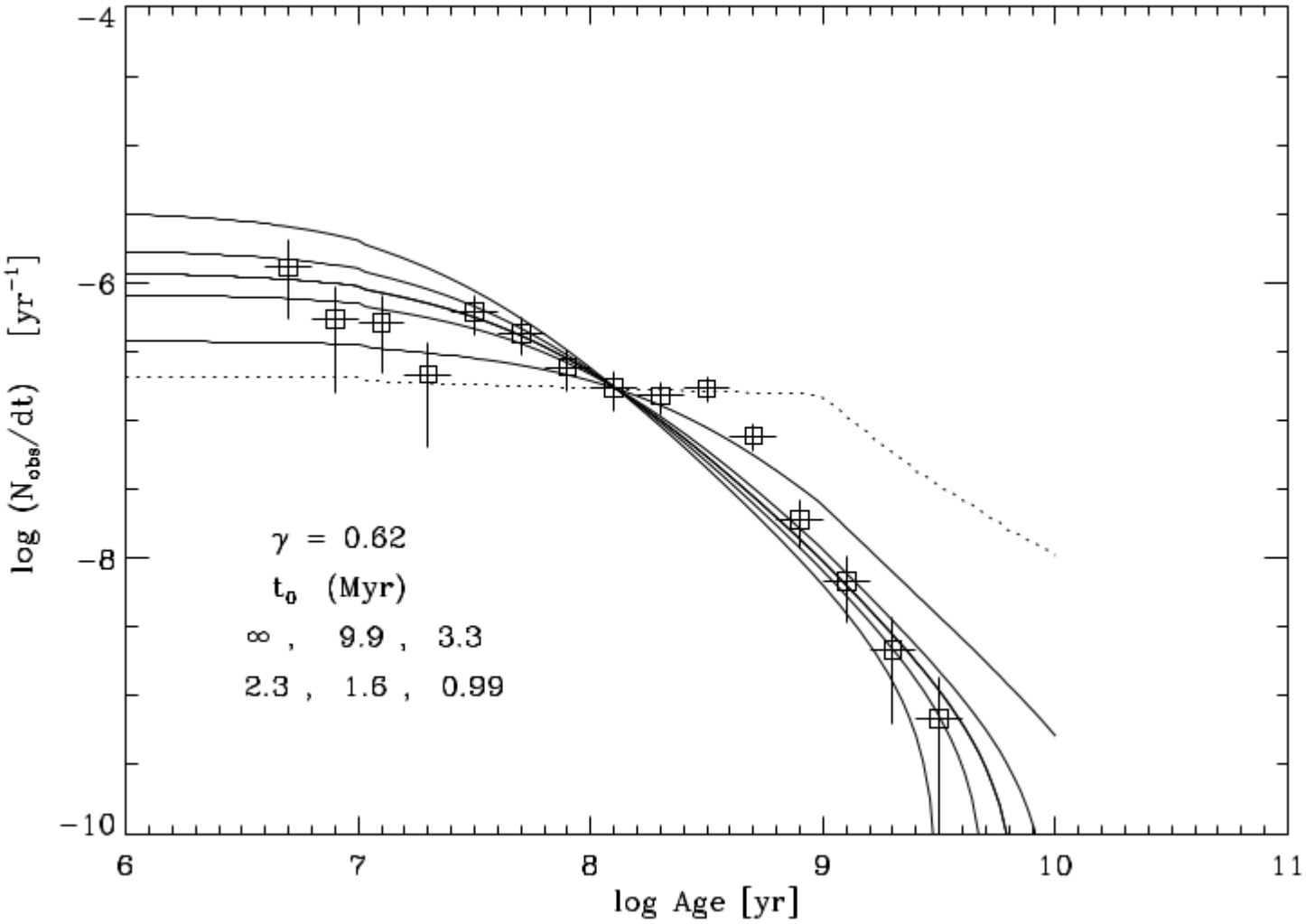
Our considerations lead to the following main conclusions:

(a) The median lifetime of galactic clusters is rather short: 50% of new clusters dissolve within $2 \cdot 10^8$ years. Only 10% of new clusters survive over a period of $5 \cdot 10^8$ years.

(b) The actual lifetimes of clusters are scattered over a large range, from at least 10^8 years to the age of the Galaxy.

→ Still valid conclusions:)

Cluster demographics (births & deaths)!
Lamers+2005 model



Model:
→ disruption time of clusters, defined as $t_{dis} \equiv (\mathrm{d} \ln M / \mathrm{d}t)^{-1}$ depends on the mass M as $t_{dis} = t_0 \, (M/M_\odot)^\gamma$ with $\gamma = 0.62$ for disruption by two-body relaxation in a tidal field.
→ good agreement with COCD data (Kharchenko+2005)

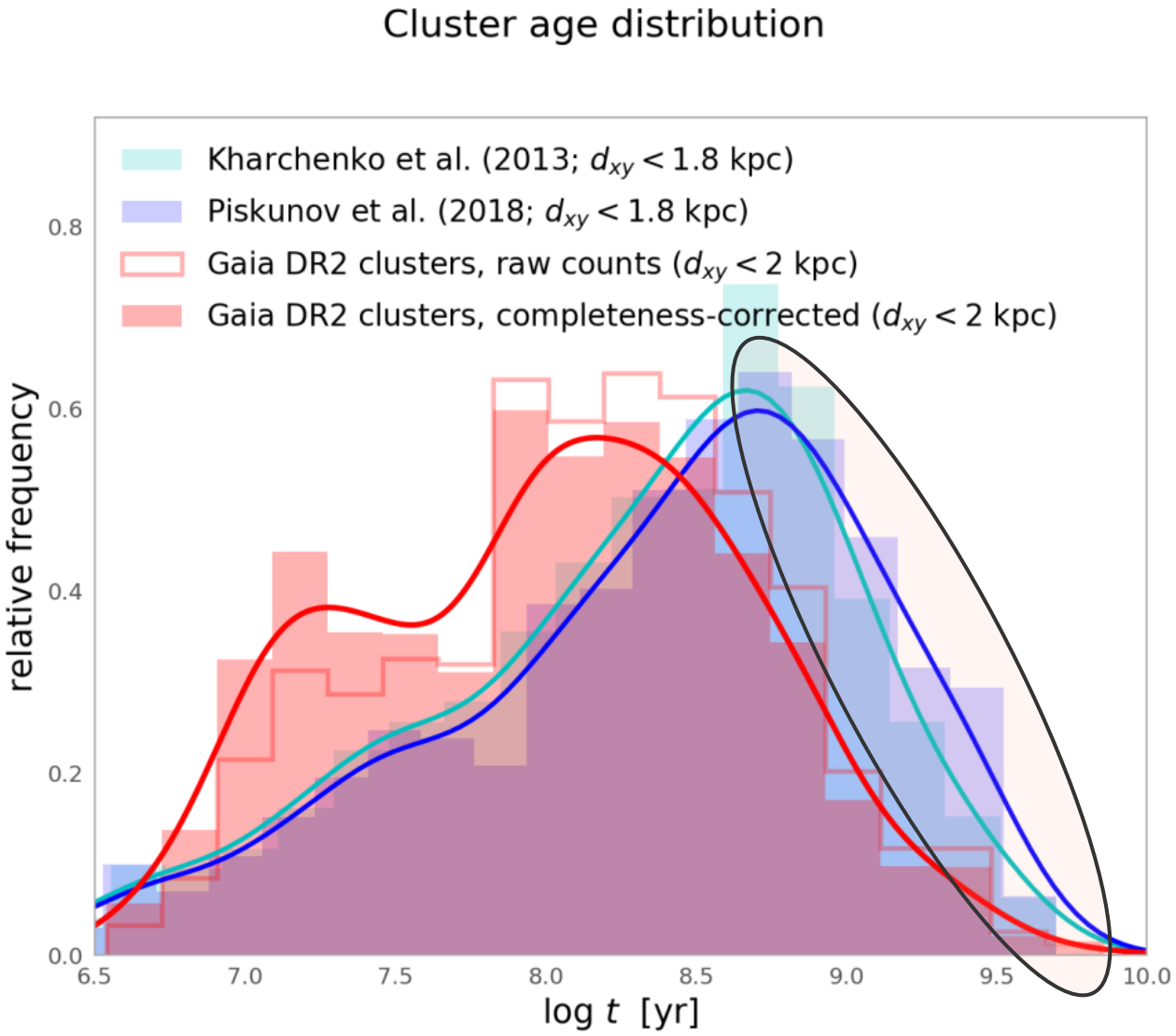
Use case of the Gaia OC catalogues: Cluster age function (Anders+2021)

Gaia as a game-changer for OC demographics:

- determined the **completeness** of the Cantat-Gaudin+2020 catalogue using the experiments of Castro-Ginard+2020

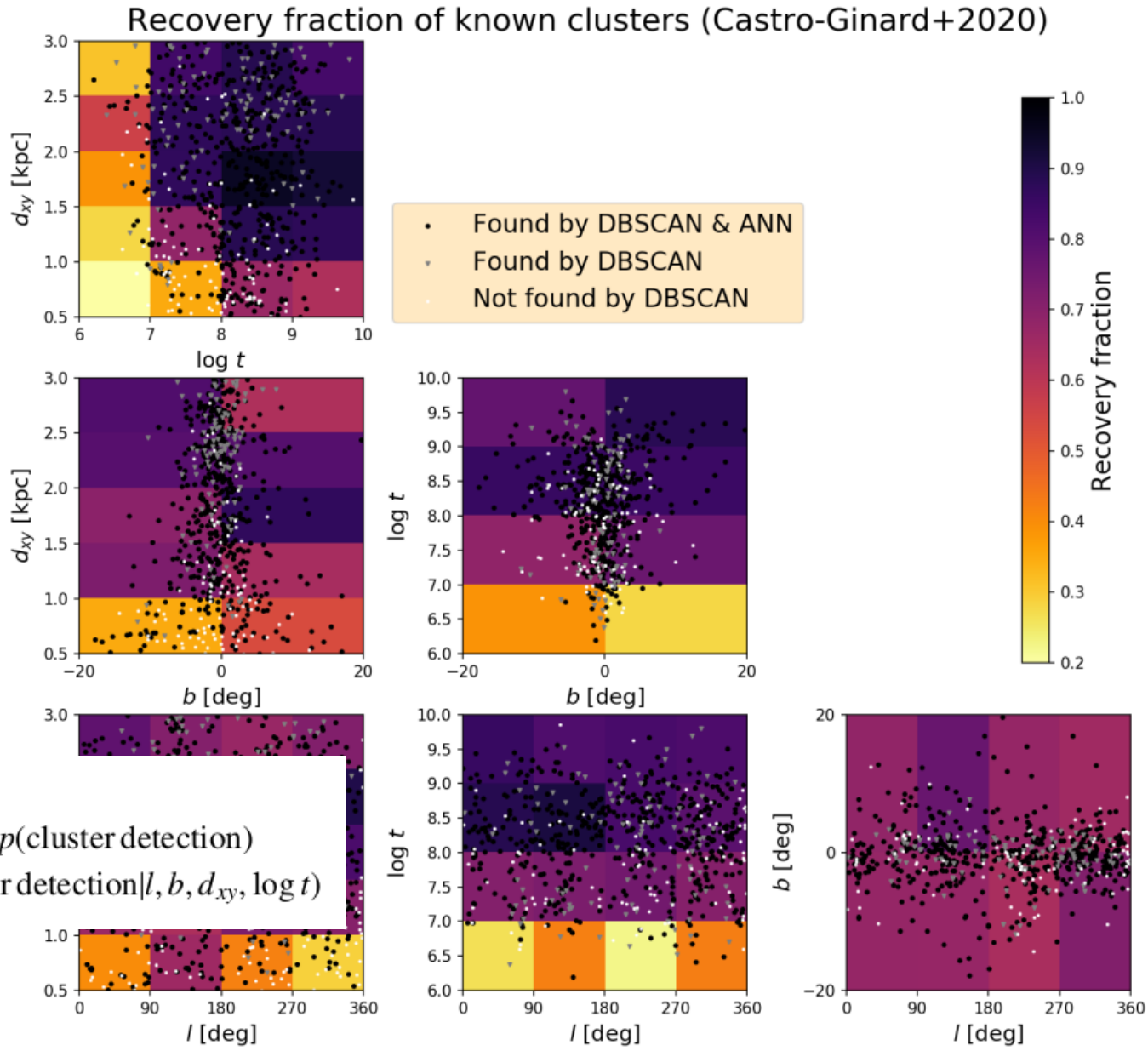
- the **tail of old OCs disappears:** many of those objects could not be confirmed (Cantat-Gaudin & Anders 2020)

- **peak at ~10 Myr** later also found in OB stars (Zari+2023)



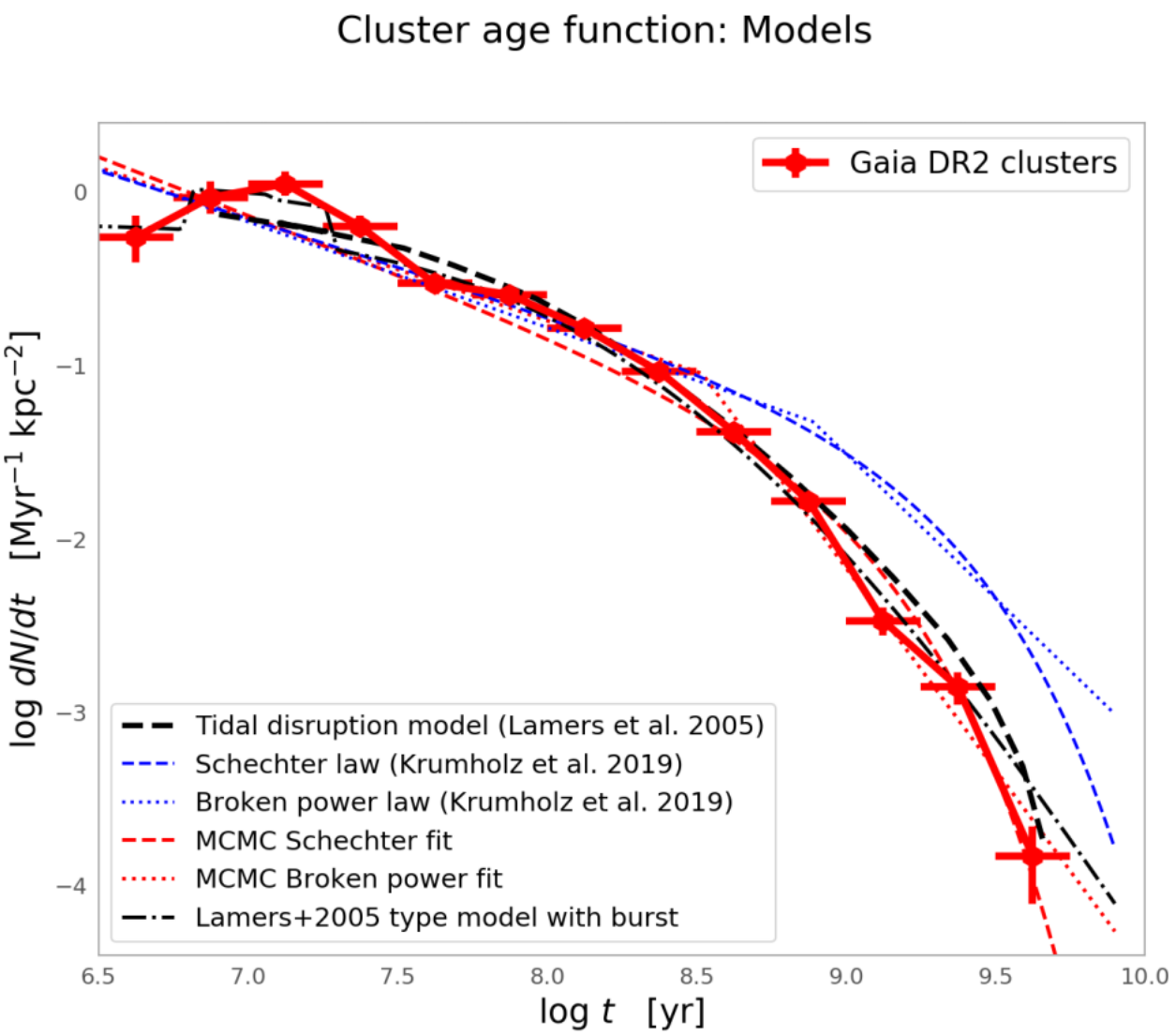
Use case of the Gaia OC catalogues: Cluster age function (Anders+2021)

- estimated the **completeness** of the Cantat-Gaudin+2020 catalogue using the experiments of Castro-Ginard+2020



$$p(\textit{Gaia}\ \text{DR2 cluster has a CGa20 age})$$
$$= p(\text{ANN converged}|\text{cluster detection}) \cdot p(\text{cluster detection})$$
$$\approx p(\text{ANN converged}|d_{xy}, \log t) \cdot p(\text{cluster detection}|l, b, d_{xy}, \log t)$$

Use cases of the Gaia OC catalogues: Cluster age function (Anders+2021)



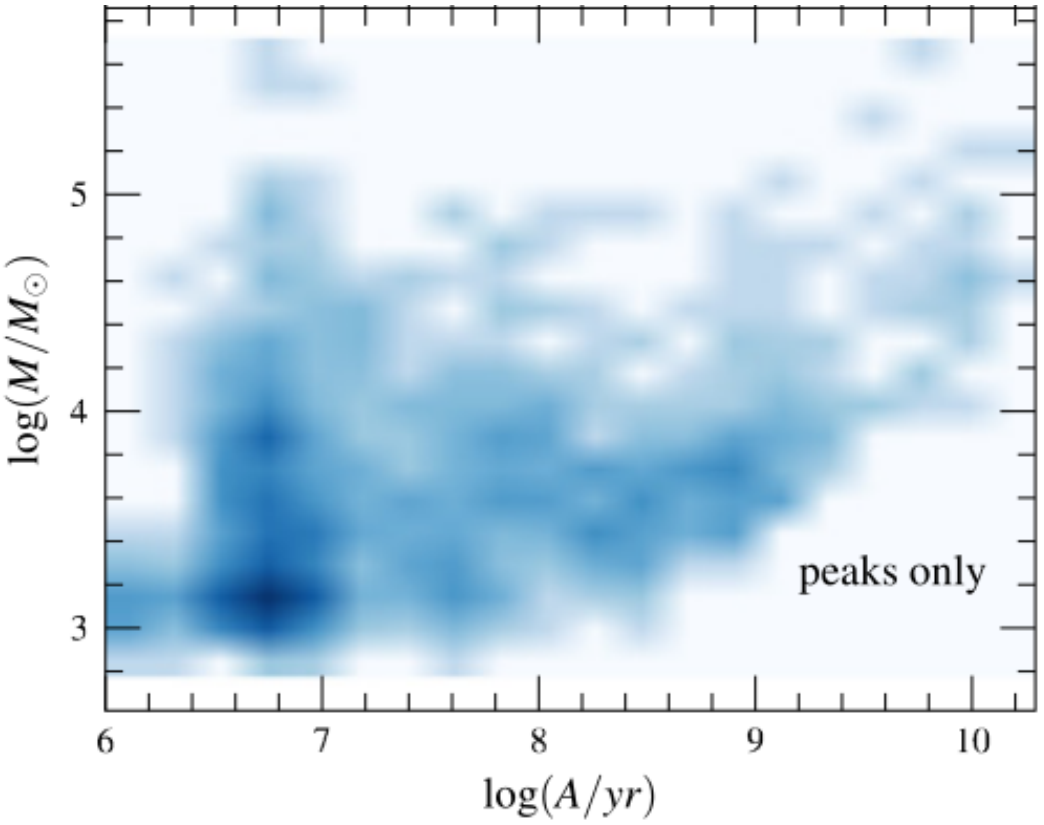
- the age function follows a Schechter or broken power law.

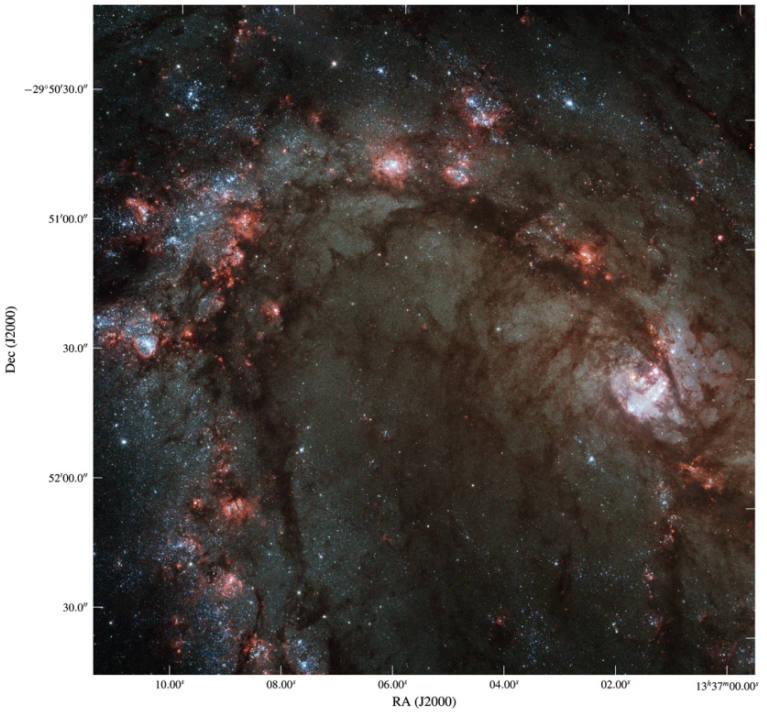
- nice agreement with the cluster destruction models of Lamers+2005 & Lamers&Gieles 2006
- but **poor discriminative power to constrain disruption timescale**..

- present-day cluster-formation rate of $\sim 0.6 \pm 0.1$ Myr^{-1} kpc^{-2}

→ Only 8 – 15 % of all stars born in the solar neighbourhood are formed in bound clusters

The need for OC masses



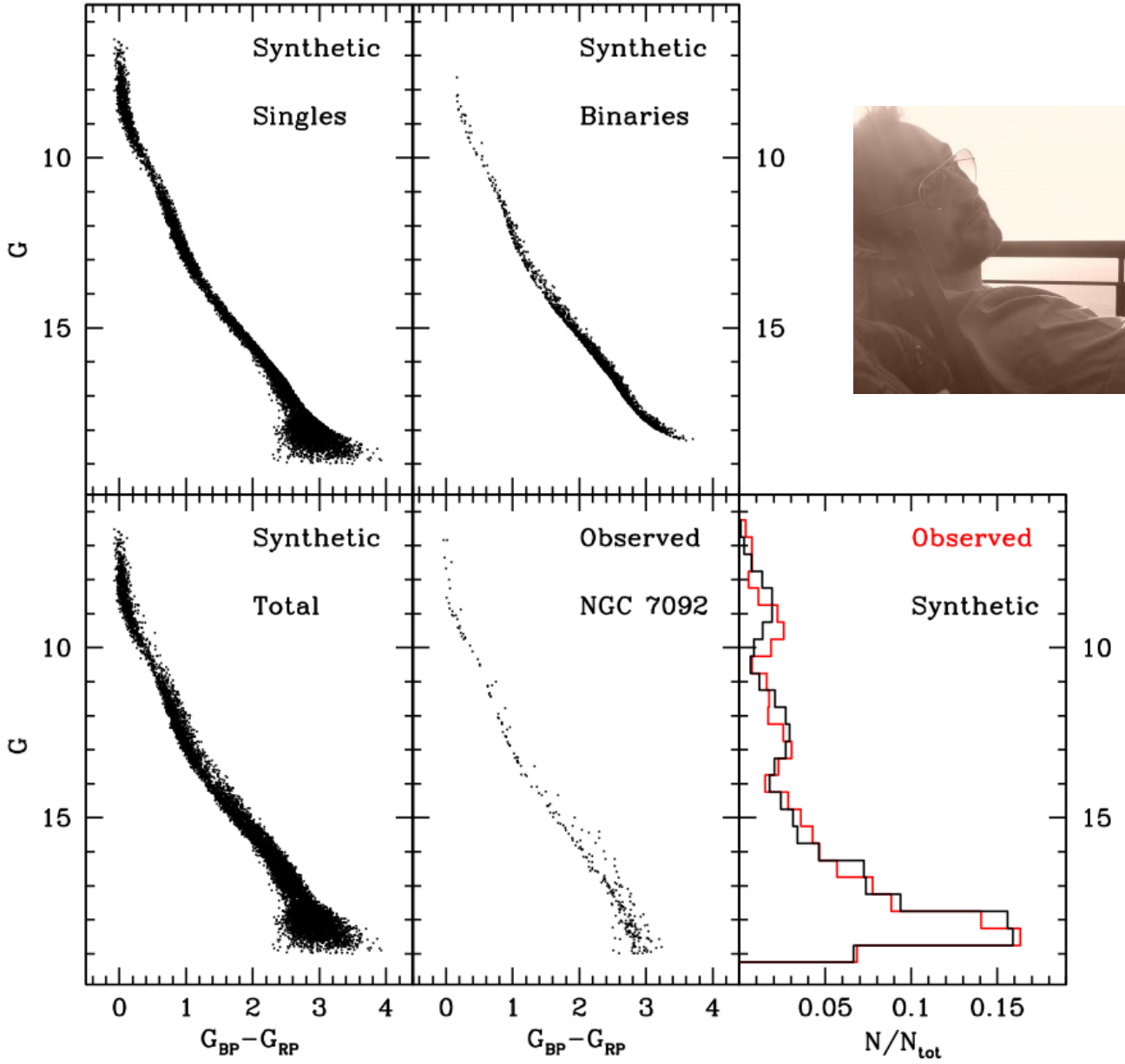


M83 clusters with HST (Fouesneau+2012)

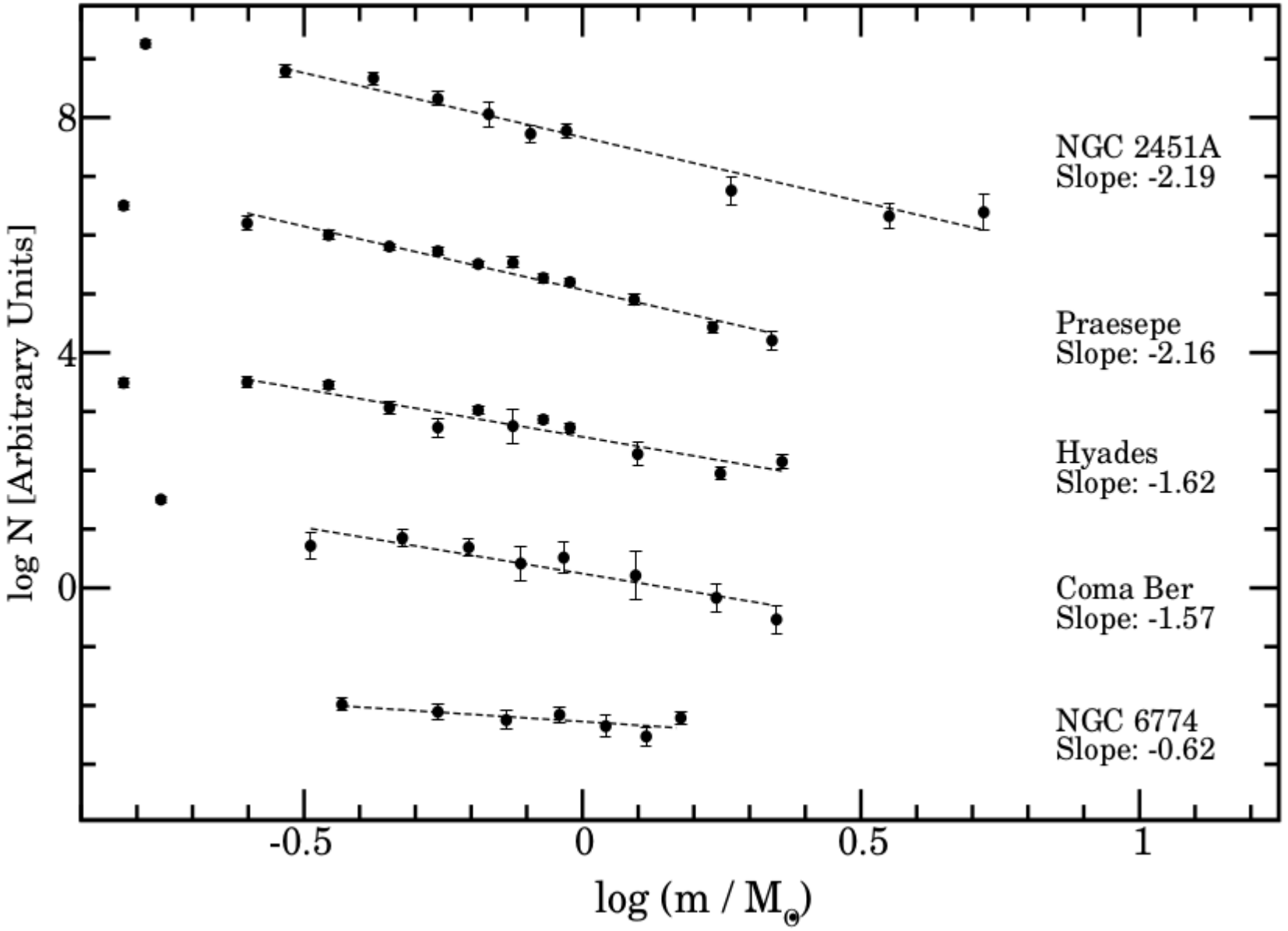
→ The joint mass-age distribution encodes the physics of cluster destruction
→ In the MW the selection function is not trivial, though…

Detailed studies of SN Ocs: Ebrahimi+2022 (12 OCs)

→ Forward simulation of the CMD

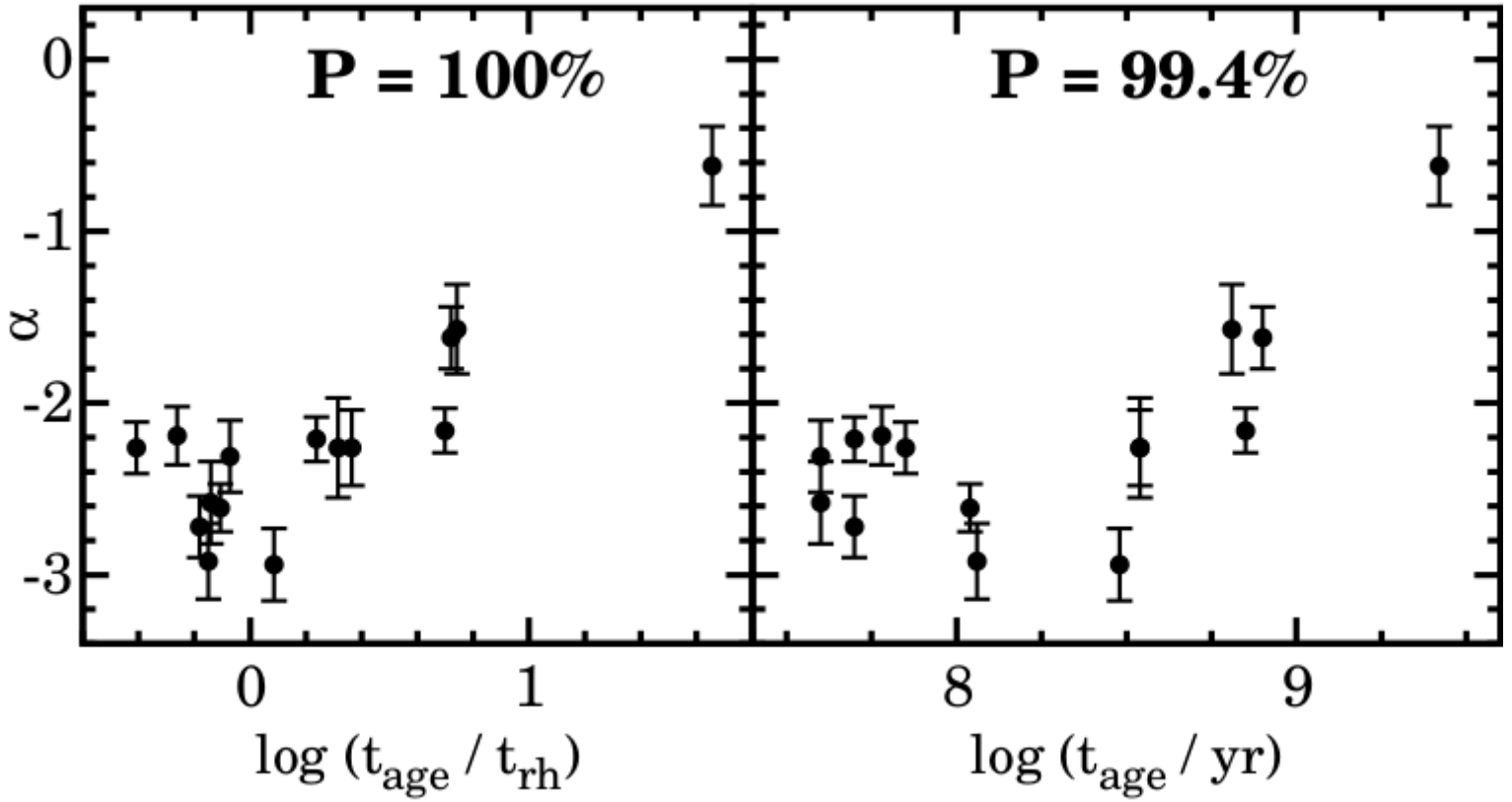


Detailed studies of SN Ocs:
Ebrahimi+2022 (12 OCs)



Detailed studies of SN Ocs: Ebrahimi+2022 (12 OCs)

Mass-function slope

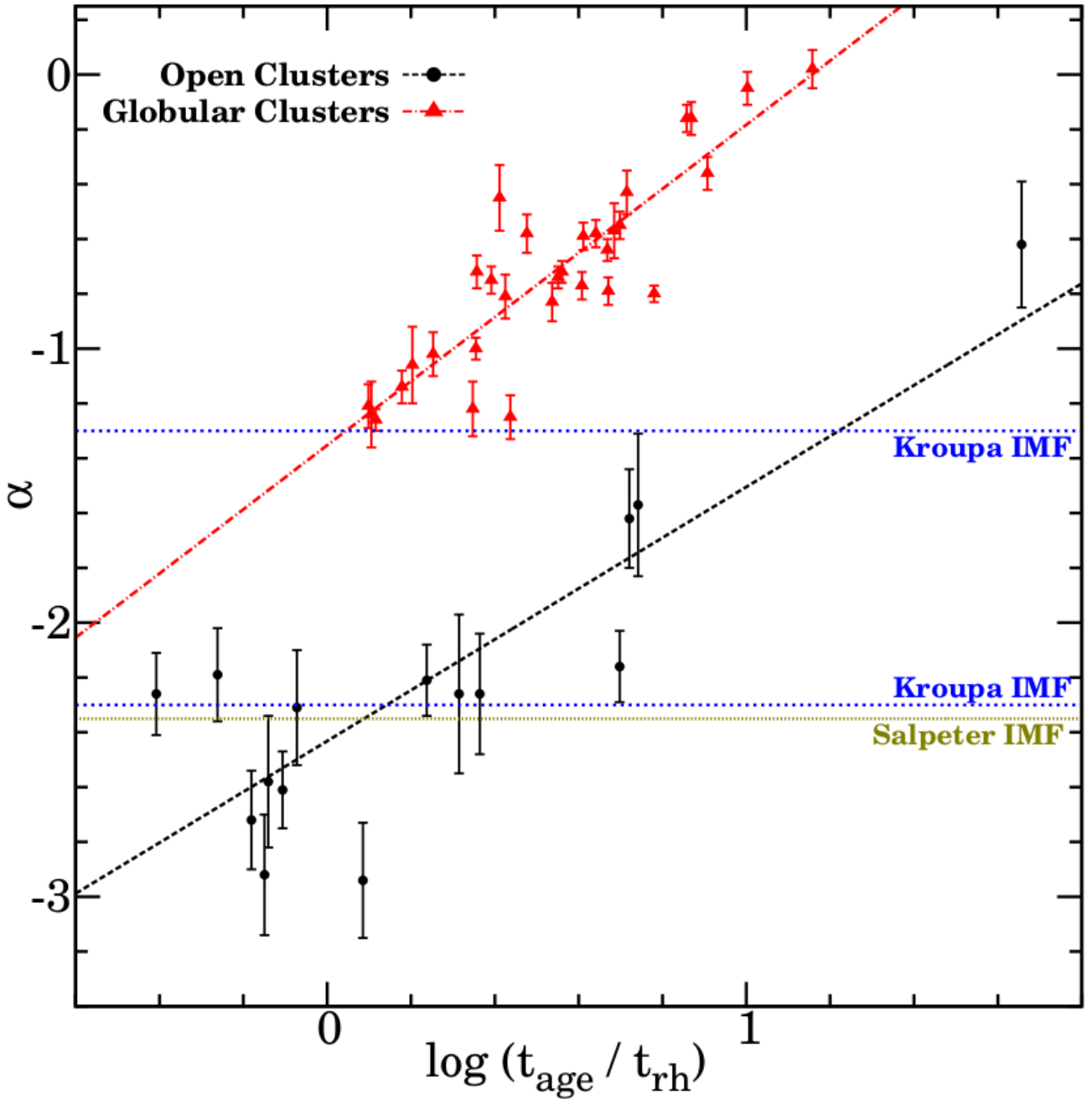


„dynamical age“

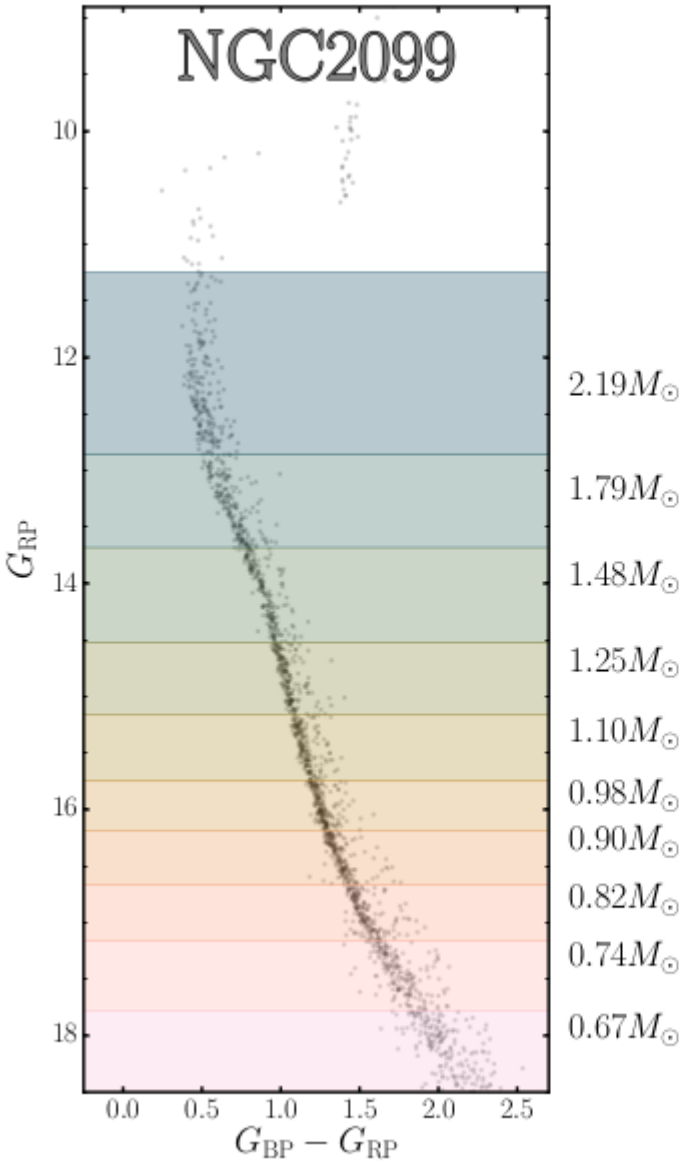
→ in line with pre-Gaia studies (Bonatto & Bica 2005, Maciejewski & Niedzielski 2007, ...)
→ Conclusion: two-body relaxation governs the shape of the PDMF

Detailed studies of SN Ocs: Ebrahimi+2022 (12 OCs)

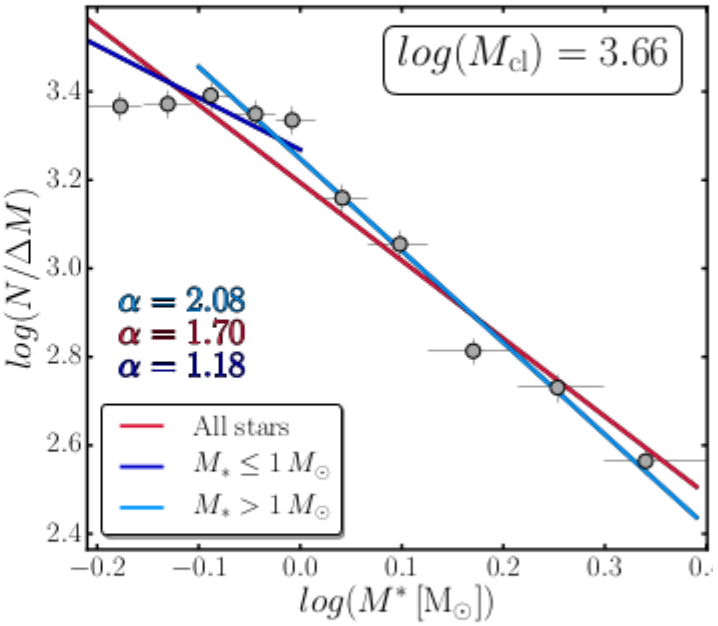
Mass-function slope

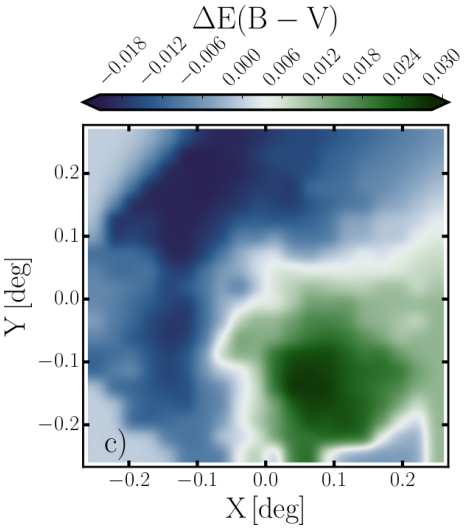


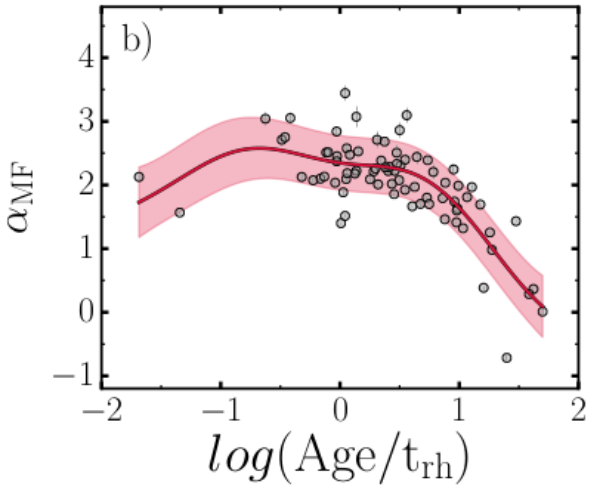
Detailed studies of SN Ocs: Cordoni+2023 (78 OCs)



+ taking into account differential extinction!



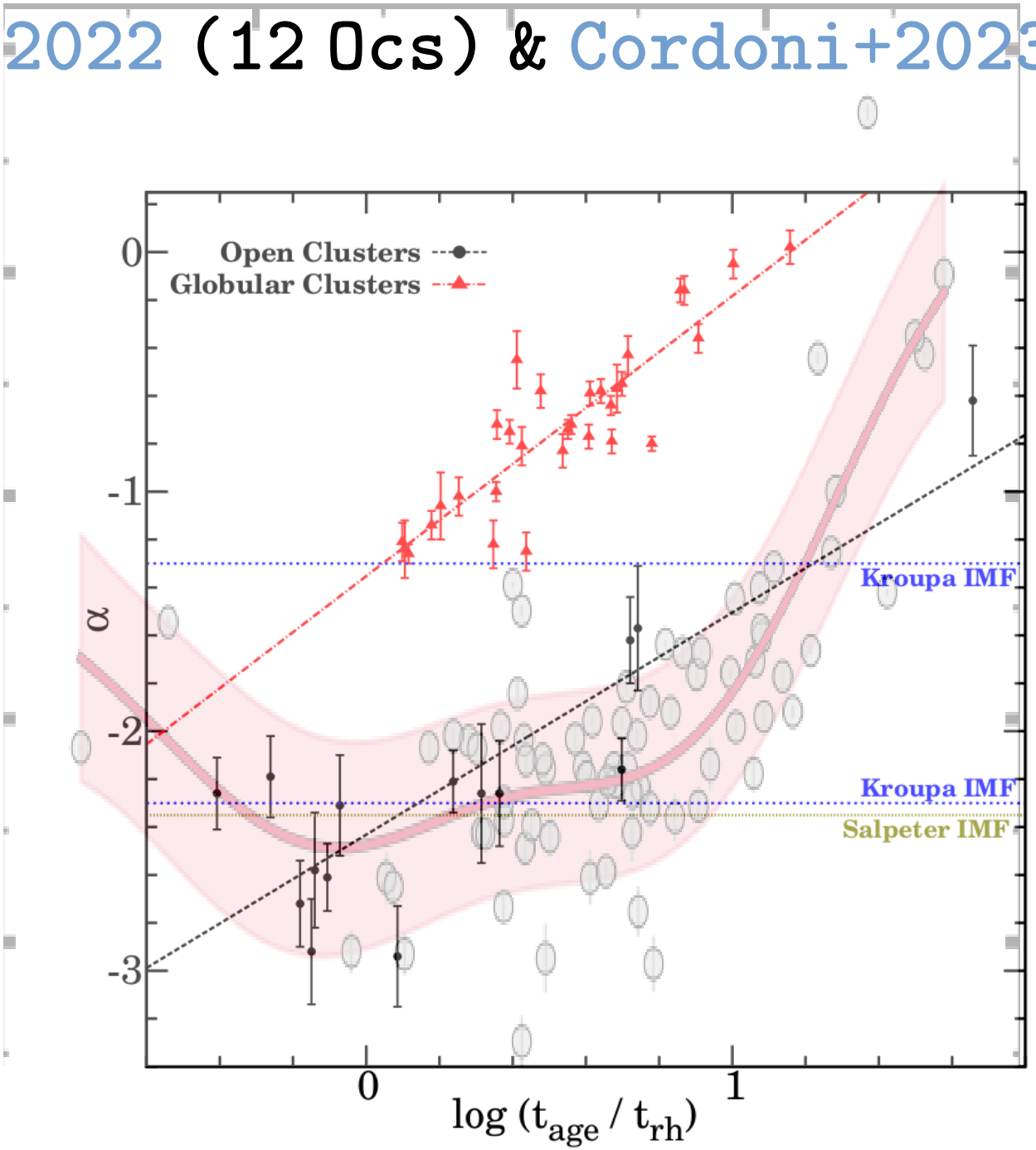




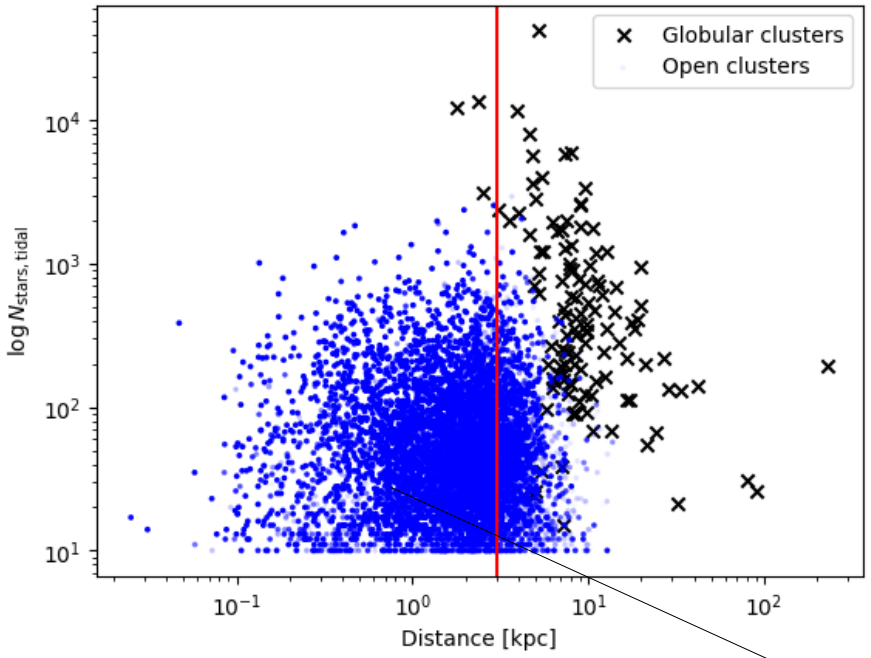
Detailed studies of SN Ocs:

Ebrahimi+2022 (12 Ocs) & Cordoni+2023 (78 OCs)

Mass-function slope

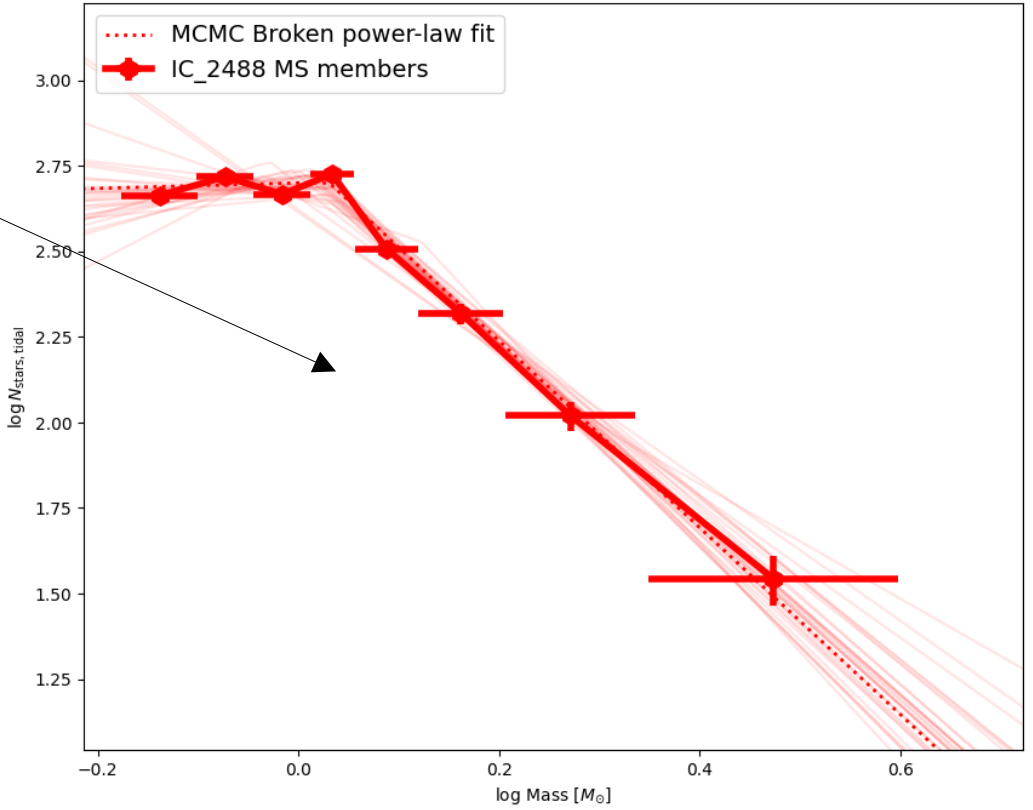


Mass functions & masses on an industrial scale (A. Zupic, MSc@UB 2023)



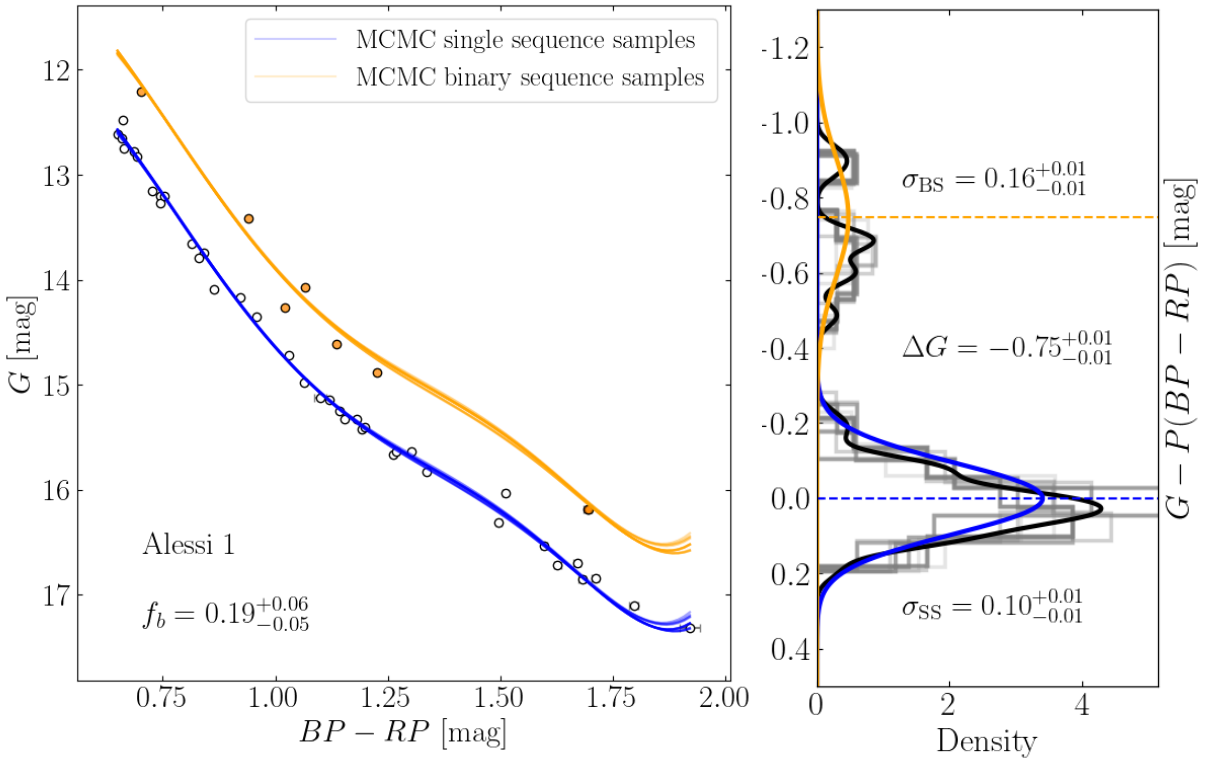
Base catalogue:
Hunt & Reffert 2023
(DR3; d < 2 kpc)

Present-day mass function: IC_2488



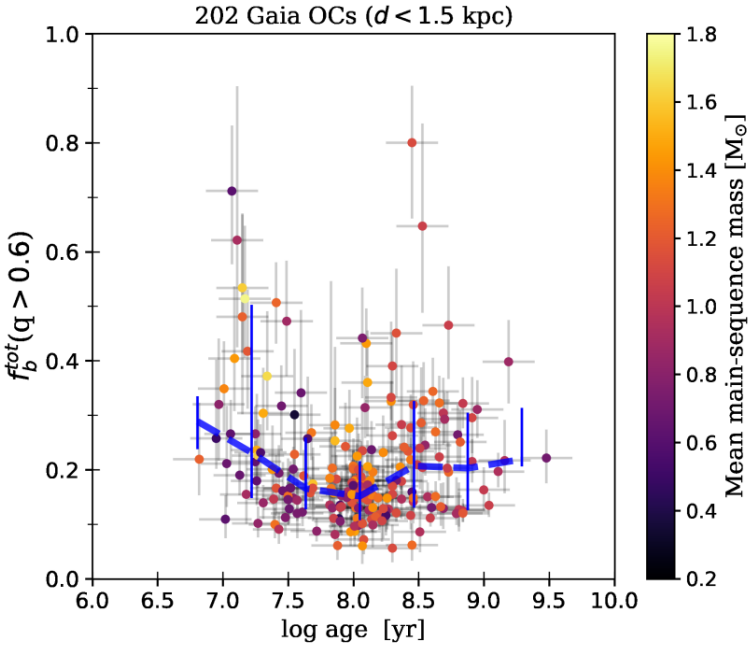
→ Mass functions & total masses for ~1000 OCs (preliminary!)
- following a very similar technique to Cordoni+2023
- ad-hoc corrections for multiplicity based on Borodina+2021

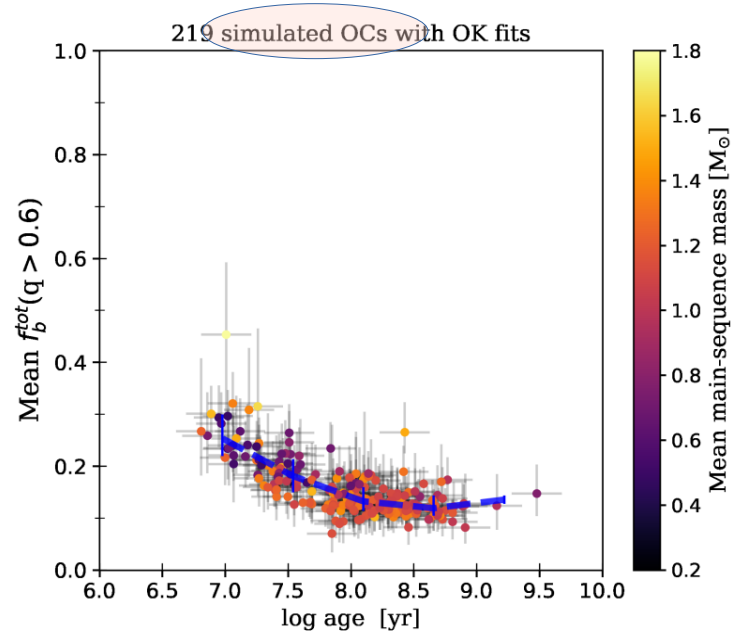
Multiplicity fractions (Donada+2023)

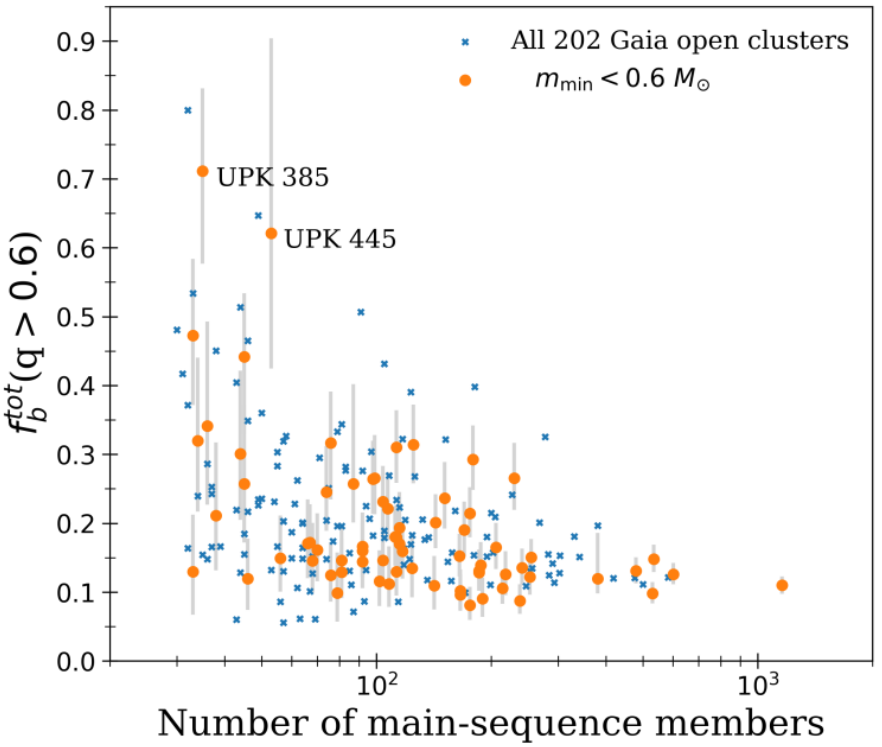


- Automatic fitting of OC main sequences incl. binary sequence
- Using the Gaia DR2 membership lists of Tarricq+2021 & Cantat+2020
- Homogeneous determination of high mass-ratio binary fraction (q>0.6) for **202 OCs**
- Comparison with custom OC simulations with the Gaia Object Generator

Use cases of the Gaia OC catalogues: Multiplicity fraction (Donada+2023)



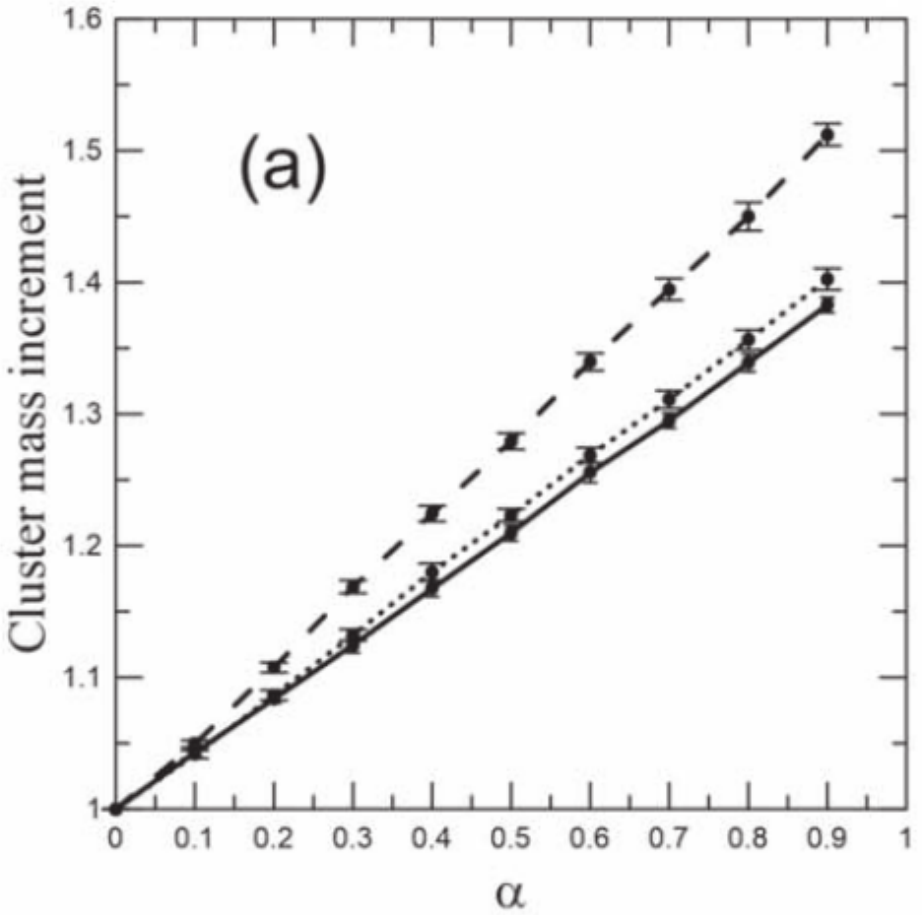




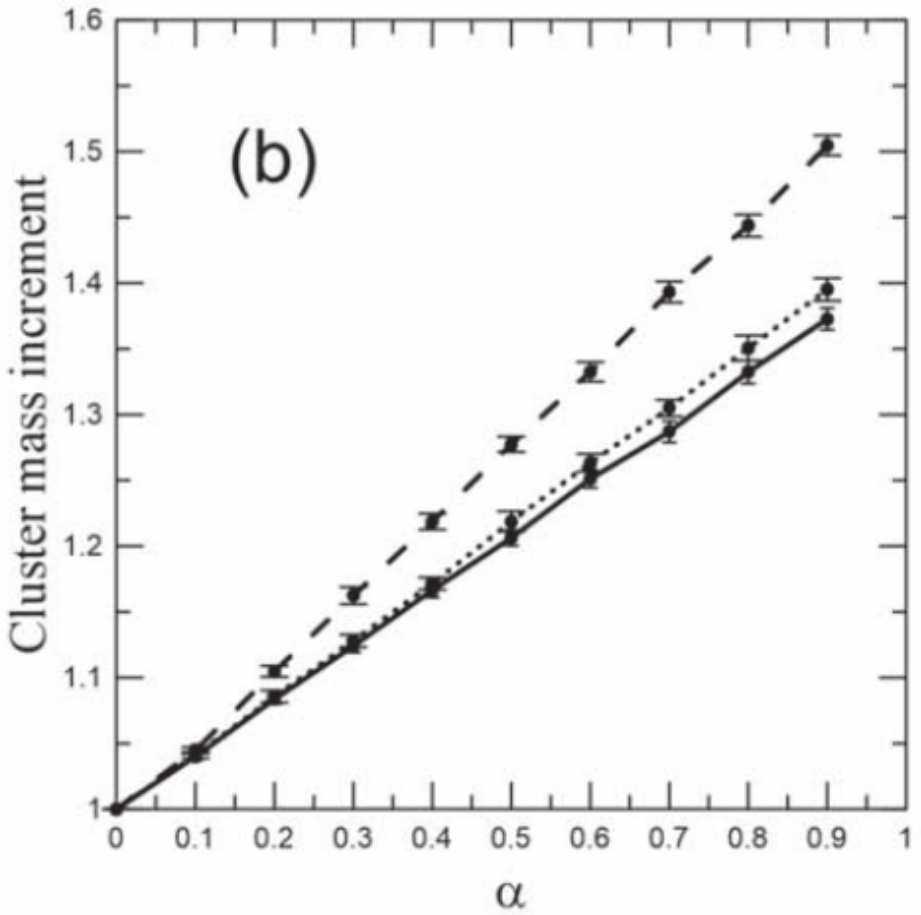
Main findings:

- Big variance in binary fractions: ~5% - ~70%
- Median f_b ~ 18%
- High f_b probably linked to almost dissolved OCs
- Trends with distance and ages are mostly produced by selection effects...
- No trends with Galactic position
- Anticorrelation of f_b with metallicity confirmed

Multiplicity: influence on total masses (Borodina+2021)



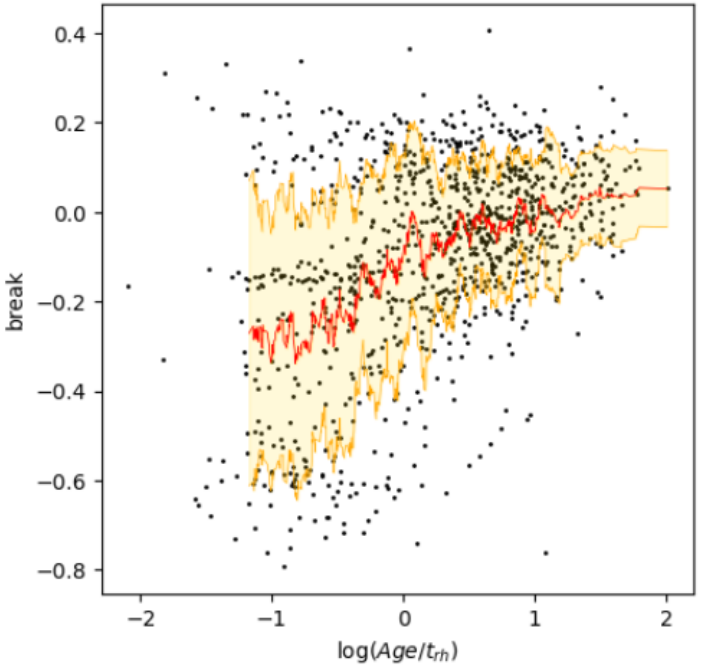
Unresolved binary fraction



Unresolved binary fraction

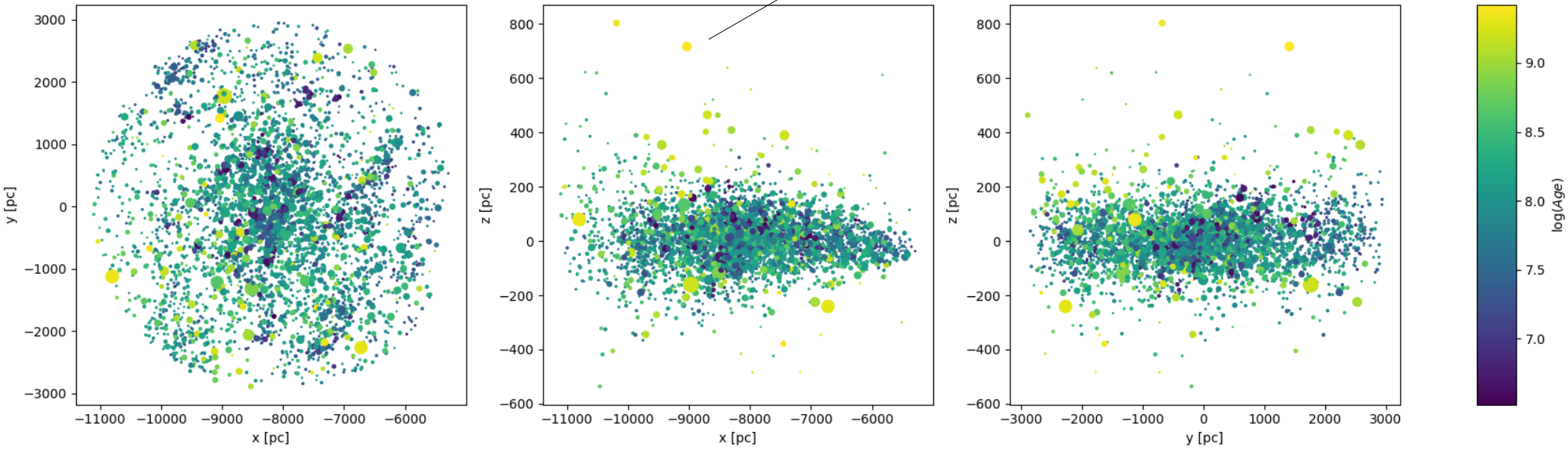
→ Not accounting for binaries (& higher-order systems) in the mass function can be **corrected for by multiplying the obtained total mass with ~1.1** (for a typical f_b)

OC masses (A. Zupic, MSc@UB 2023)

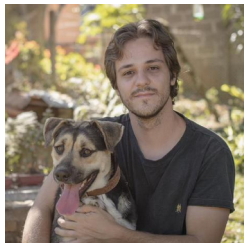


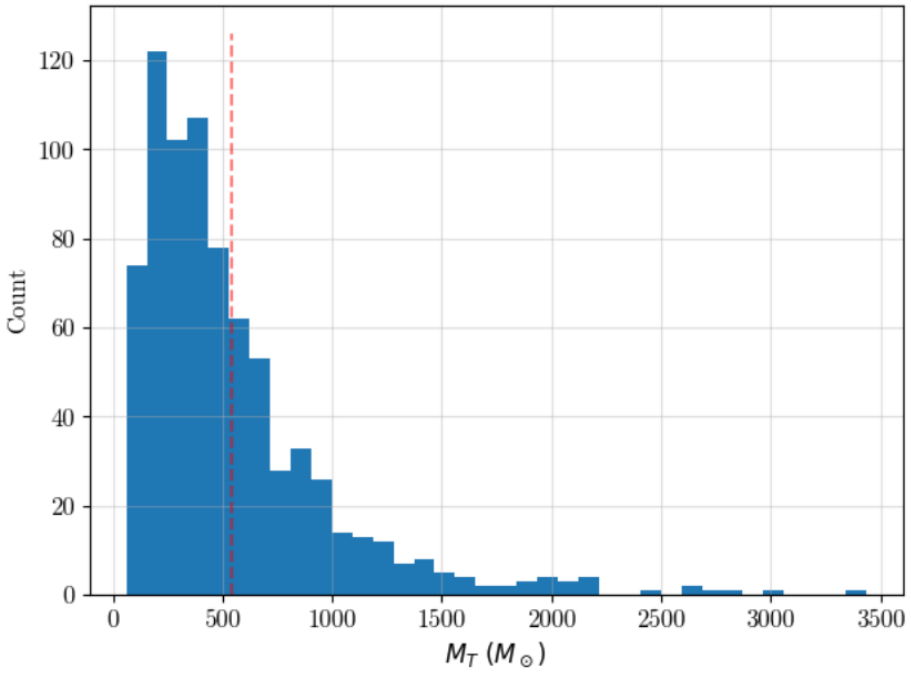
- Mass functions found to evolve with dynamical age = age/t_{rh} (Ebrahimi+2022, Cordoni+2023)
- Working on a catalogue of total tidal masses for further inferences (to better constrain cluster formation & destruction rates/mechanisms)
- Again, the selection function is complex… depends on {l, b, d, age, mass} – at least…

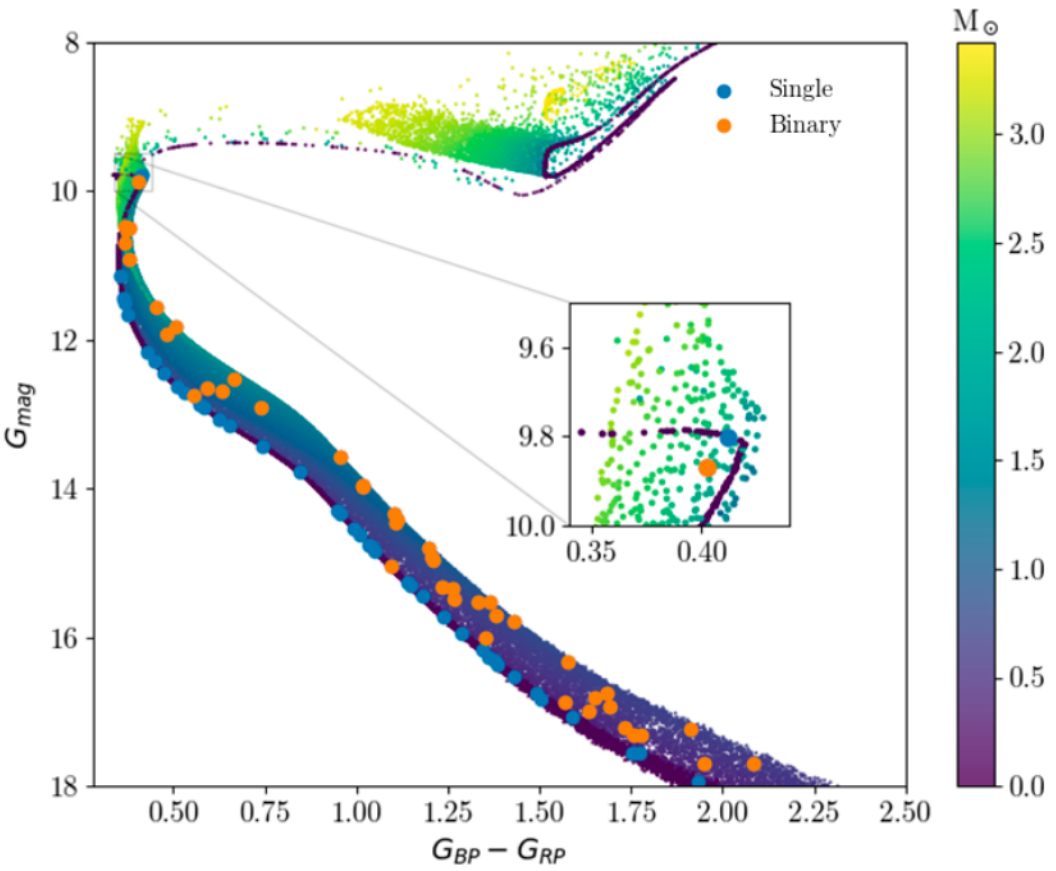
size ~ tidal mass



Use cases of the Gaia OC catalogues: Total masses (A. Almeida+2023)



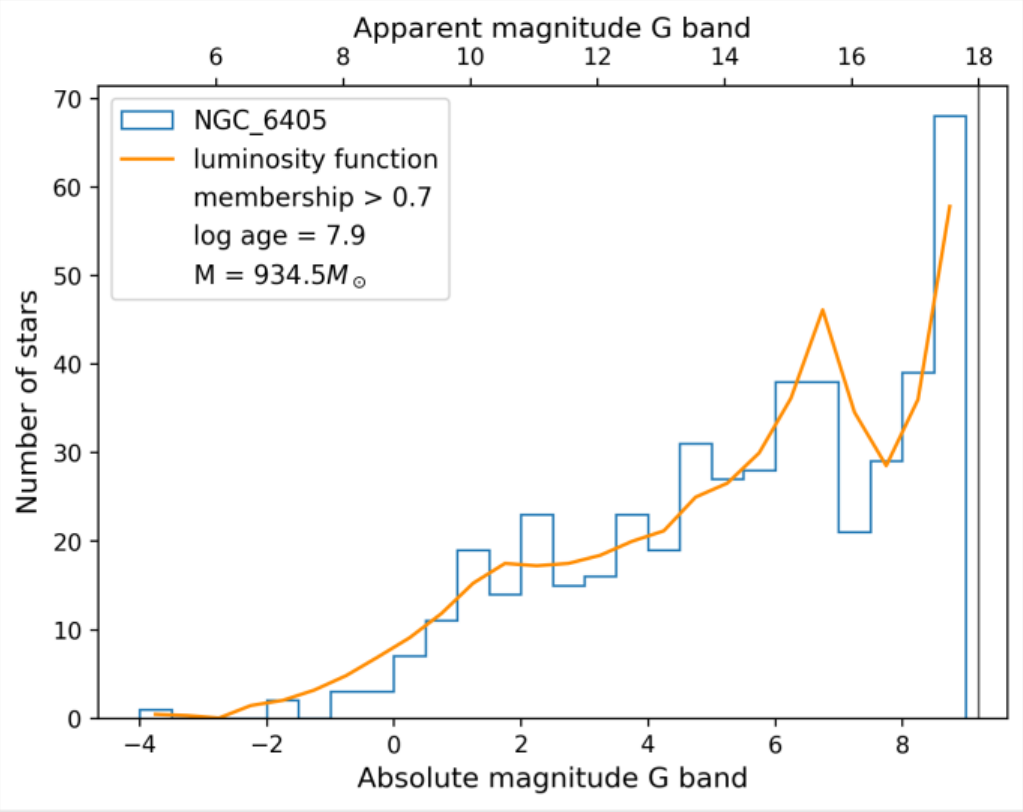




→ Base catalogue: Dias+2021 (Gaia **DR2)** clusters (d < 1.5 kpc)
→ Accuracy of the method strongly relies on the parameters of Dias+
→ **All** members are used (so these were not strictly tidal masses)

Use cases of the Gaia OC catalogues: Tidal masses (D. Almeida+, in prep.)

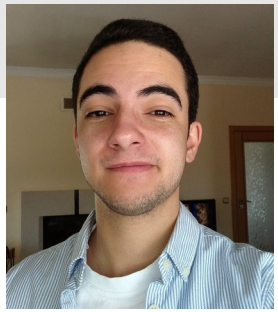
Luminous mass - determined by comparing the **observed luminosity distributions** to the **theoretical luminosity function** (LF).



Ciências ULisboa

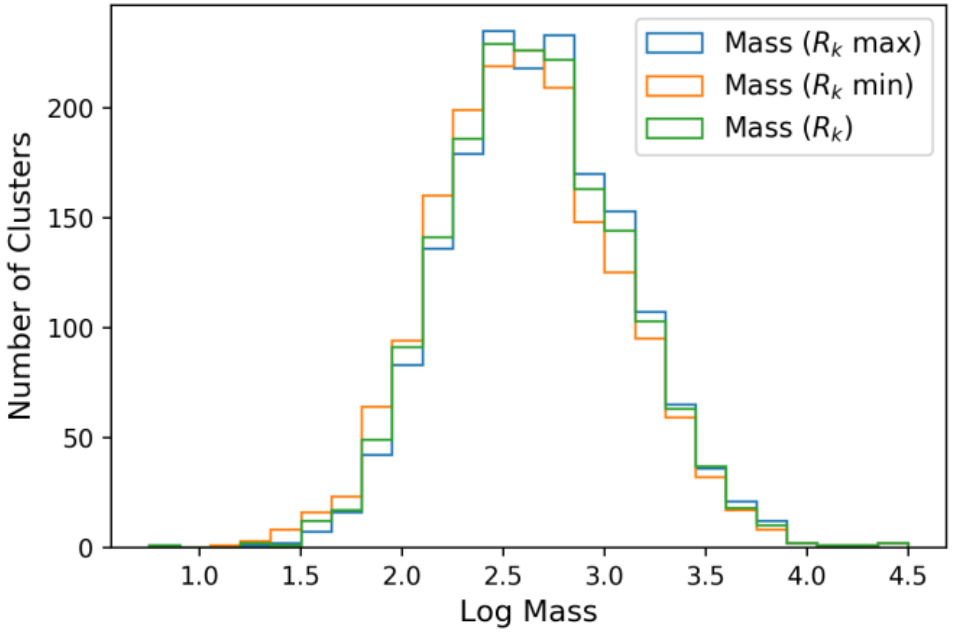
Select stars with **membership > 50%** that are **gravitationally connected** to the cluster, i.e., stars **inside** the **tidal radius**.

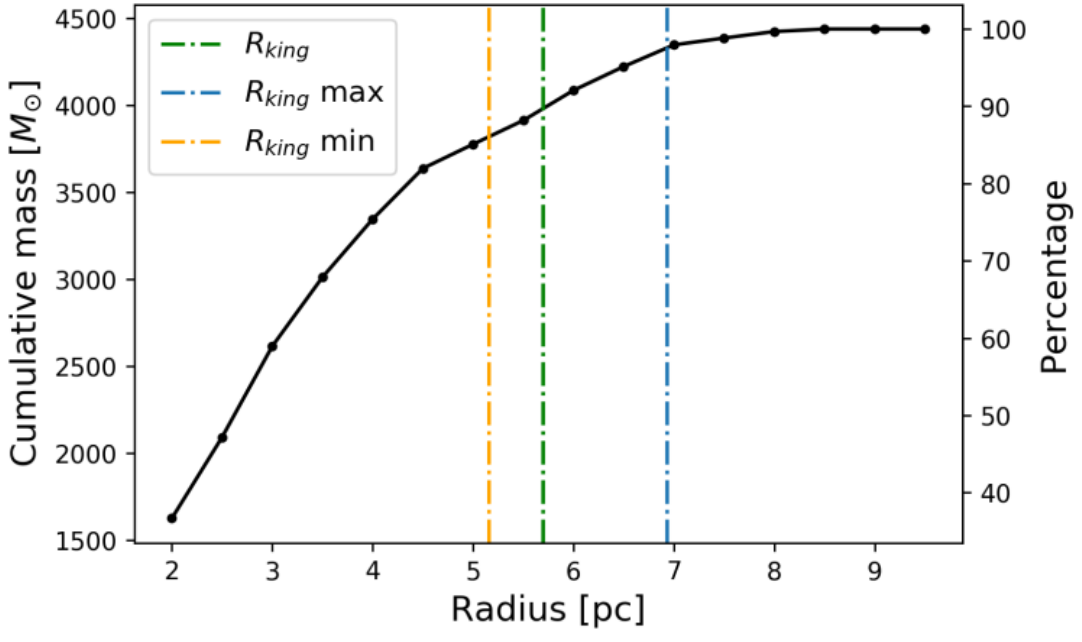
Radius where the **gravitational force** from the cluster **balances** the **tidal forces** from the **host** galaxy.



→ Base catalogue: Dias+2021 (Gaia **DR2)** clusters (d < 1.5 kpc)
→ Impact of binaries not clear… but overall mass estimates agree well with A. Almeida+2023

Use cases of the Gaia OC catalogues: Tidal masses (D. Almeida+, in prep.)



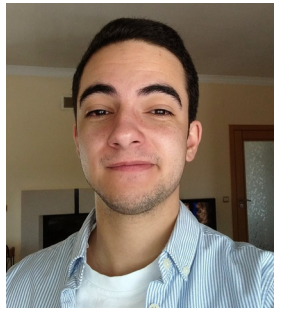


Mass inside the minimum R_k is ≈ 8% less and inside the maximum is ≈ 6% more.

Uncertainties in the tidal radii **do not** have a significant **impact on the mass**!

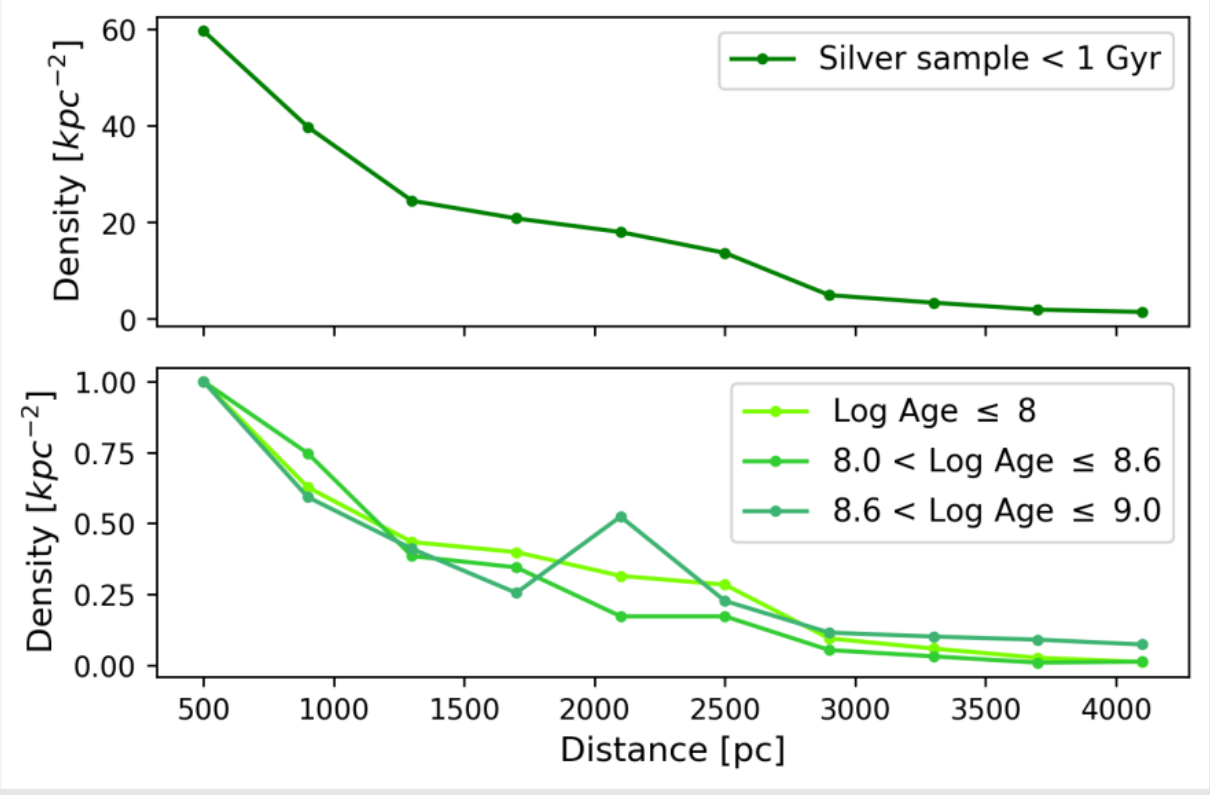
→ Peak at log(M) = 2.7
Standard deviation of 0.4

Ciências ULisboa



Use cases of the Gaia OC catalogues: Tidal masses (D. Almeida+, in prep.)

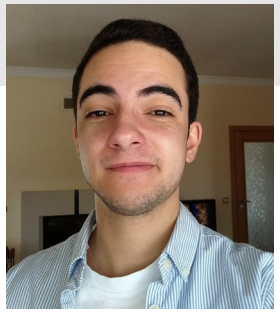
Sample completeness



Under the assumption that our position in the Galaxy is not special, the density should remain constant in a complete sample. But, as seen in the plot, the density is not constant and decreases with the distance and this is also verified for the full sample.

The density decreases with the distance, but it decreases similarly for every age. This indicates that the selection effects introduced are similar at every age.

→ May be valid to first order…? See E. Hunt's talk



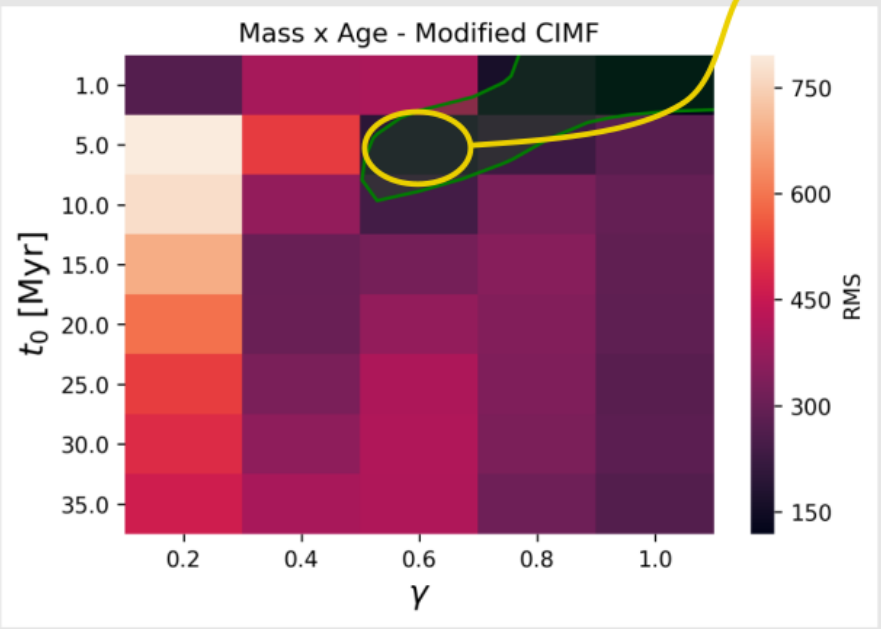
Use cases of the Gaia OC catalogues: Tidal masses (D. Almeida+, in prep.)

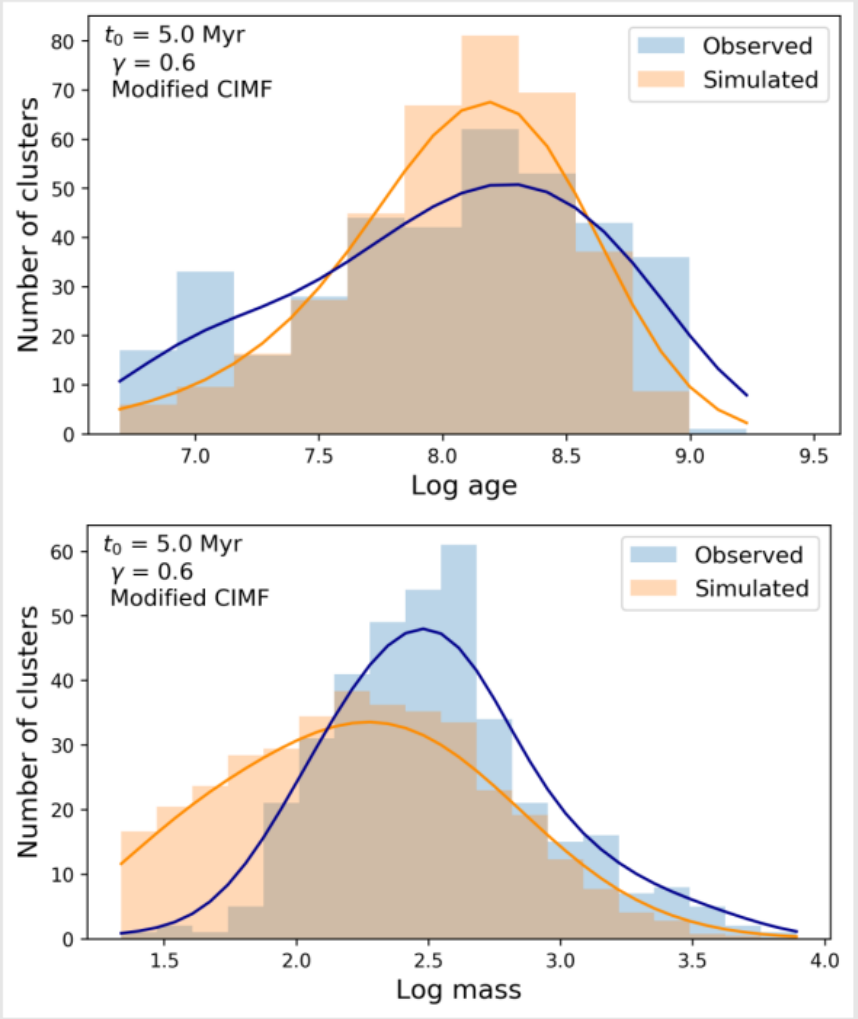
Mass loss simulations – with new CIMF

CIMF = Cluster Initial Mass Function

Ciências ULisboa

Sample used: OCs in **Silver** sample within **2 kpc** with ages under 1Gyr.

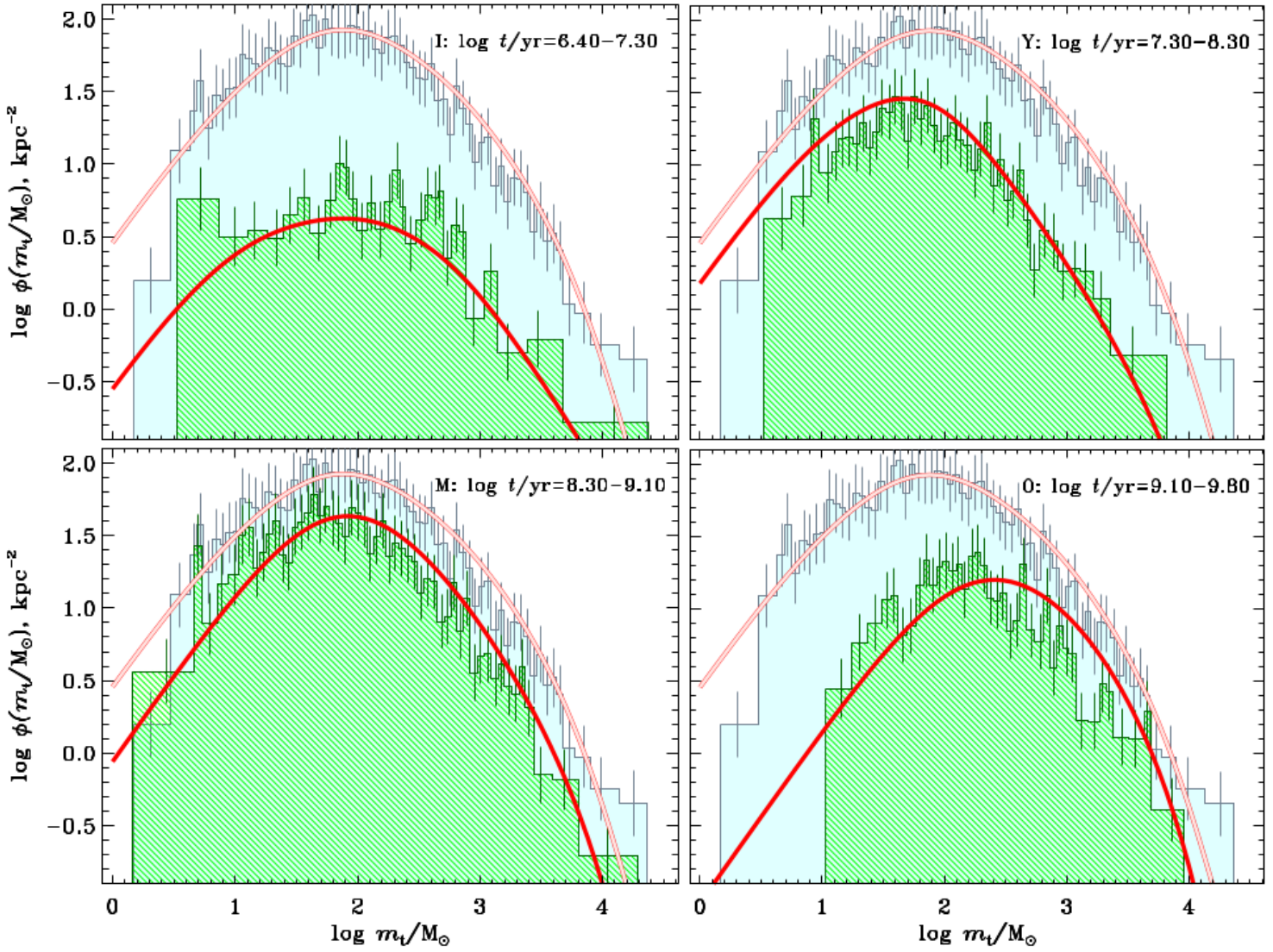




Peak of the simulated masses is **closer** to the observed mass peak

→ The joint mass-age distribution can indeed constrain cluster formation rate, CIMF, & cluster disruption – also for the Milky Way!

Use cases of the Gaia OC catalogues: Mass-age distribution (Just+2023)



Base catalogue:
MWSC; d < 1.8 kpc

Parameter	Value
- CFR (Eq. 19)	
β	0.81 kpc^{-2} Myr^{-1}
- CIMF (Eq. 20)	
k_0	1.5×10^{-4} M$_\odot^{-1}$
$M_\star$	1000 M$_\odot$
s	2.4
x_1	0
x_2	1.2
m_S	85000 M$_\odot$
- stellar evol. $\mu(t)$ (Eq. 21)	
p_0	1.0078
p_1	–0.07456
p_2	–0.02002
p_3	0.00340
- violent relax. (Eq. 22)	
n_b	0.1
t_v	5 Myr
- cluster dissolution (Eqs. 23 to 25)	
a_1	–0.2
a_2	0.9
c	0.23 Gyr^{-1}
M_{br}	5000 M$_\odot$

→ Nice modelling effort! But **based on a really outdated catalogue**...

Asterisms: They are still among us!

Just+2023:

As it follows from above, the current status of cluster population characterization with *Gaia* is unstable and swiftly developing. Despite the high quality and homogeneity of data on individual stars, this cannot be determined for a representative cluster sample nor for high-significance astrophysical parameters, such as the luminosities or masses characterising the cluster population with regard to its formation and evolution. This is why we base this study on the MWSC sample, as it provides the necessary fundamental qualities such as estimated completeness and an extended set of relevant parameters, including almost 100%-coverage with tidal radii. Our ultimate aim is based on inde-

...

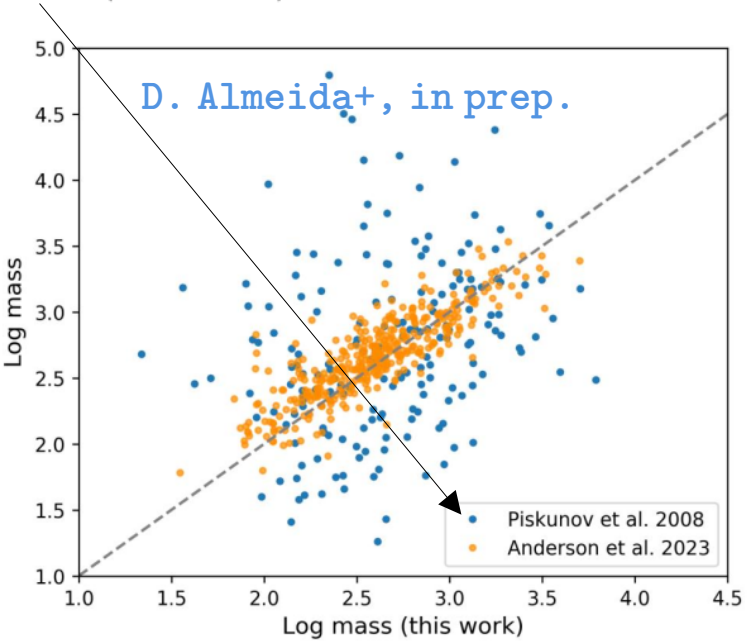
The results of the MWSC were published in a series of papers and submitted as online catalogues to the CDS archive[4].

[4] https://cdsarc.cds.unistra.fr/ftp/J/A+A/558/A53; https://cdsarc.cds.unistra.fr/ftp/J/A+A/568/A51; https://cdsarc.cds.unistra.fr/ftp/J/A+A/581/A39; https://cdsarc.cds.unistra.fr/ftp/J/A+A/585/A101.

4. Tidal masses

To determine the tidal mass of the cluster (m_t), we follow King (1962) and use a condition for the balance of gravitational forces between the Galaxy and the cluster on a circular orbit:

$$m_t = \frac{r_J^3}{G}\left(\frac{1}{R}\frac{\partial\Phi}{\partial R} - \frac{\partial^2\Phi}{\partial R^2}\right). \quad (2)$$



These are known to be asterisms since 2018.. Don't use them.

Summary

→ OC ages and tidal masses encode the Galactic cluster formation and destruction history

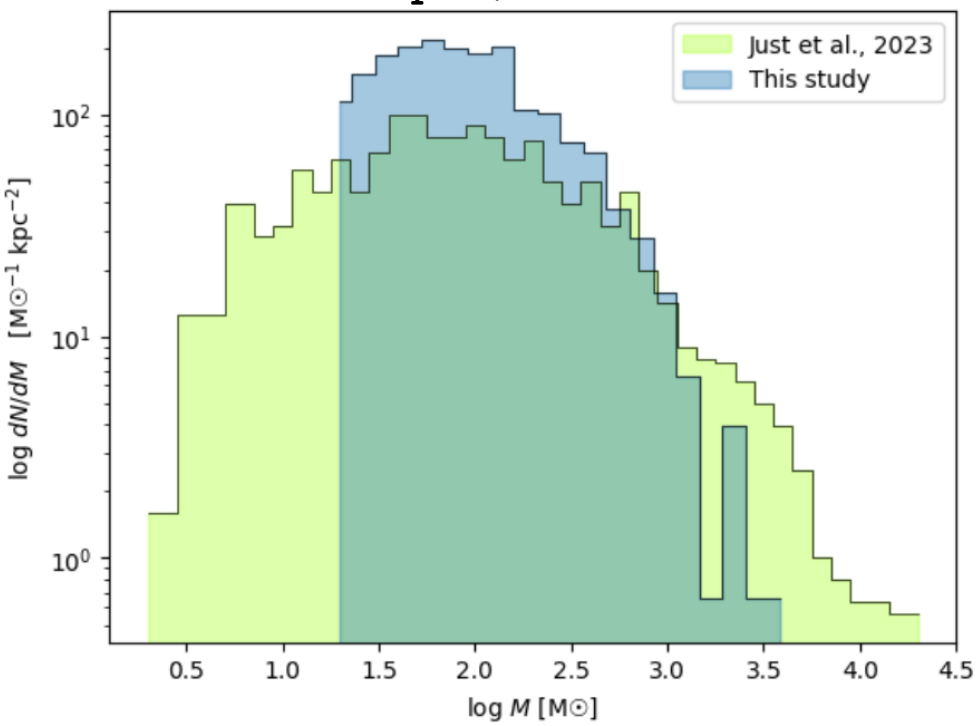
→ We are starting to get reasonable mass estimates for larger samples

→ We still need better (and more) mass estimates to better constrain the destruction time-scales and the GCMF

→ Equally important, we also need a well-determined selection function for the sample!

→ There is no turning back to before Gaia:)

A. Zupic, MSc@UB 2023



This happened in September.. slides at https://indico.icc.ub.edu/event/252/