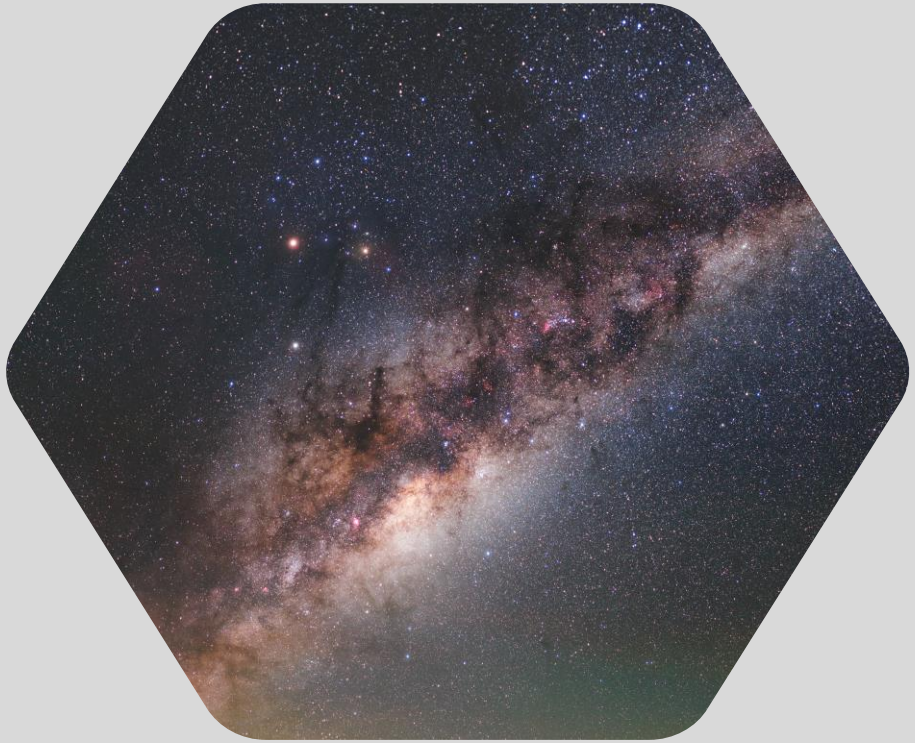
The Milky Way Revealed by Gaia:
The Next Frontier



Credits: ESO/P. Horálek

MASS LOSS IN OPEN CLUSTERS

Duarte Almeida
& André Moitinho

5-7 September 2023

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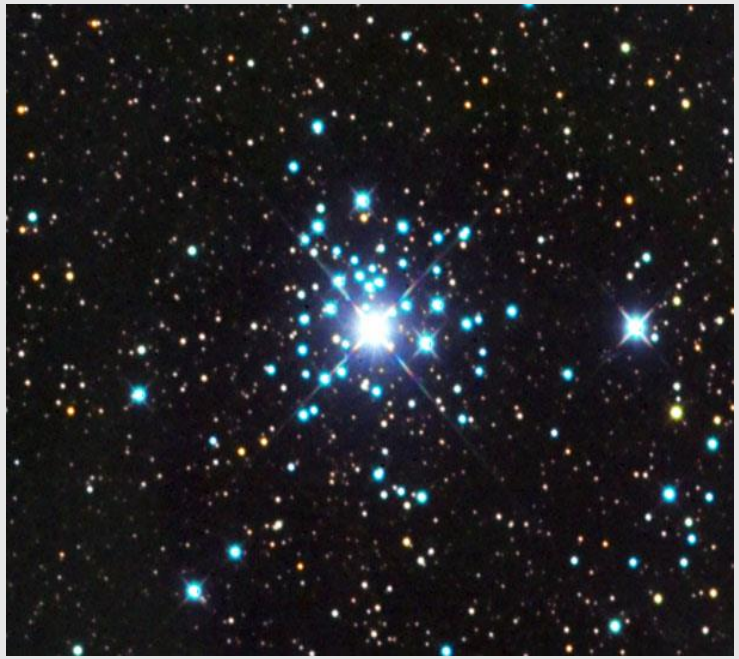
Motivation

Most **stars** are **formed** in **clusters** which later **dissolve** into the field population due to internal dynamics and tidal interactions → The dissolution process **drives** the **observed mass and age distribution.**



Credit: Langkawi National Observatory

Young open cluster NGC 2362
Age = $10^{7.2}$ years

Credit: DSS 2

Old open cluster NGC 188
Age = $10^{9.8}$ years

Motivation

t_0 = **disruption timescale**

γ = mass dependence of the disruption time:

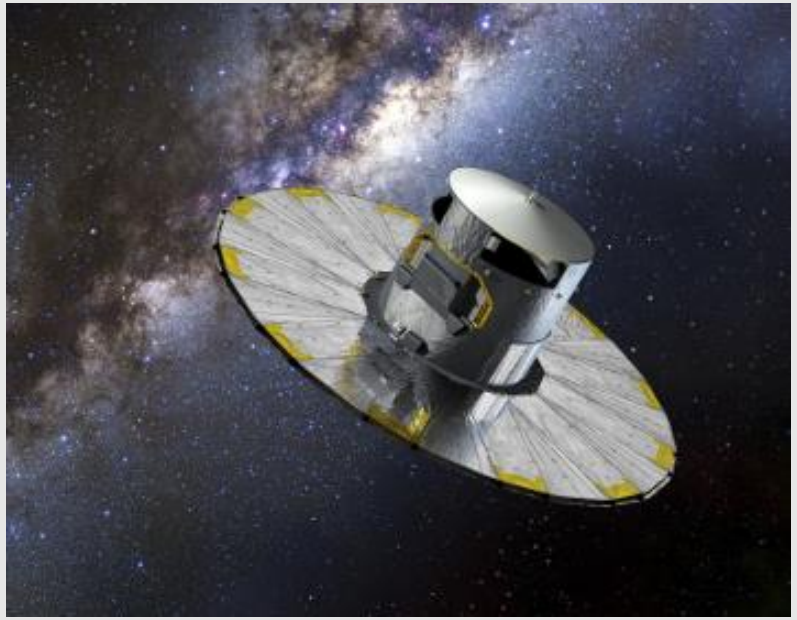
$$t_{dis} = t_0 (M/M_\odot)^\gamma$$

t_0 = 3.3 Myrs

γ = 0.6 Lamers et al., 2005; Gieles et al., 2004

Determined using the **age distribution only**.

With **Gaia**, we can **revisit** these results and use both **age and mass distributions together**, which is the **novel approach** of our study.

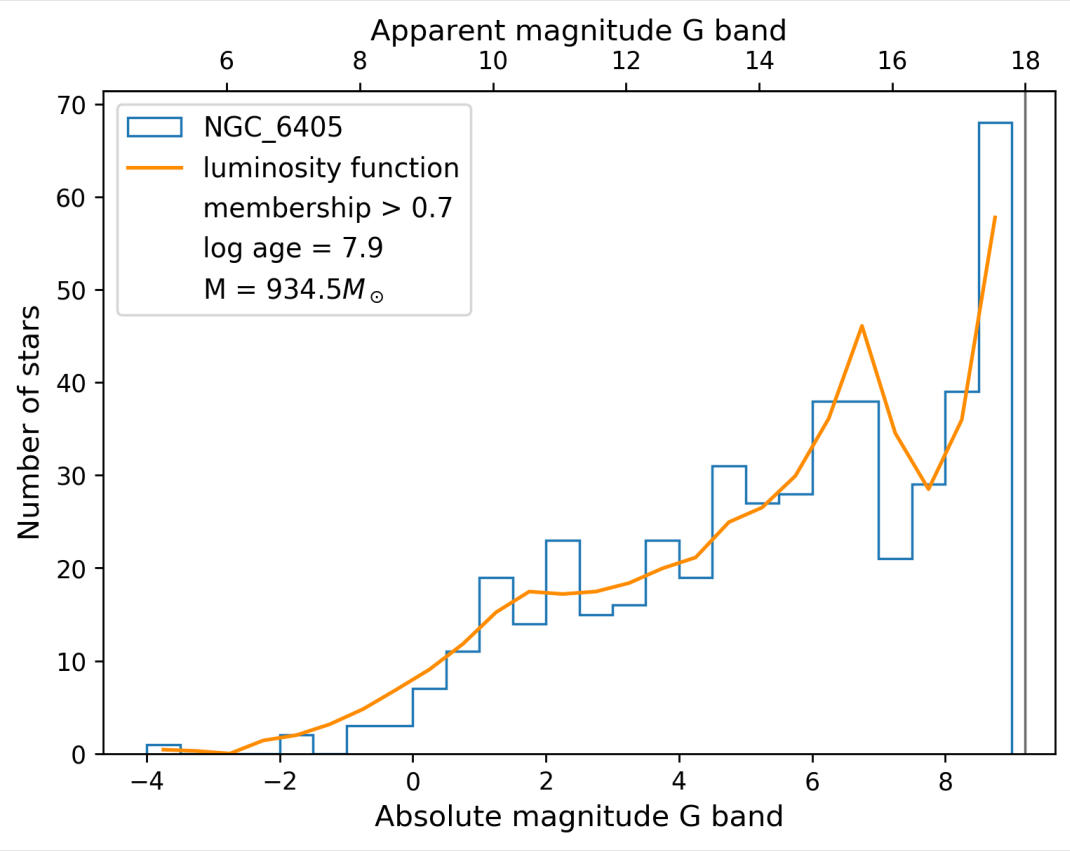


Credits: ESA – D. Ducros, 2013

→ Sample: **1724** OCs from **Dias et al. 2021 catalogue** (Gaia DR2)

Star selection for mass determination

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



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.

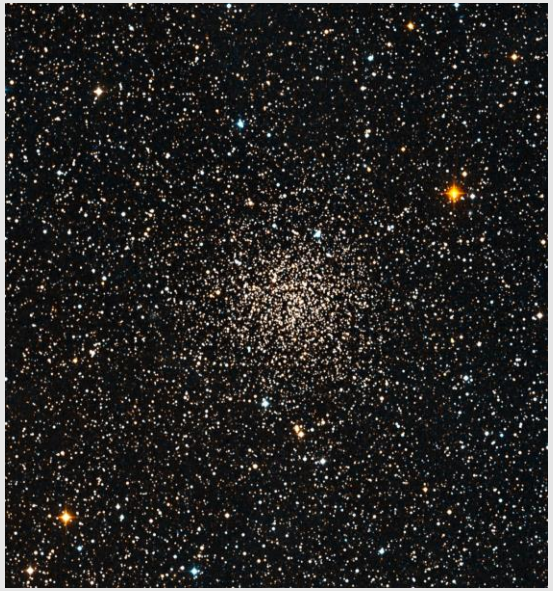
Radii determination

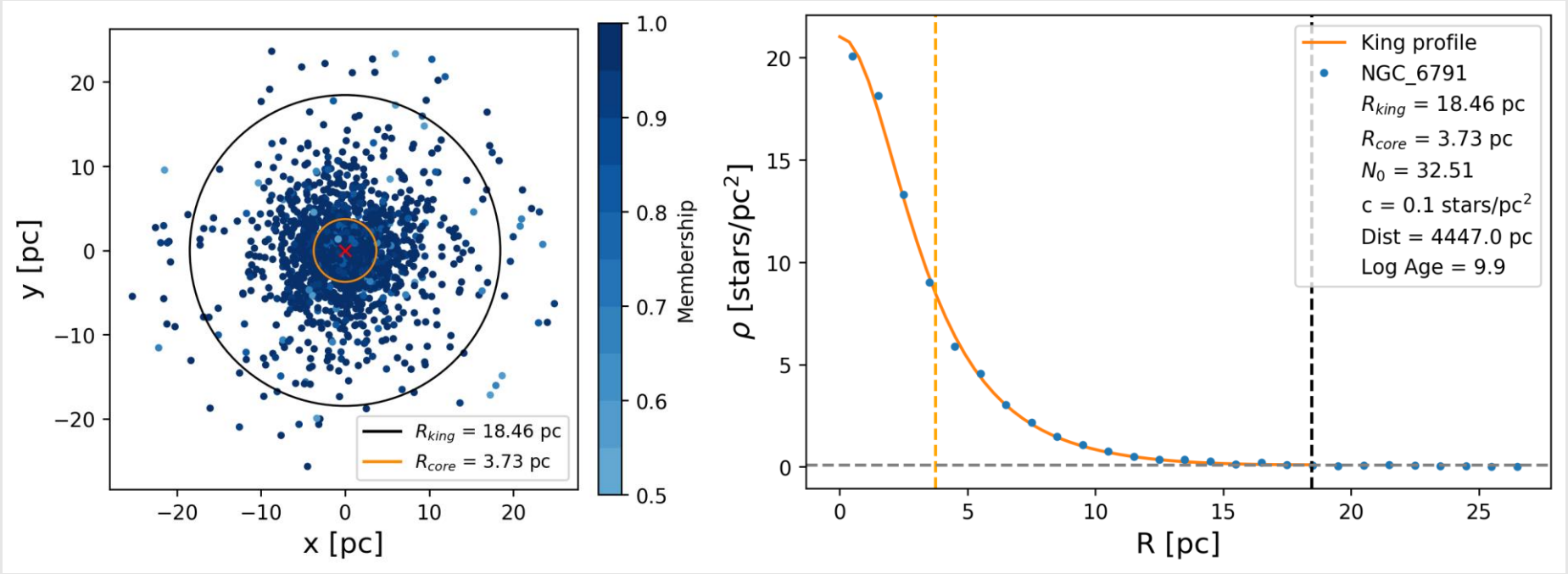
Fitted the **radial density profile** with the **King function** (King, 1962) using a Non-Linear Least-Squares Fitting package.

Used **Maximum Likelihood Estimation** to obtain the **King parameters** and **uncertainties.**

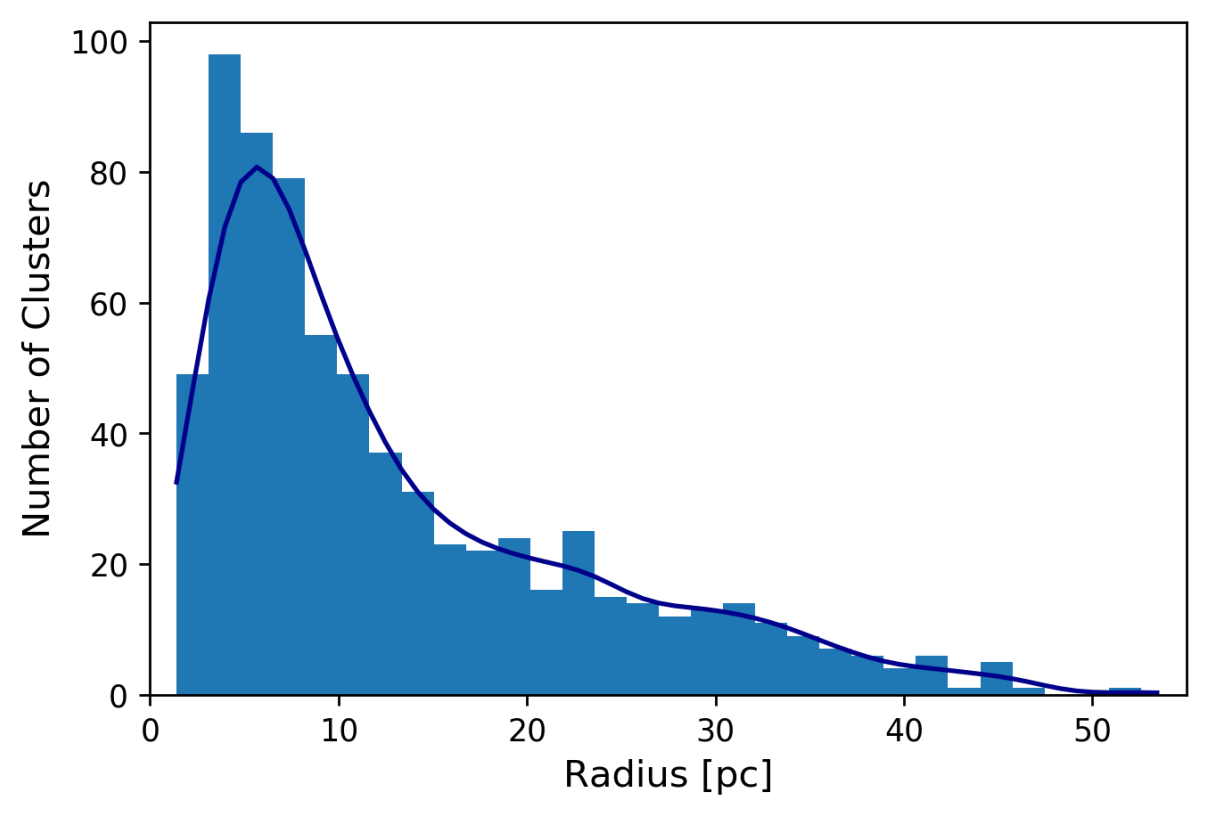
$$n(R) = \begin{cases} N_0 \left(\frac{1}{\sqrt{1+(R/R_c)^2}} - \frac{1}{\sqrt{1+(R_k/R_c)^2}} \right)^2 + c & if\ R < R_k \\ c & if\ R \geq R_k \end{cases}$$

R_{king} = radius where density is indistinguishable from the background





Radii determination

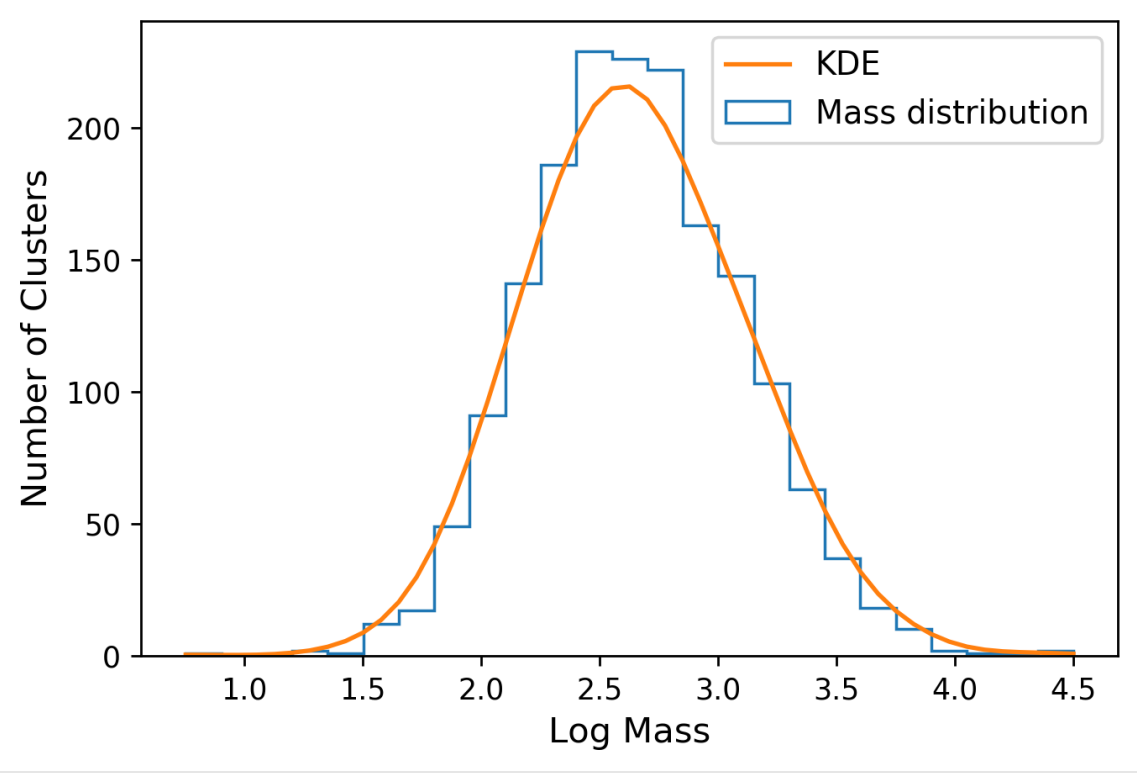


Median **tidal** radius = 10 pc

Consistent with literature:
Hunt (2023); Piskunov (2008)

Median lower uncertainty R_{king} = 47%
Median upper uncertainty R_{king} = 95%

Mass results



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

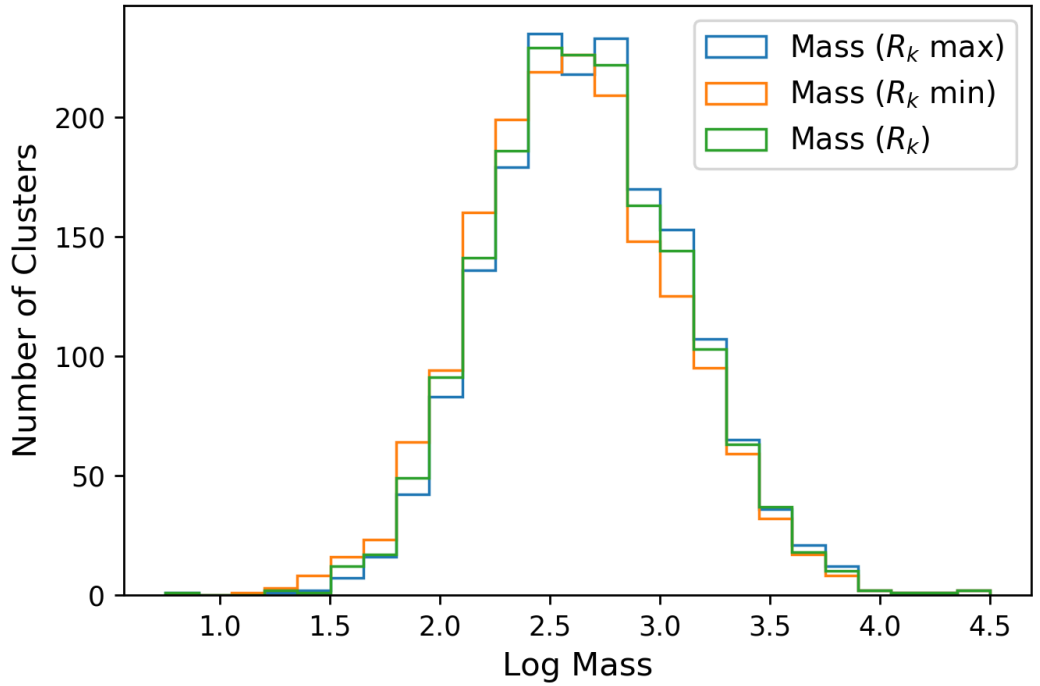
Median mass = 450 $M_{\odot}$

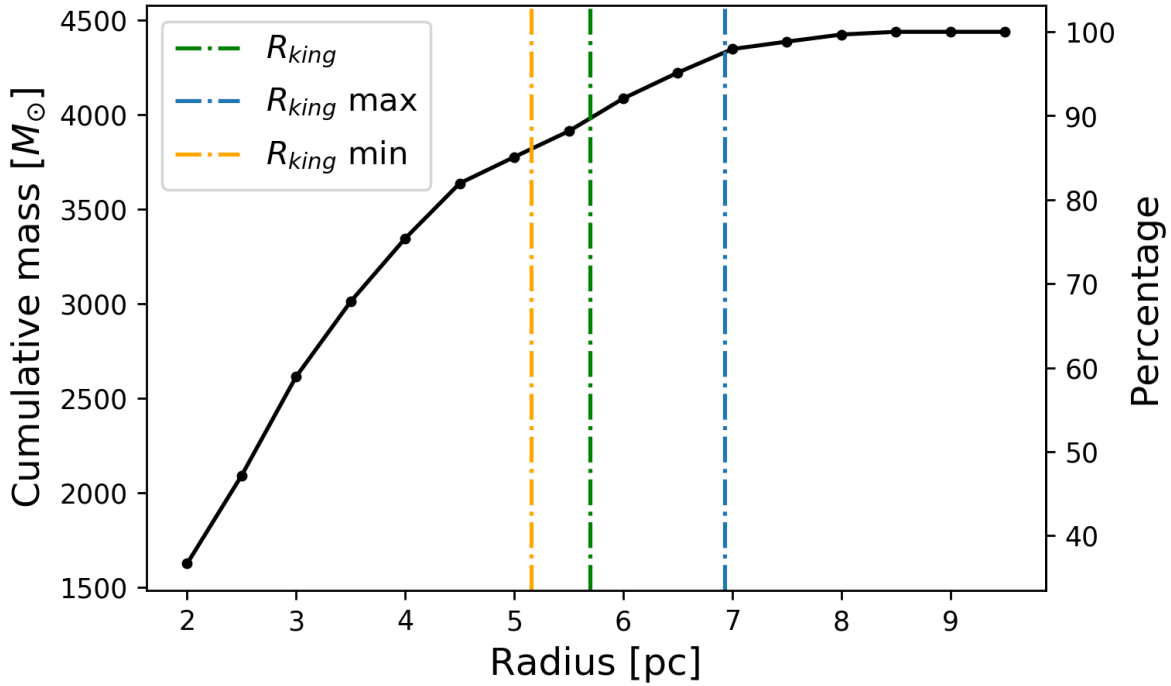
Error of the method estimated through **bootstrap** analysis. Median error of **4%**
→ our method is **robust**

Similar distribution of **mass** when compared to the catalogues in **literature** (Almeida et al., 2023, Piskunov et al., 2008)

Mass results

To study the **effect** of the **tidal radius uncertainty**, we determined the mass considering **stars inside R_k ± uncertainty**





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

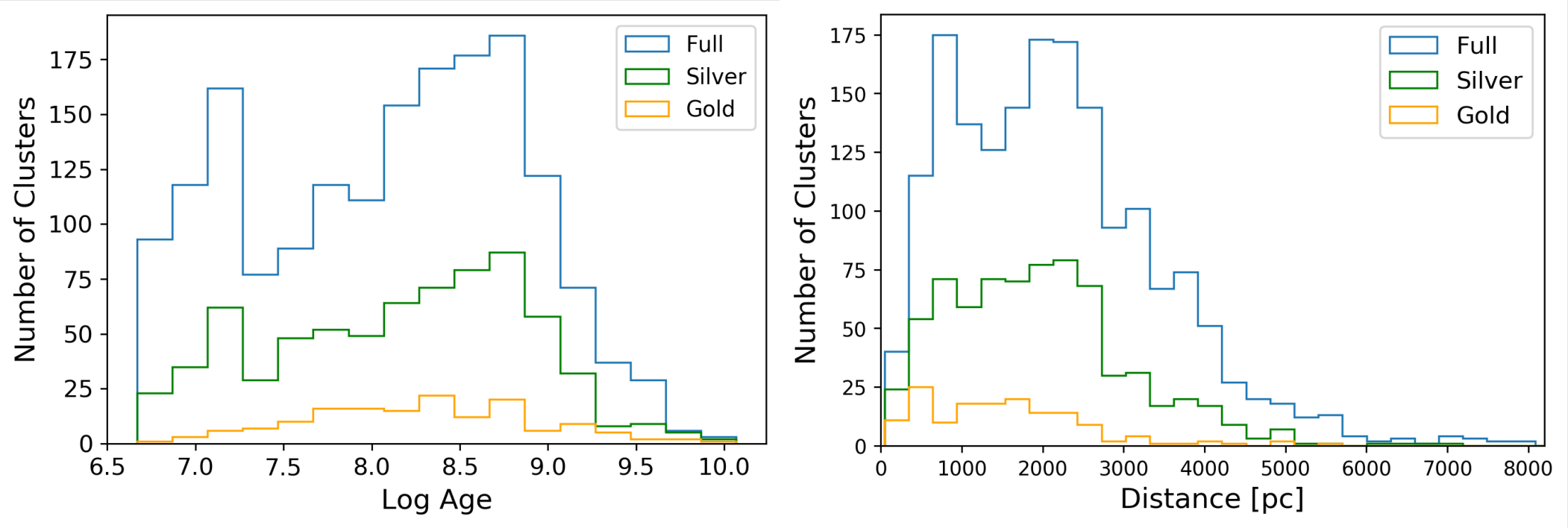
Uncertainties in the tidal radii **do not** have a significant **impact on the mass**!

Sample selection

Clusters were **classified** regarding the **quality** of the determination of the radius, mass and their colour-magnitude diagram.

- **Silver sample** - intermediate and high-quality results.
- Gold sample **-** only best quality results.

Full Sample = 1724 Open Clusters
Silver sample = 713 OCs
Gold sample = 153 OCs



→ Completeness analysis (in additional slides)

Mass loss simulations

1) Simulate a population of open clusters
2) Allow them to lose mass over time
3) Compare the simulated distribution of ages and masses to the observations

Lamers et al., 2005 found that the **decrease of mass** for an open cluster is approximated by:

$$\mu(t; M_{\rm i}) \equiv \frac{M(t)}{M_i} \simeq \left\{ (\mu_{\rm ev}(t))^{\gamma} - \frac{\gamma t}{t_0} \left(\frac{M_\odot}{M_{\rm i}} \right)^{\gamma} \right\}^{1/\gamma}$$

Stellar Evolution

t_0 = **disruption timescale**

γ = mass dependence of the disruption time:

$$t_{dis} = t_0 (M/M_\odot)^{\gamma}$$

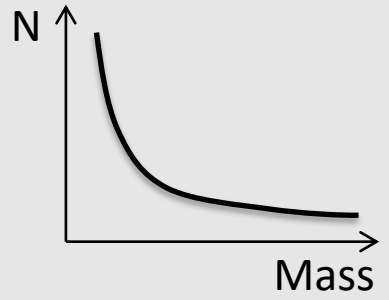
We assumed:

- **Constant** rate of cluster **formation**
- **Initial Cluster Mass Function** as a power law:

$$\frac{dN}{dM} = M_{min} M^{-\alpha}$$

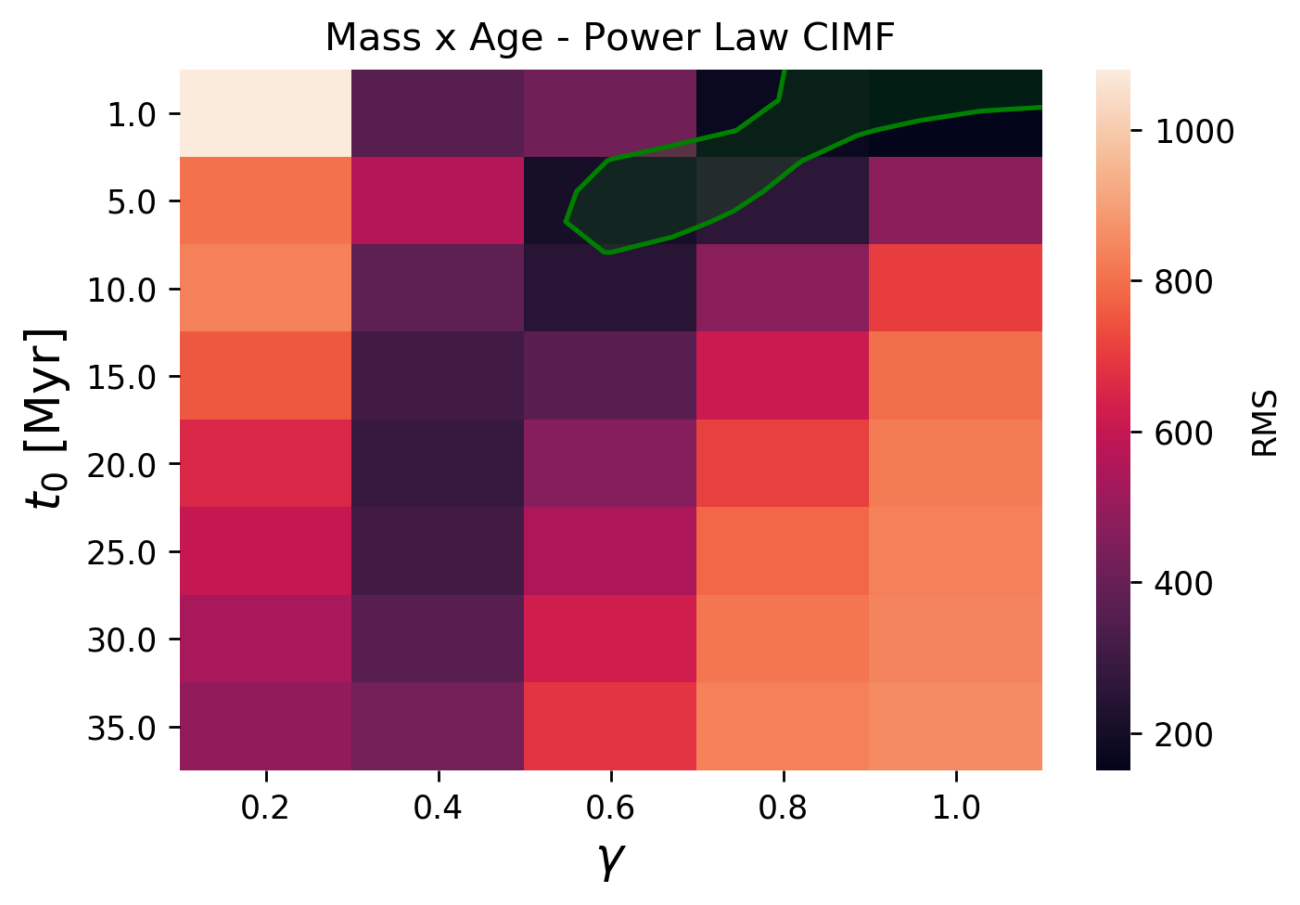
with $\alpha \sim 2$, $M_{min} = 100\ M_\odot$ and $M_{max} = 3 \times 10^4\ M_\odot$

(Lamers & Gieles 2006)



Mass loss simulations

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



CIMF = Cluster Initial Mass Function
Green line = 1.5σ contour

t_0 = 5 Myr and **γ = 0.6**

→ For a cluster with 4000 $M_\odot$ the dissolution time is around 700 Myr.

Consistent with literature:
Lamers et al., 2005: t_0 = 3.3 Myr; γ = 0.62

Mass loss simulations

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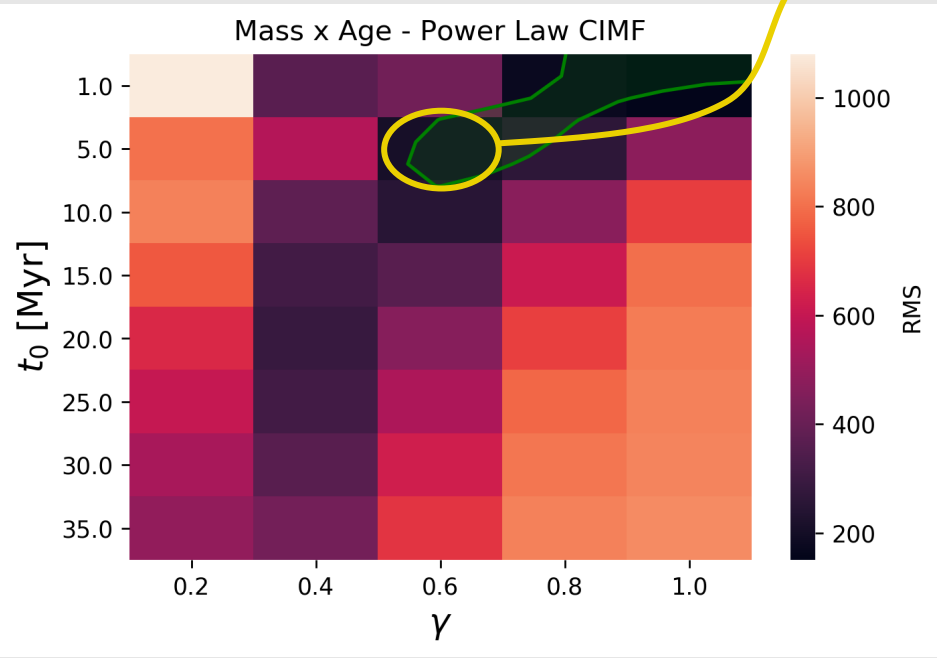

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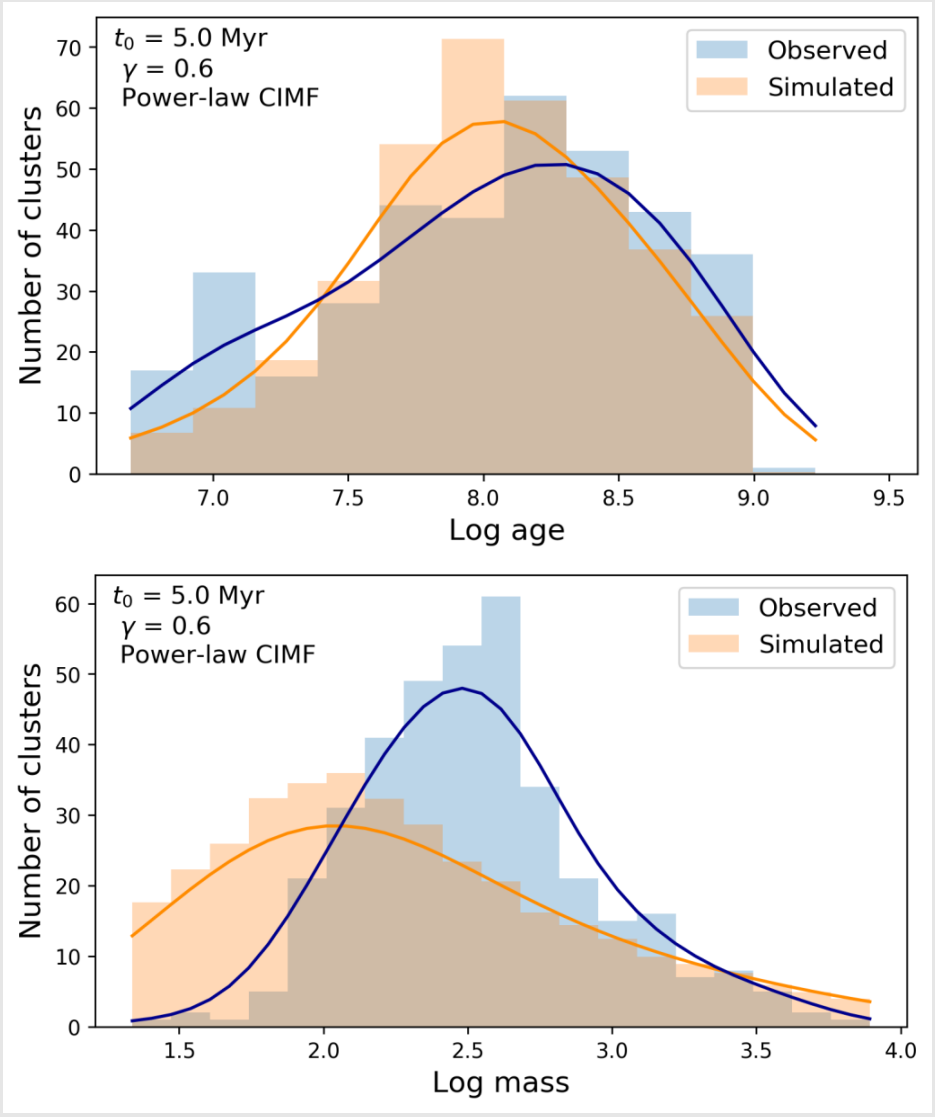

Despite the agreement for the age distributions, **the mass distributions don't show a good match!**

Mass loss simulations

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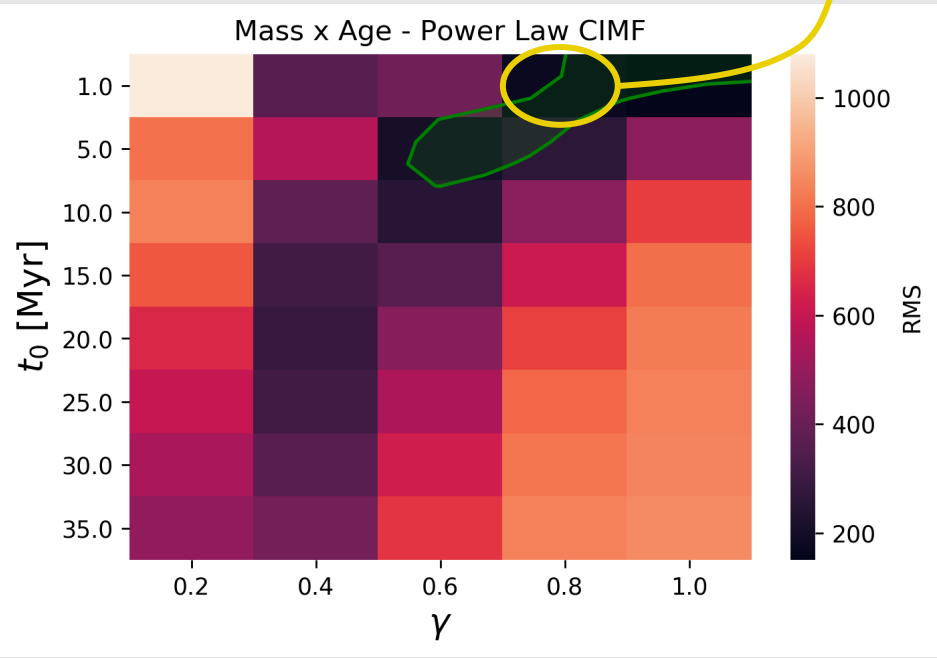
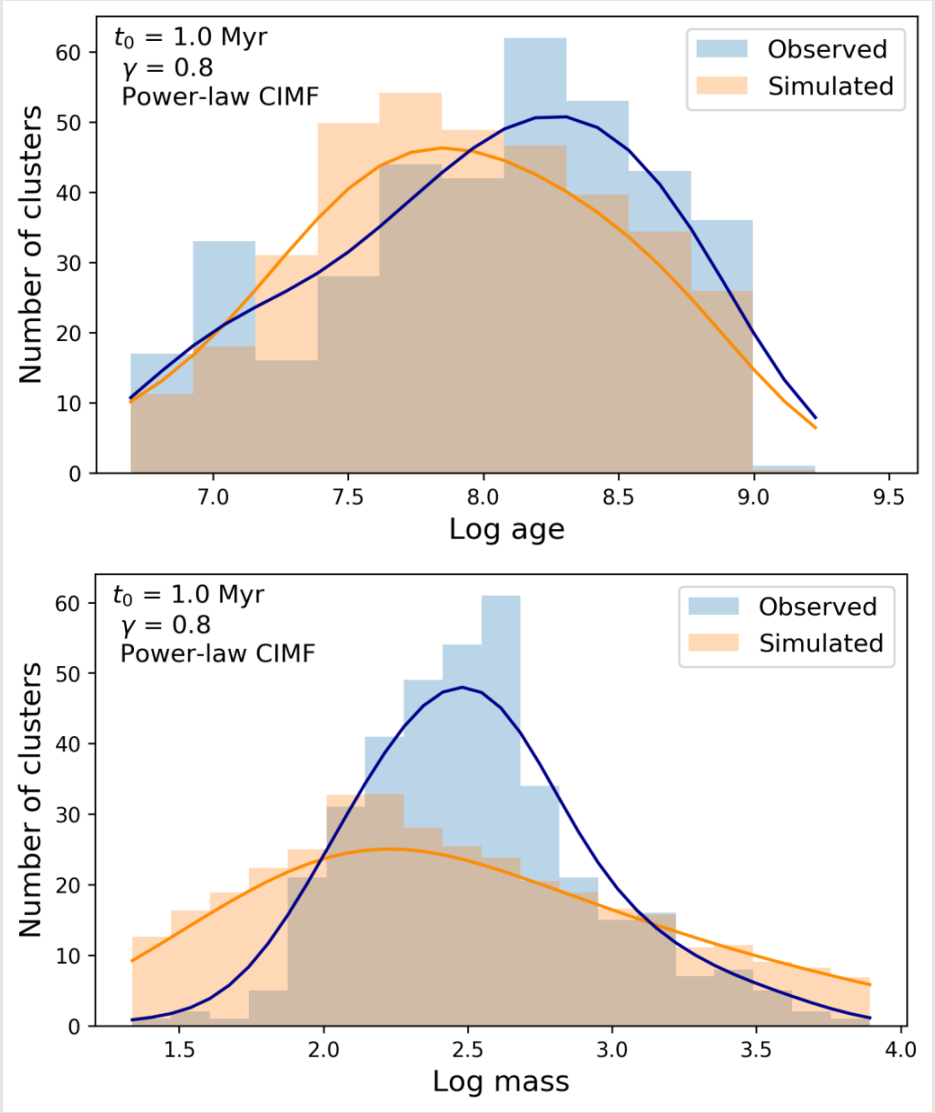


t_0 = 1 Myr and γ = 0.8



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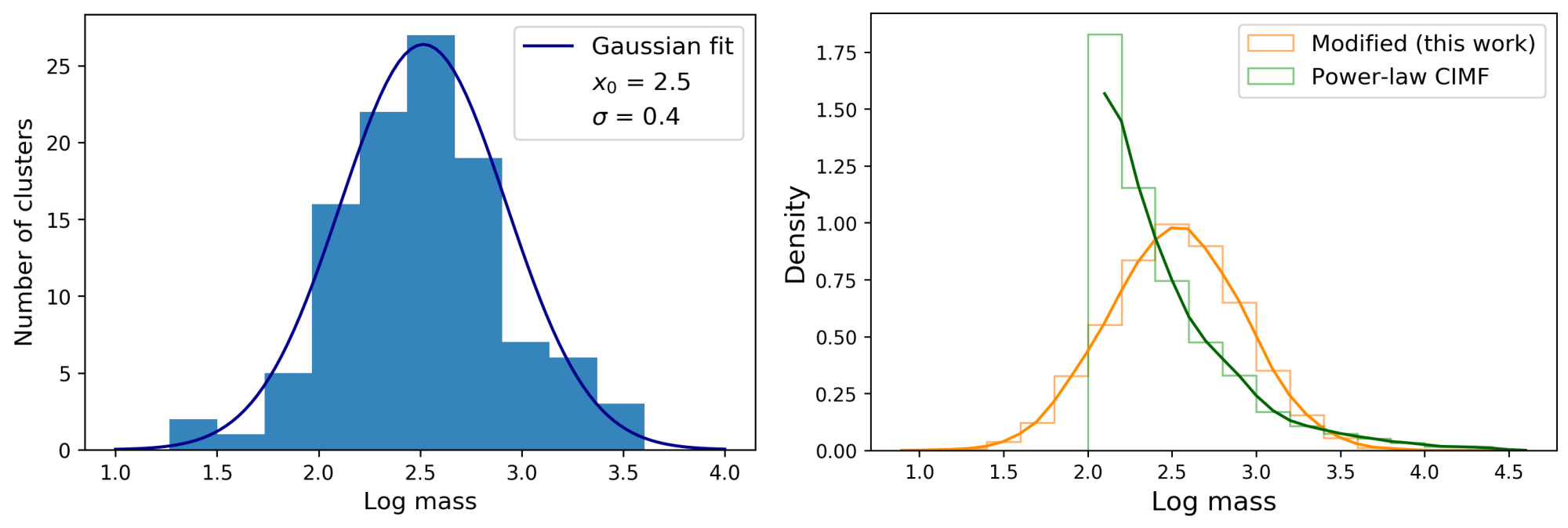
Mass loss simulations



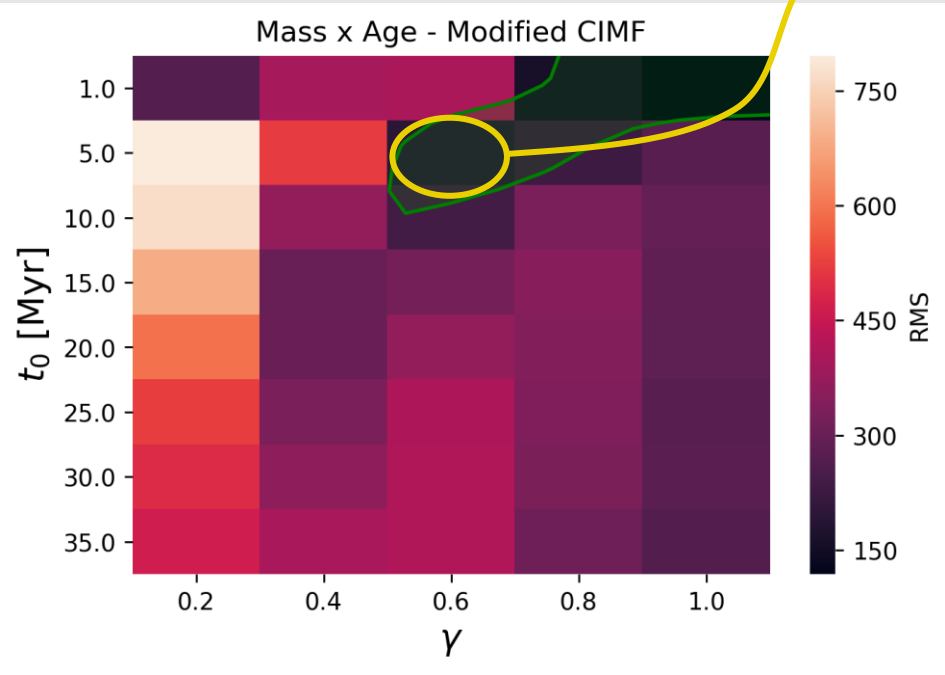
The **Cluster Initial Mass Function** used should **reflect** the **mass** distribution **at early ages**.

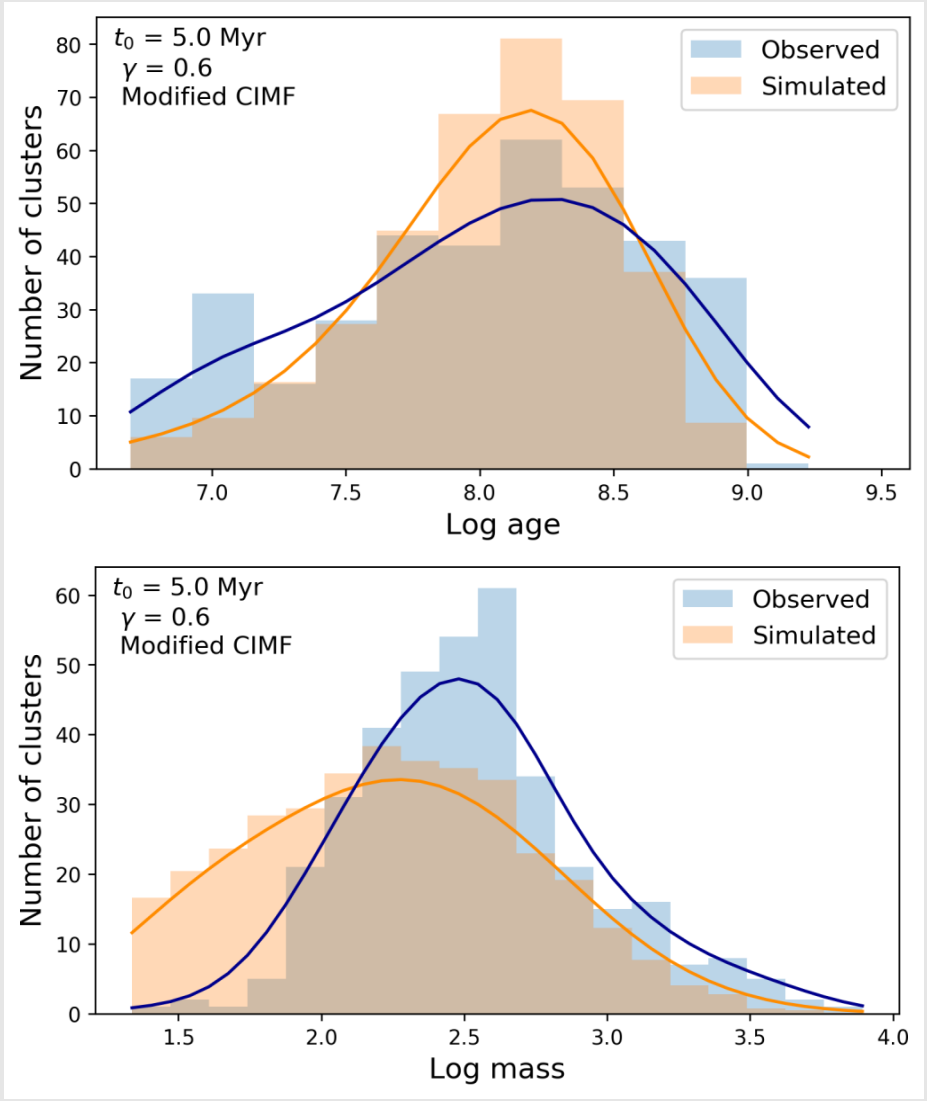
→ We **modified** the **Cluster Initial Mass Function** to a **log-normal** (instead of a power-law) to **test** the effect of changing the CIMF.

Mass loss simulations – with new CIMF

CIMF = Cluster Initial Mass Function

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

Mass loss simulations – with new CIMF

CIMF = Cluster Initial Mass Function

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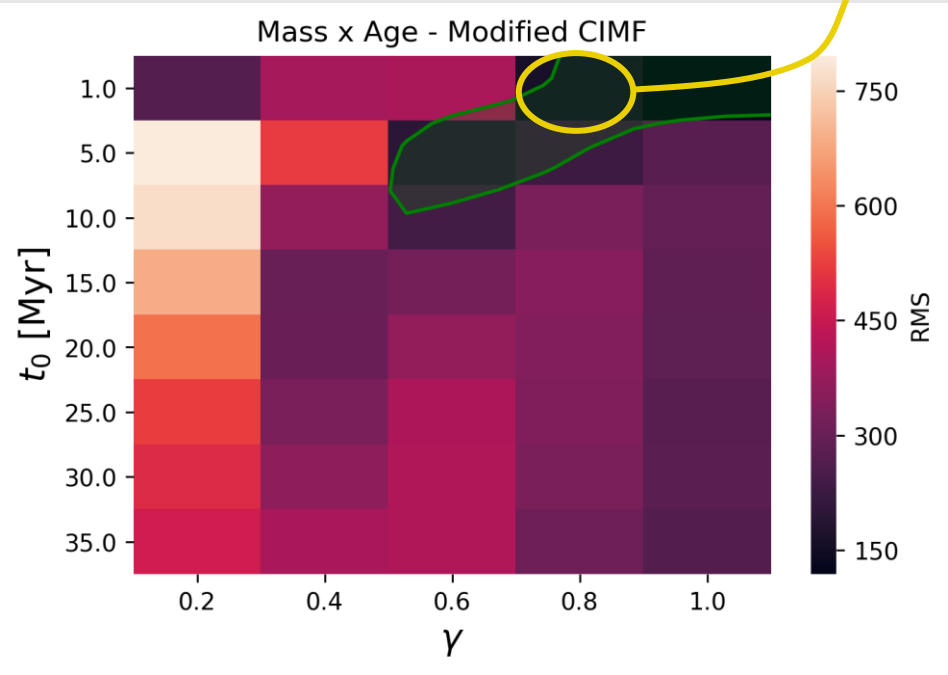

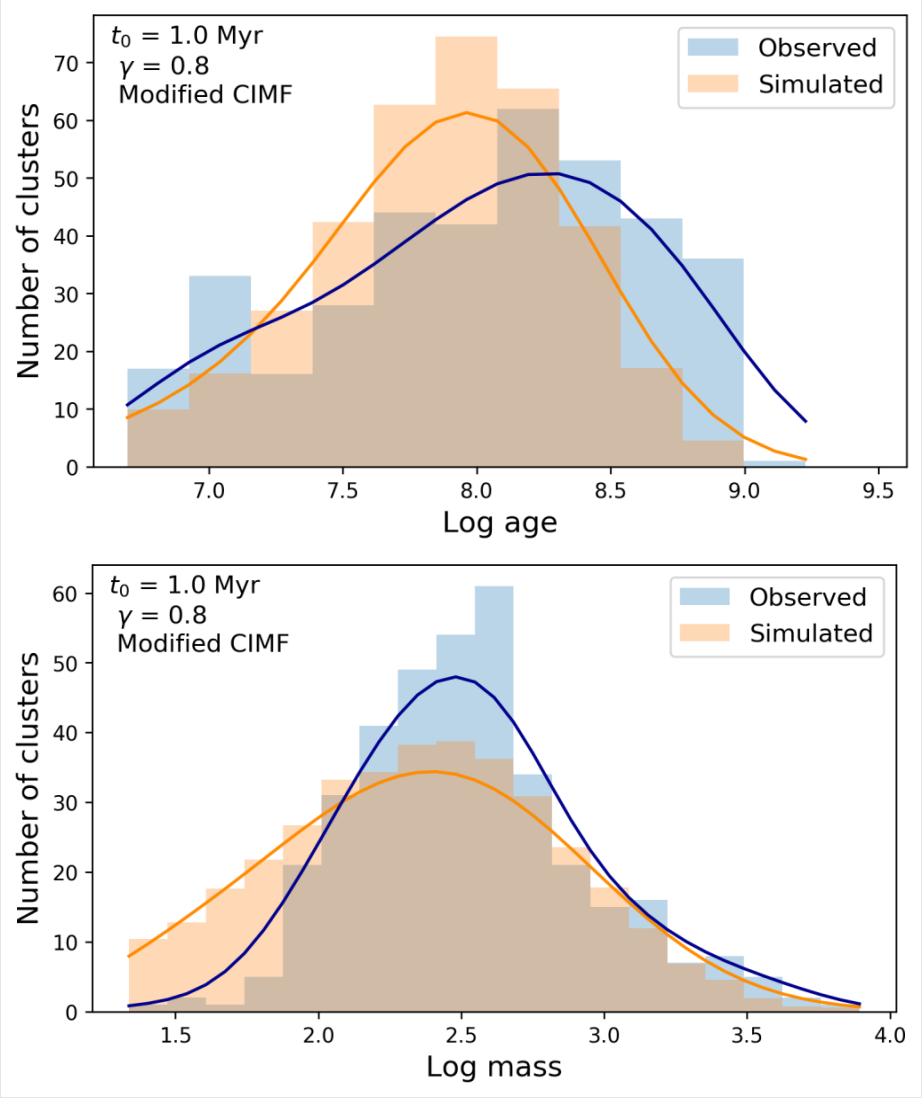

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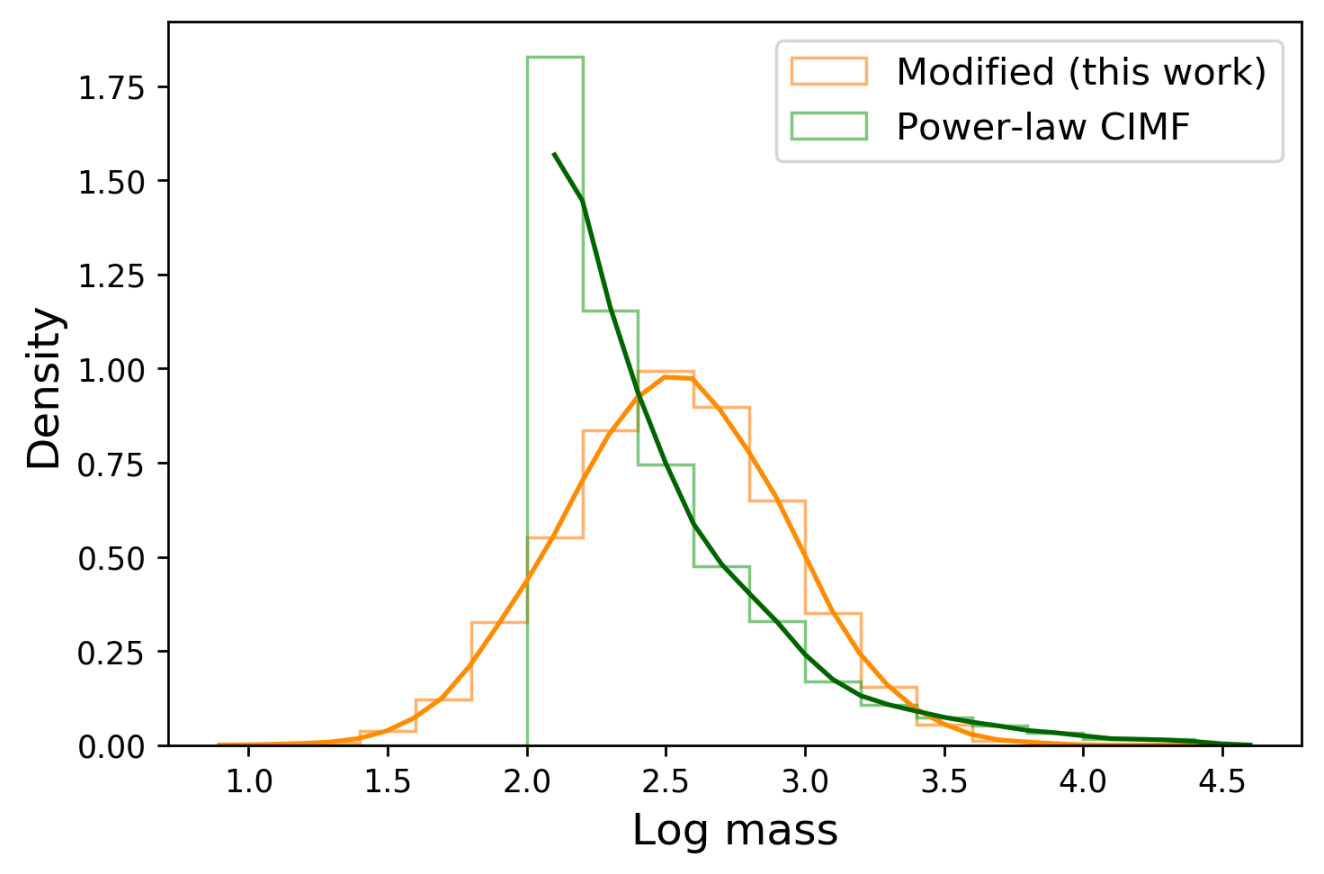
Mass loss simulations – with new CIMF

CIMF = Cluster Initial Mass Function



→ CIMF of embedded OCs might not be the same for non-embedded clusters

This suggests a previously **unexplored mass dependence** associated with the **cluster emergence process**

→ Less clusters of low mass survive the emergence process than expected

Conclusions

- In this study, we built a **Gaia-based mass and radii catalogue of OCs.**
- The **mass and age** distributions were used to **constrain** the **mass loss** in the **solar neighbourhood.**
- Disruption parameters from the **literature do not give good agreement for the mass distributions** so a different Cluster Initial Mass Function might be needed.
- We presented a **modified** Cluster Initial Mass Function which led to a **better agreement** with the observed mass distribution, suggesting a **mass dependence** in the emergence process.

Thank you!

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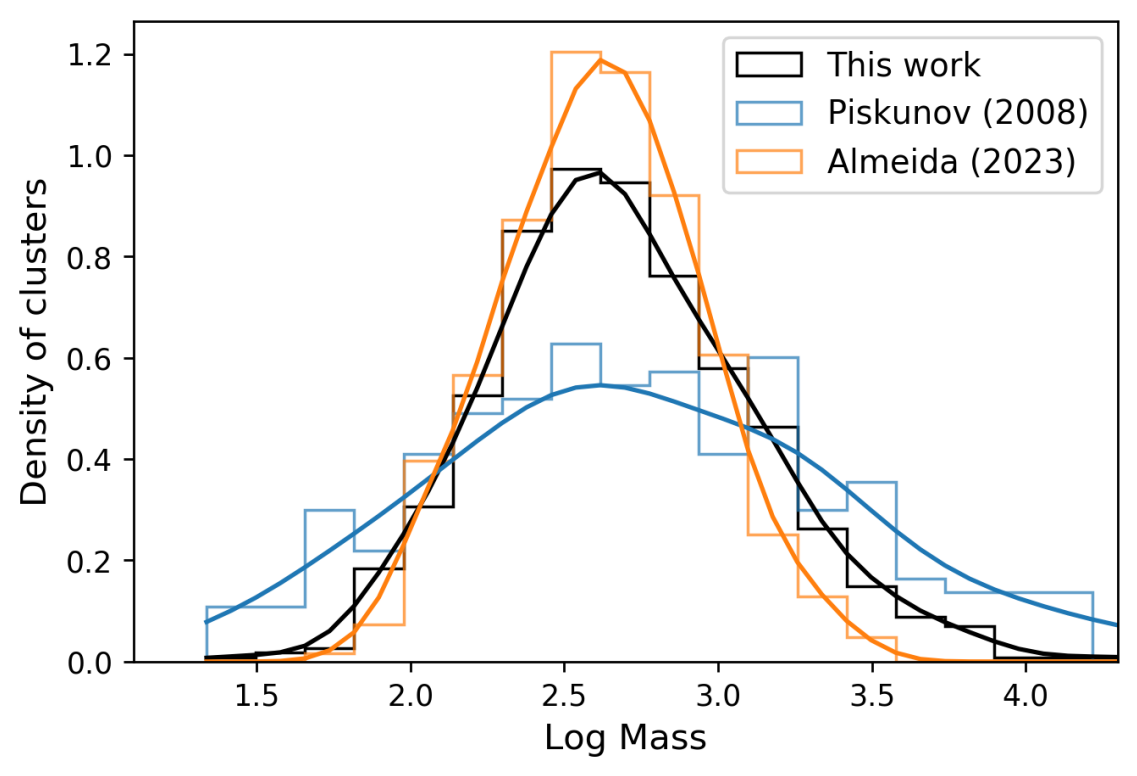
Acknowledgement: This work was supported by the Portuguese Fundação para a Ciência e a Tecnologia (FCT) through the Strategic Programme UIDB/FIS/00099/2020, UIDP/FIS/00099/2020 and UI/BD/154465/2022 for CENTRA.

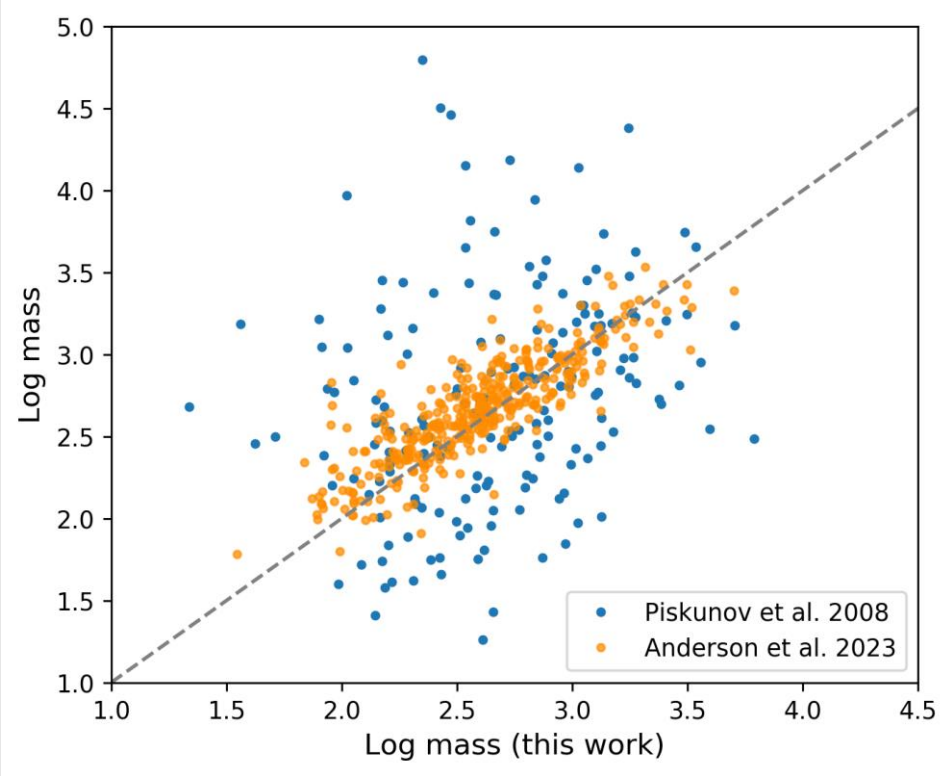
Additional Slides

Mass determinations

Comparison with other catalogues



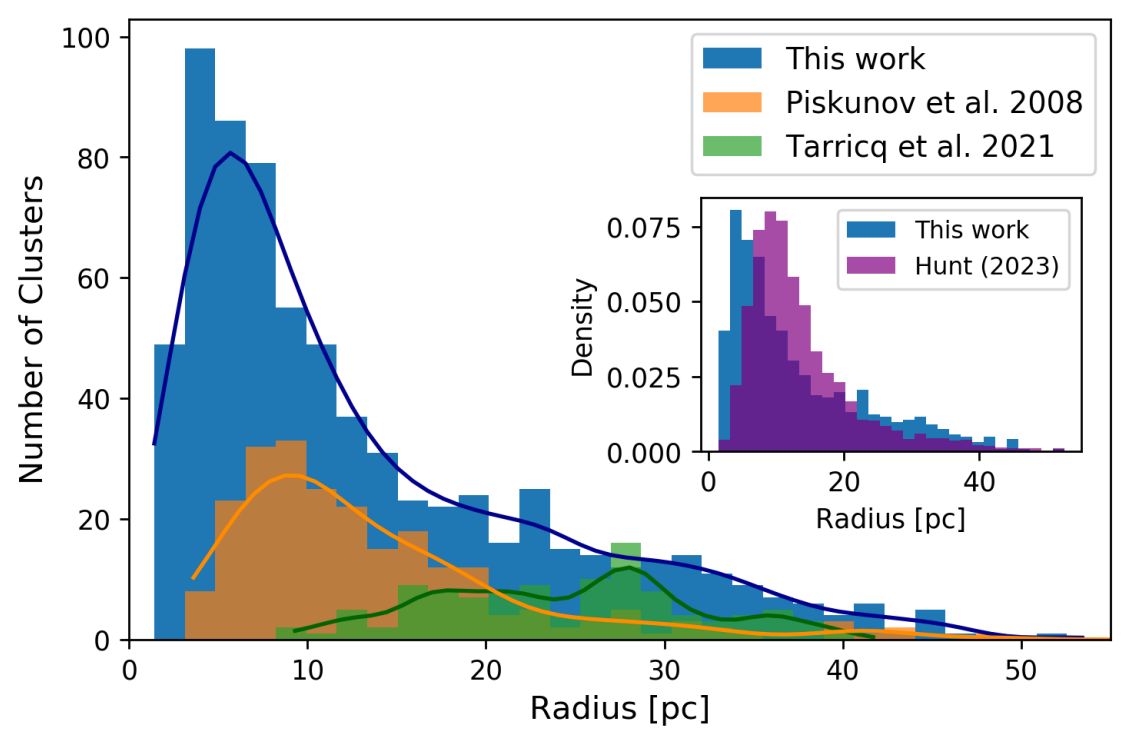
→ **Similar** distribution of **mass** when compared to the catalogues in **literature**

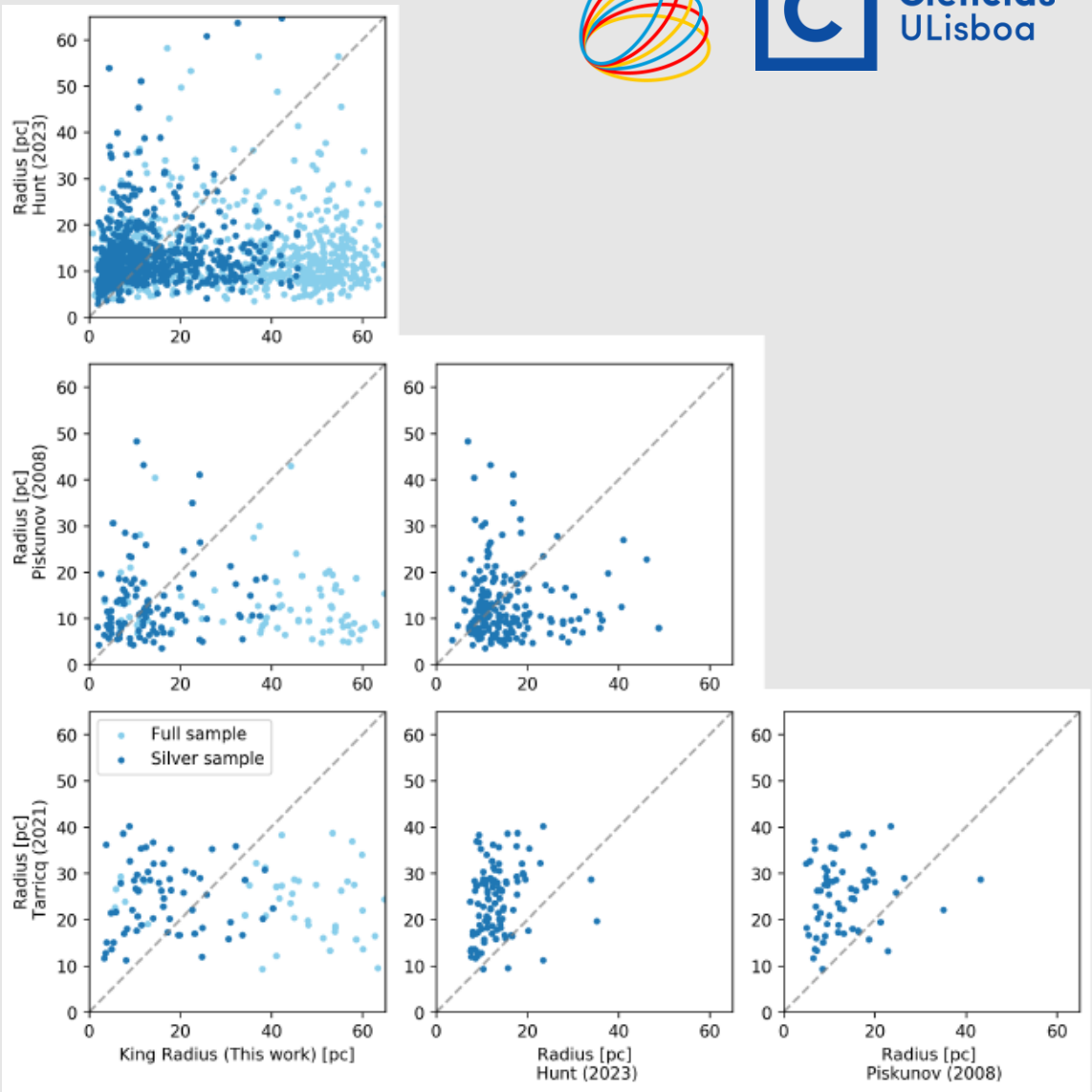


→ The **individual** values are **compatible** with Almeida et al. 2023 which validate the **robustness** of our mass catalogue

Radii determinations

Comparison with other catalogues



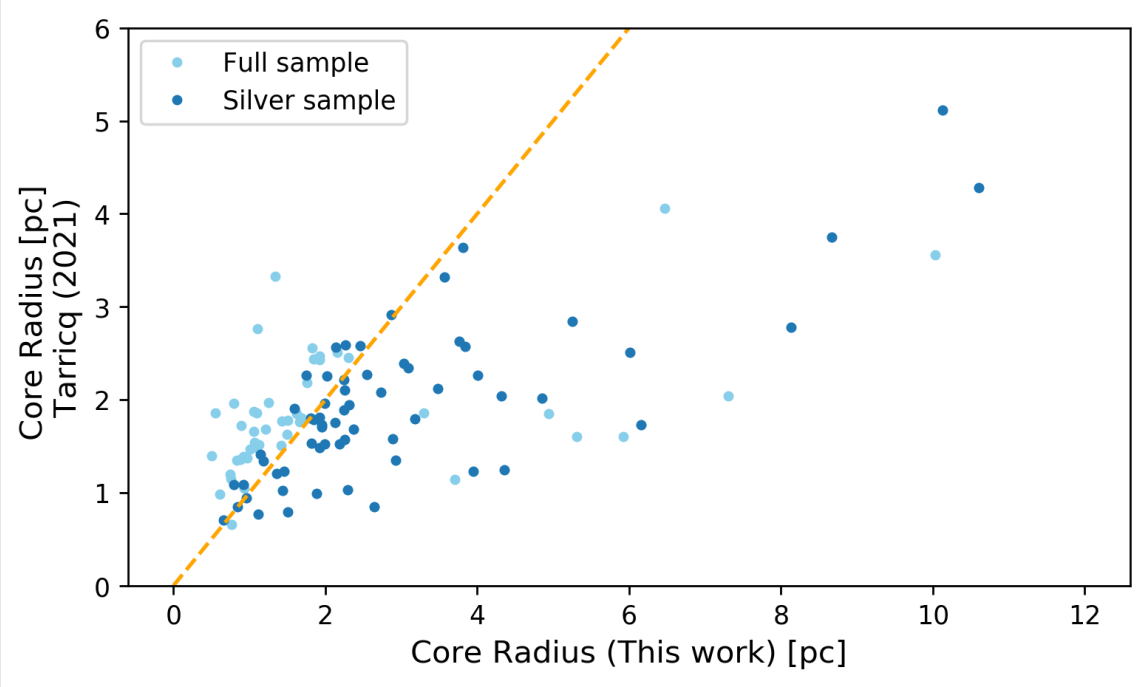


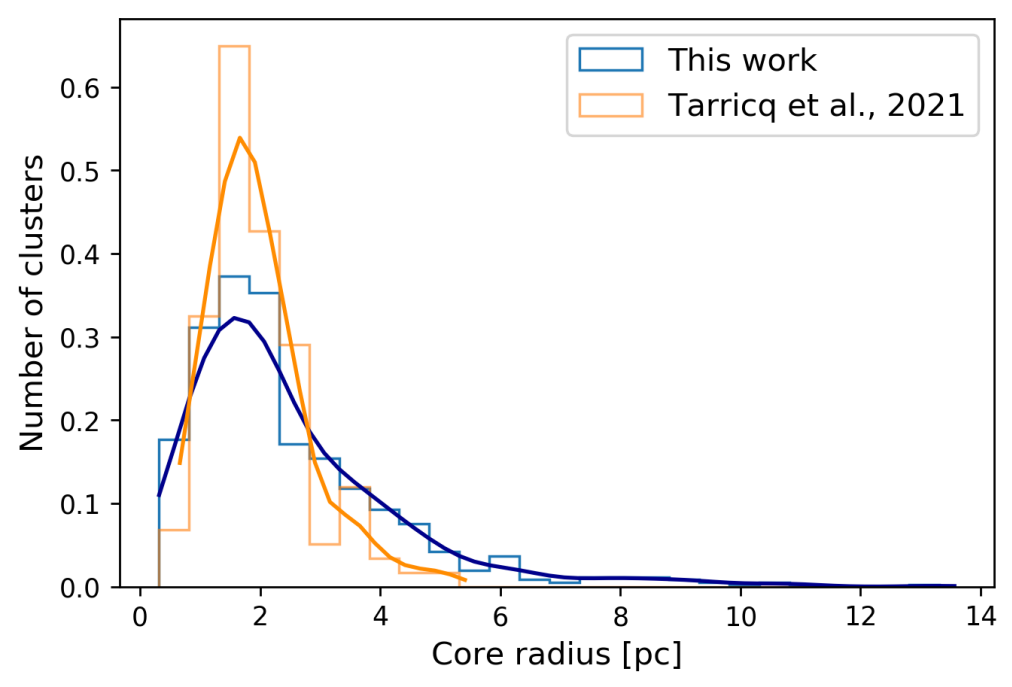
Median lower uncertainty R_{king} = 47%

Median upper uncertainty R_{king} = 95%

Comparison with other studies

Tarricq et al. (2021) reports the determinations of 164 tidal radii and 145 core radii. In our sample, we have 109 OCs in common.





Our method leads to similar values of the **core radius**

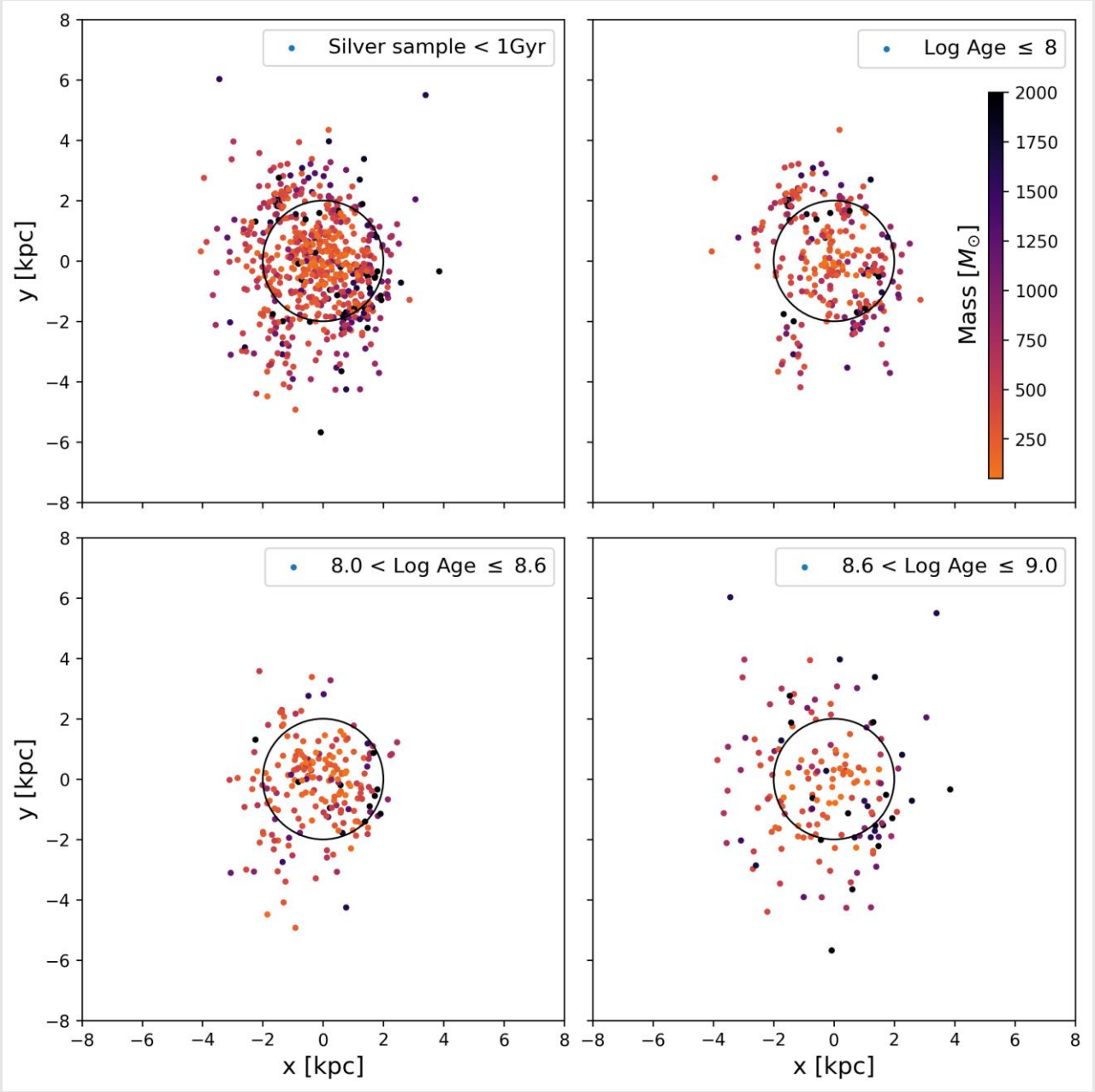
Sample completeness

We separated the clusters by age as young (log(age) ≤ 8), intermediate (8 < log(age) < 8.6) and old clusters (log(age) ≥ 8.6).

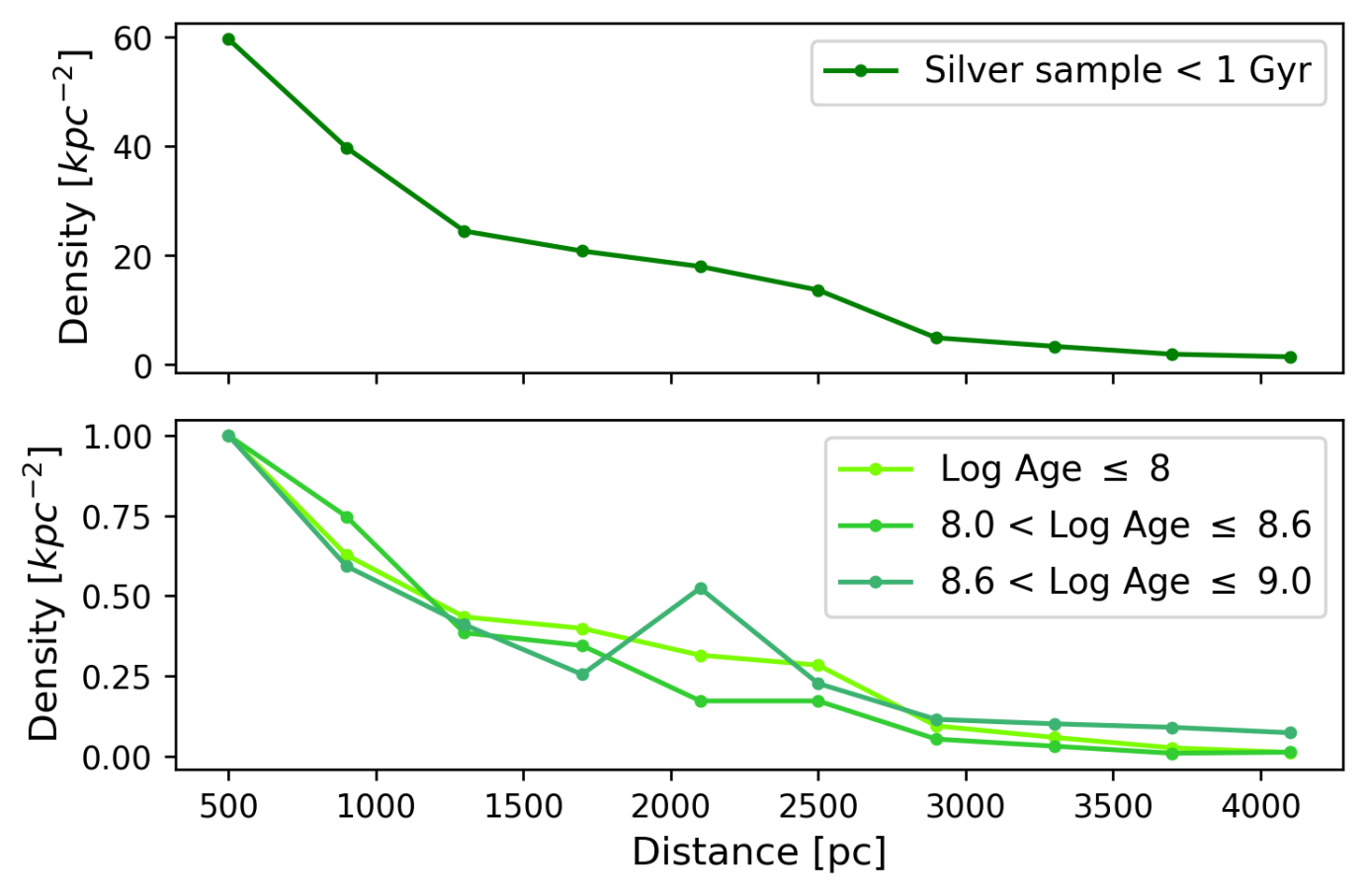
At young ages, the clusters are still clustered near their birthplace in the spiral arms.

At intermediate and higher ages, the structure is less visible and the distribution appears more homogeneous

From the spatial distribution, it is possible to establish a 2 kpc limit after which the distributions are visibly incomplete.



Sample completeness



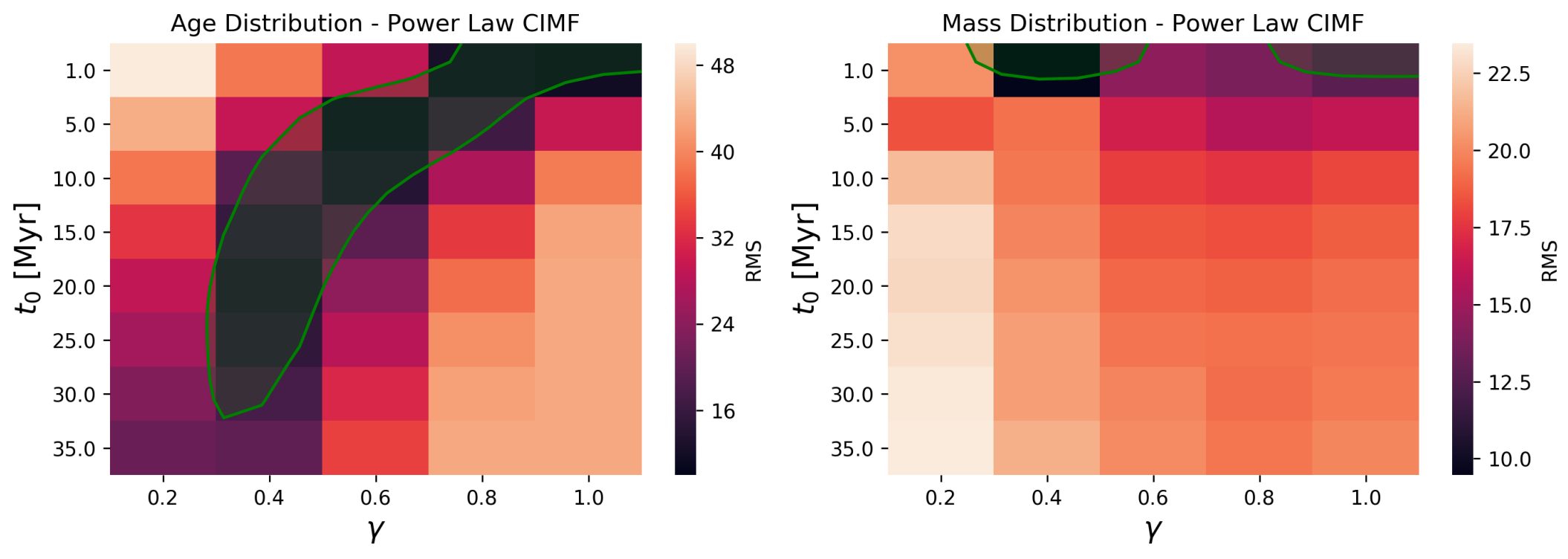
Under the assumption that our position in the Galaxy is not special, the density should remain constant in a complete sample. But, as seen in the plot, the density is not constant and decreases with the distance and this is also verified for the full sample.

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.

Mass loss simulations

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

CIMF = Cluster Initial Mass Function



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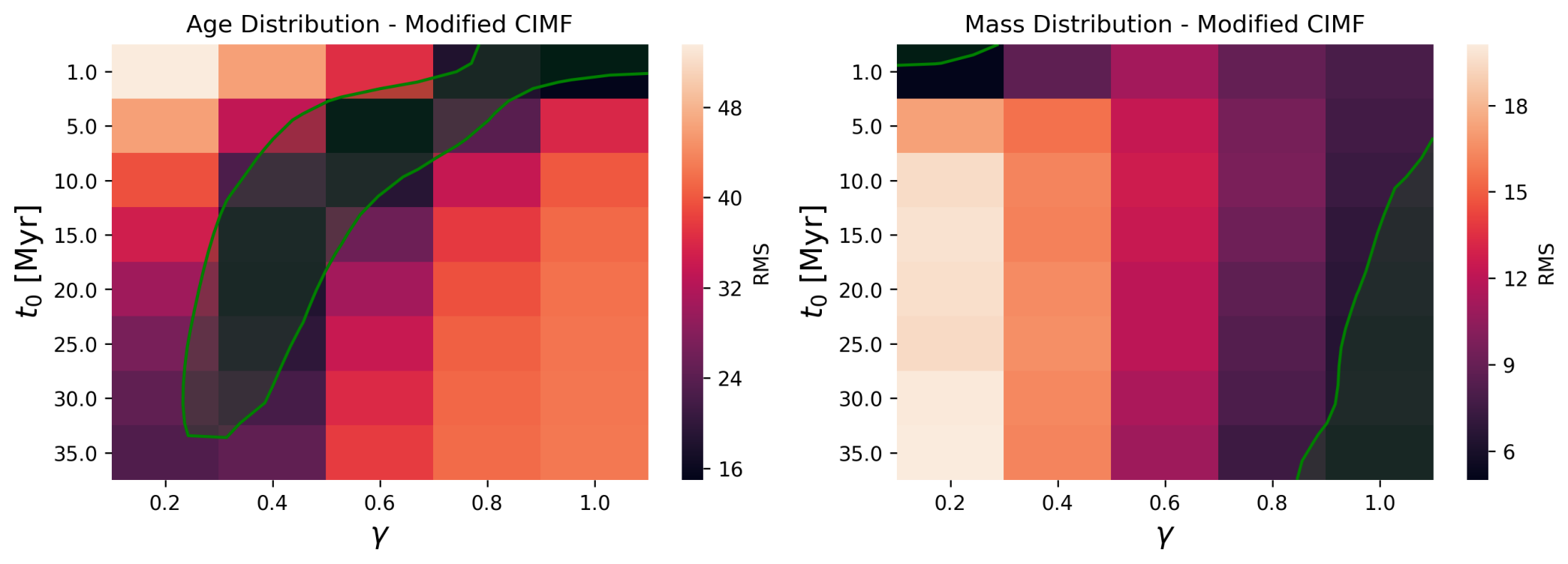

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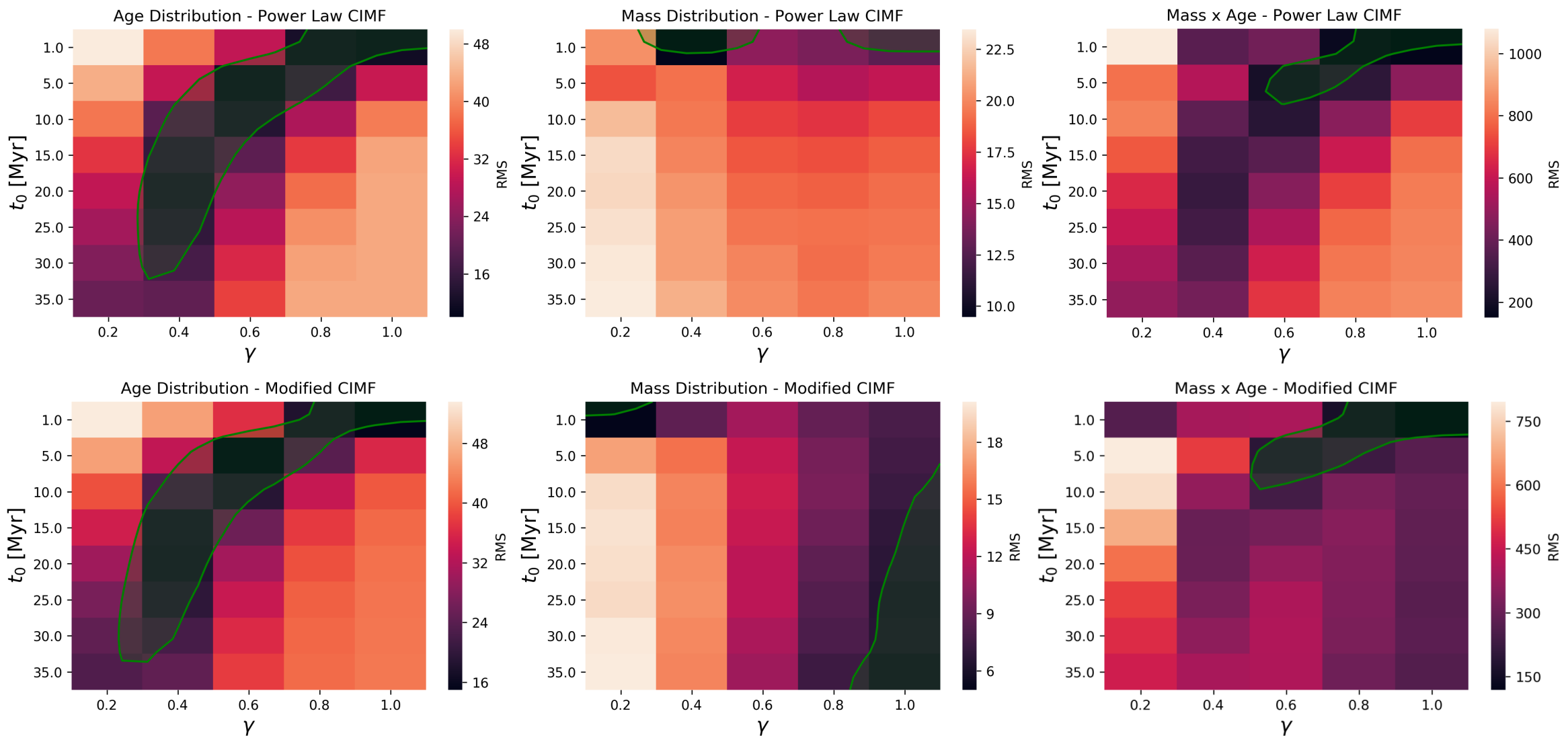
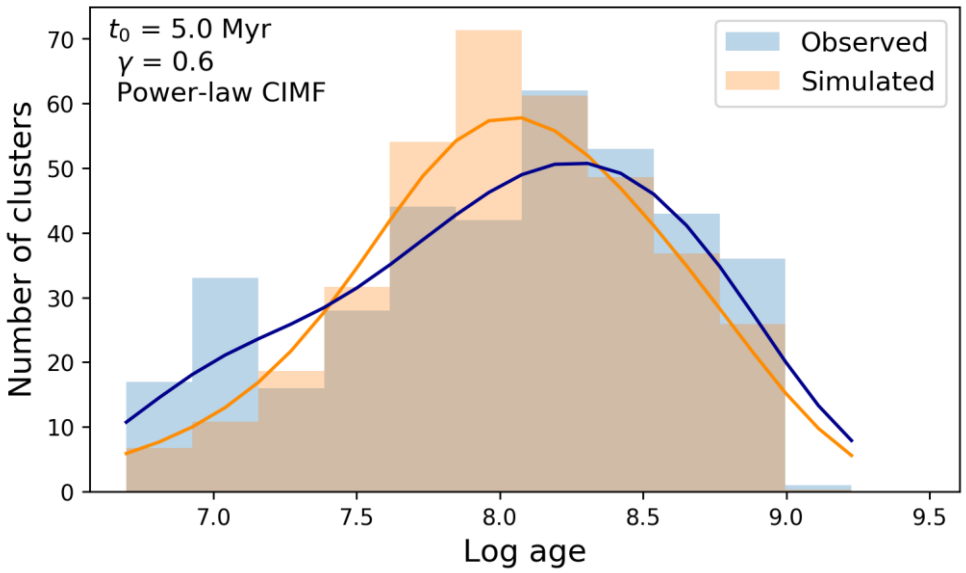
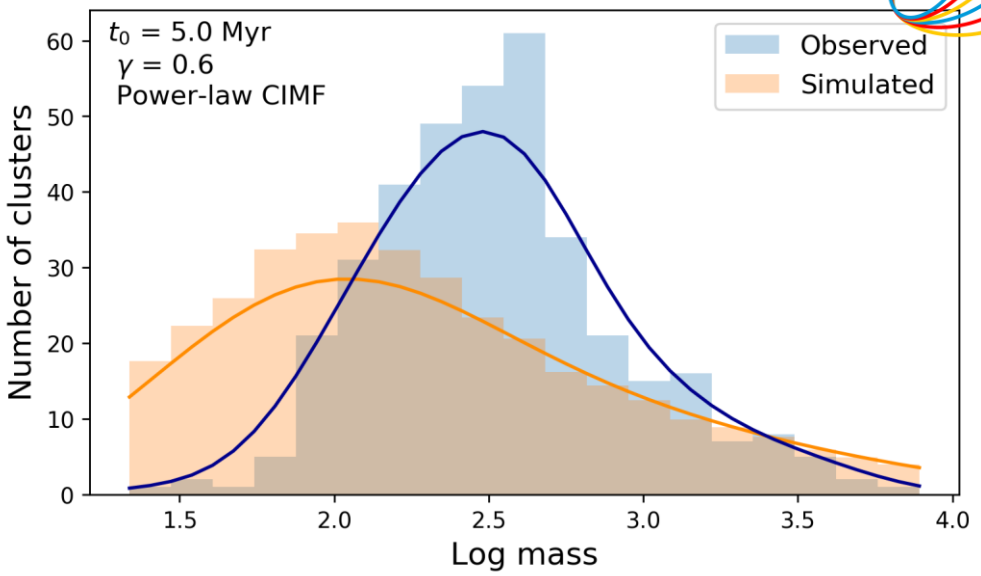
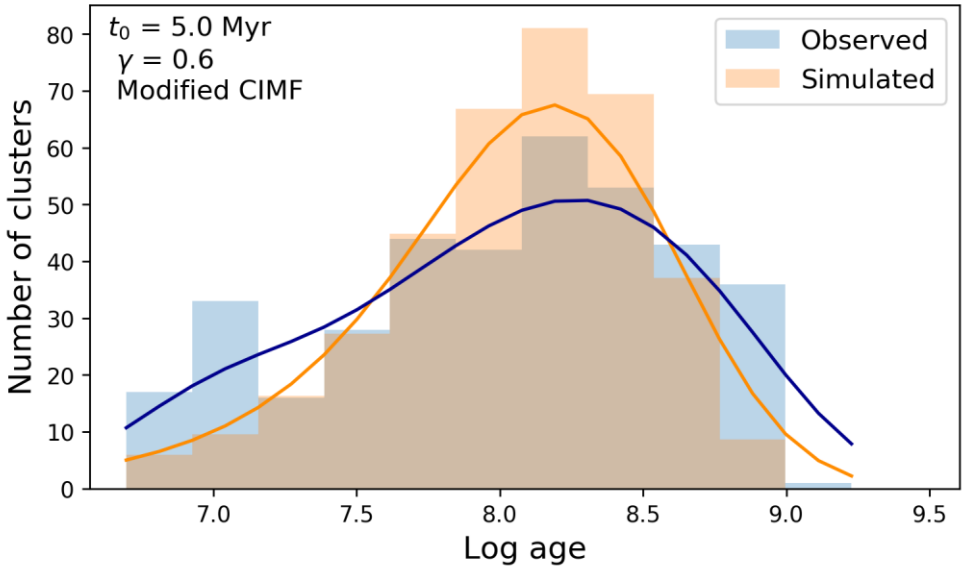
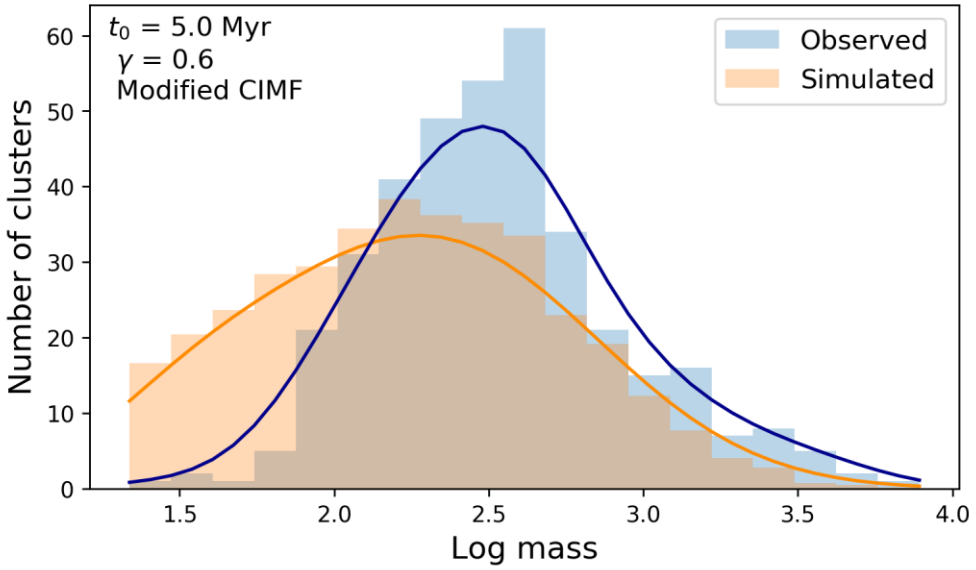


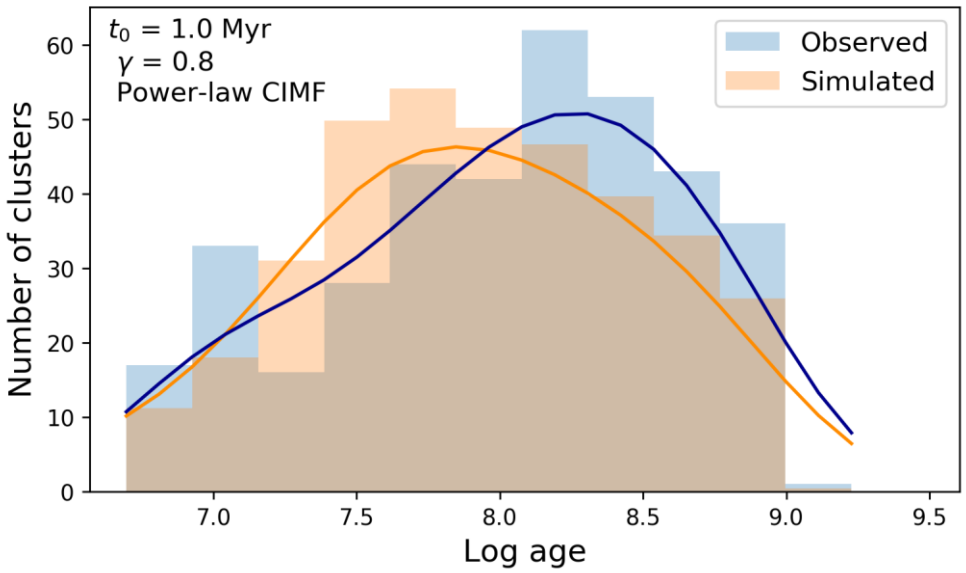


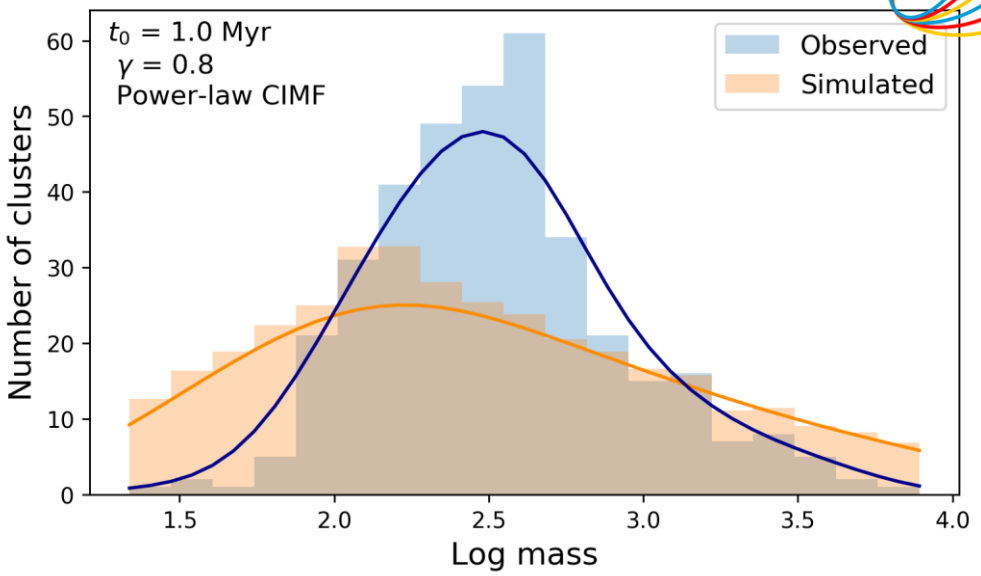


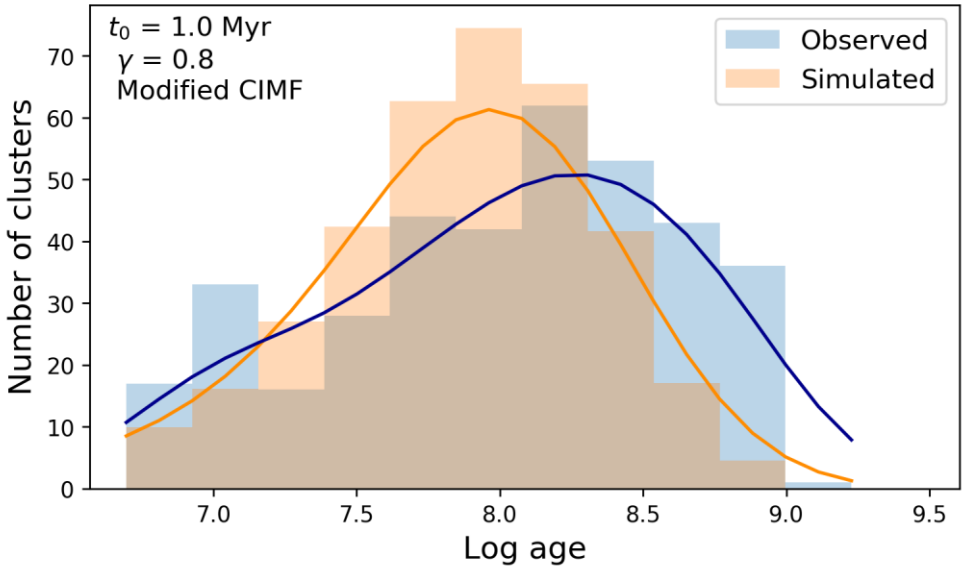


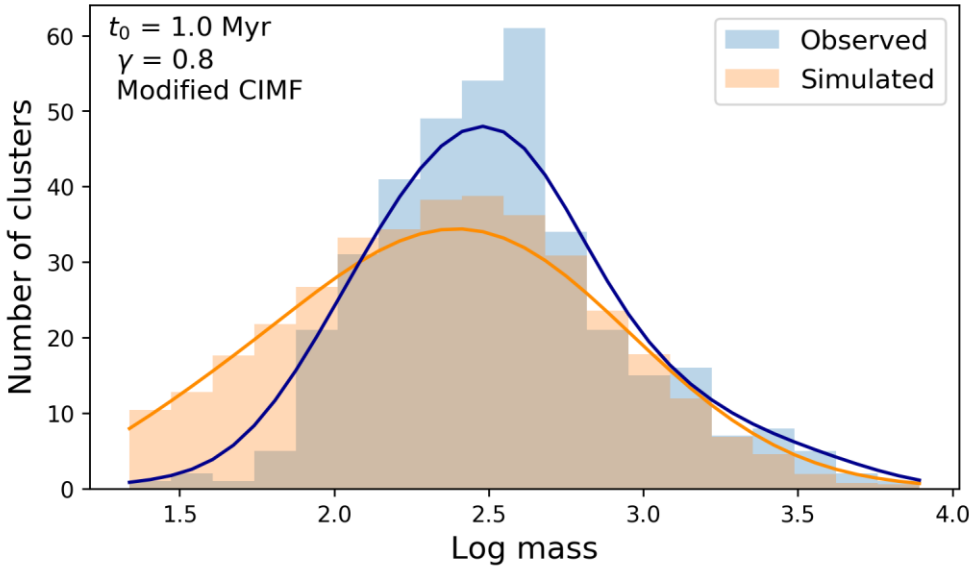


Peak of the simulated masses is **closer** to the observed mass peak!









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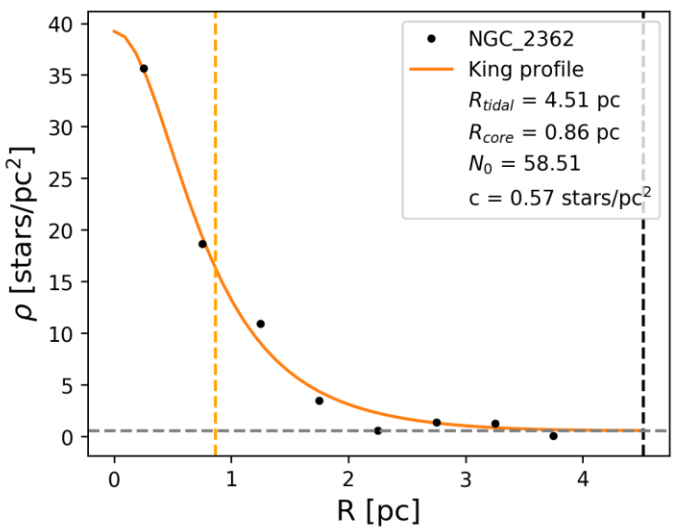
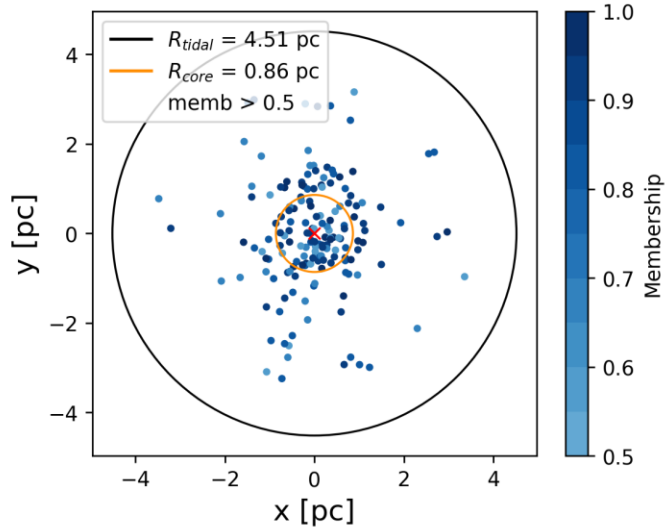
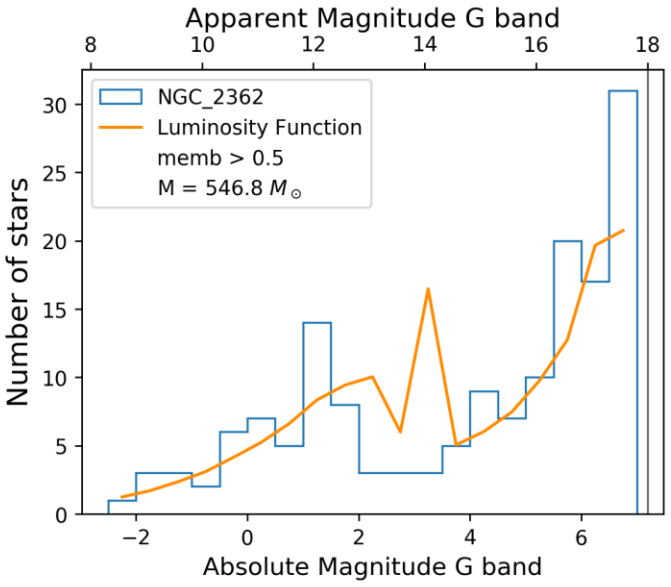
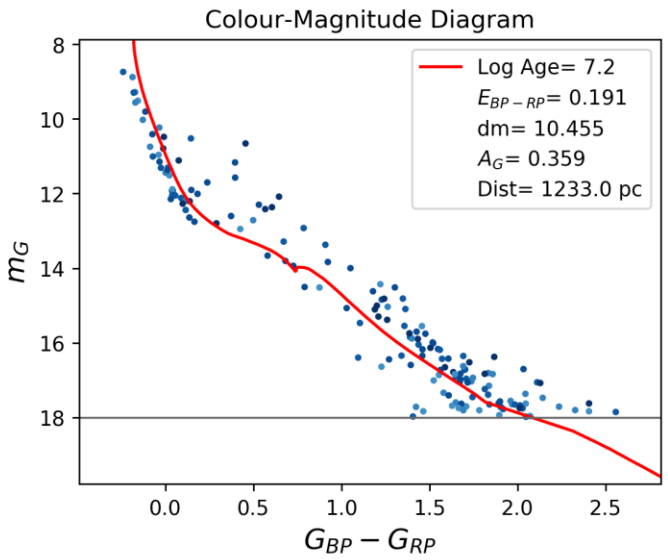
Additional Slides

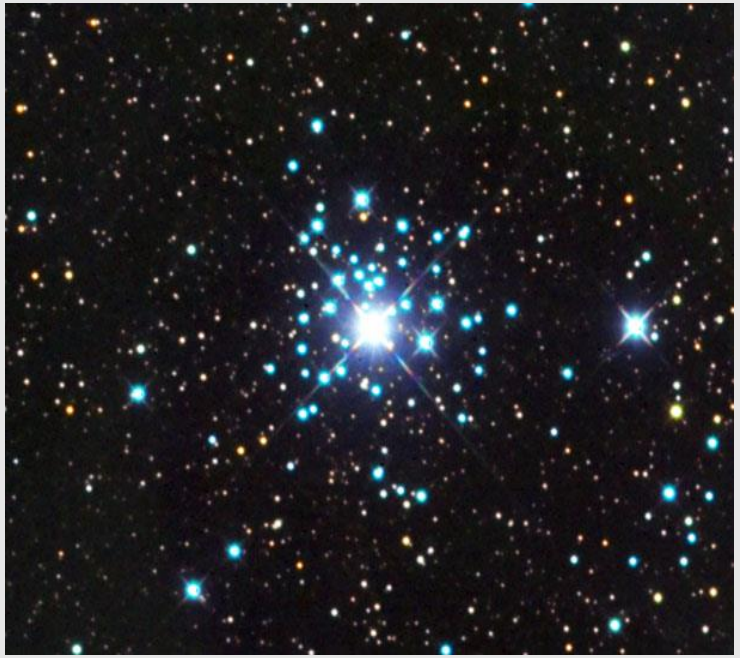




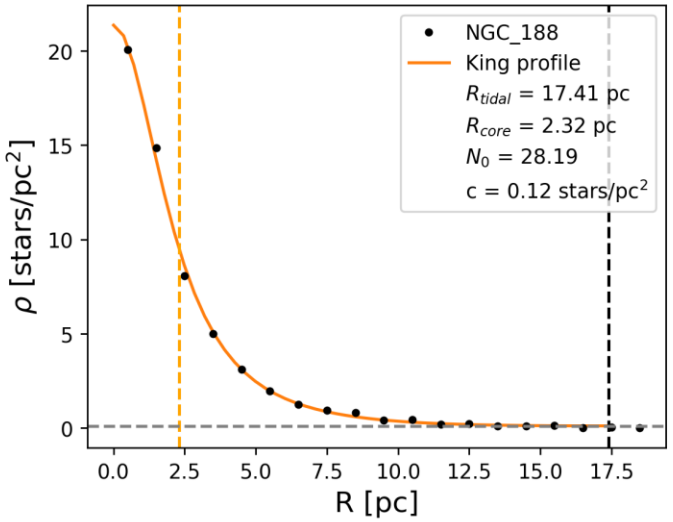


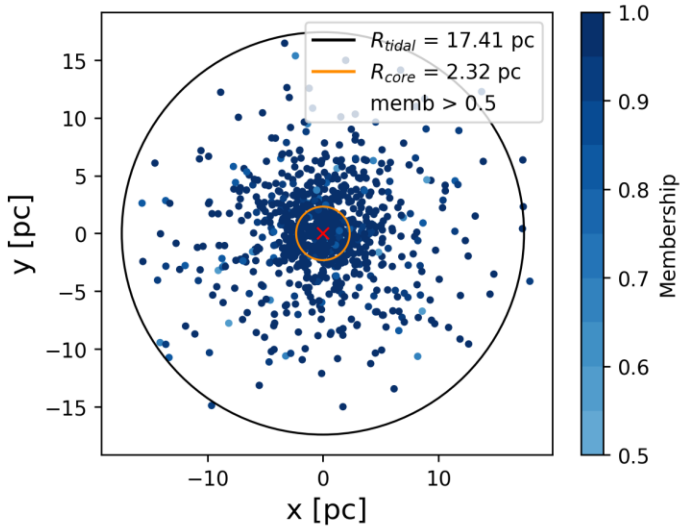


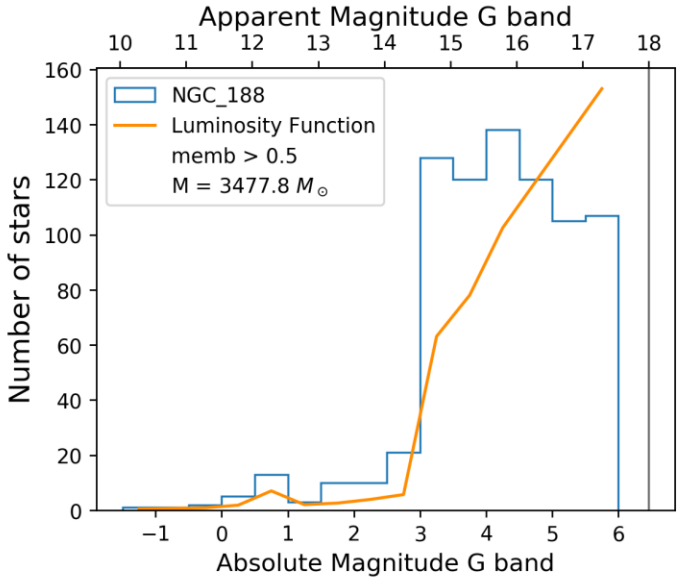
Wide-field view of the sky around the young open cluster NGC 2362

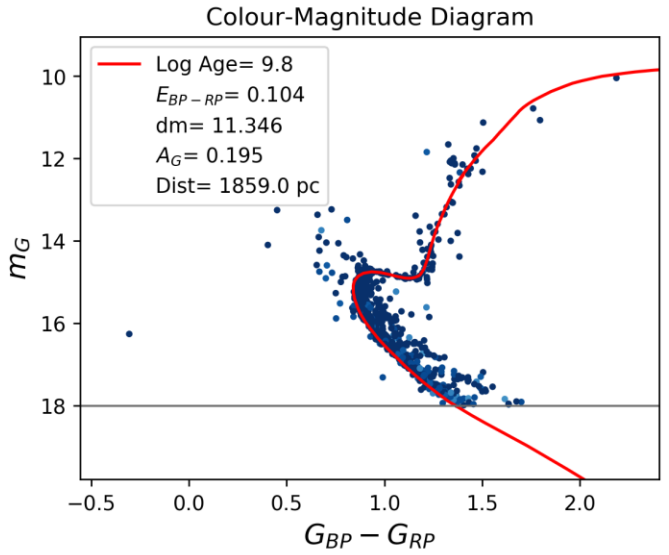


Additional Slides

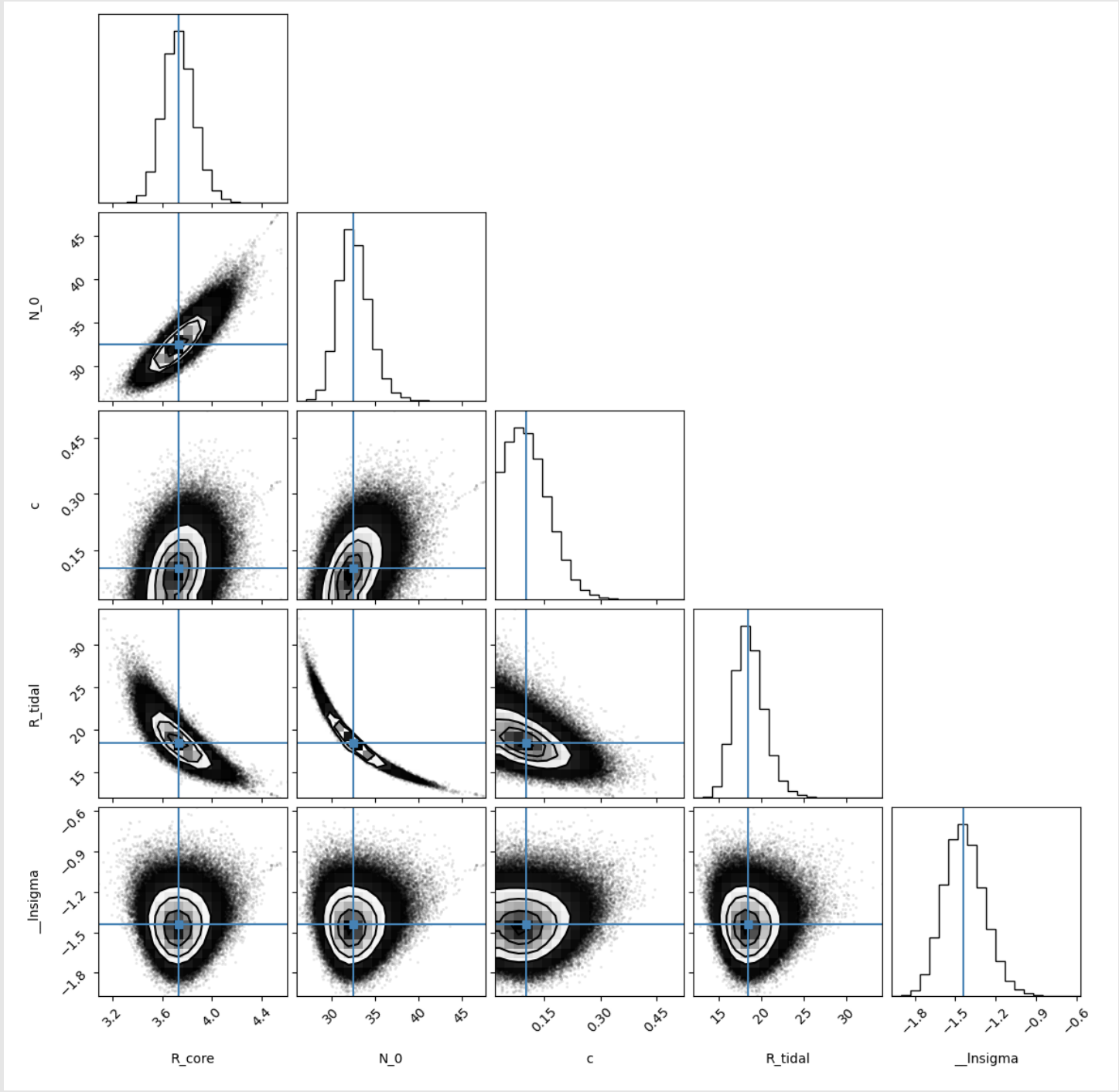








Wide-field view of the sky around the old open cluster NGC 188



Emcee results from NGC 6791
Maximum Likelihood Estimation from emcee

Parameter	MLE	Median	Uncertainty
R_core	3.73000	3.72799	0.12389
N_0	32.5000	32.51427	1.76253
c	0.09000	0.10255	0.05770
R_tidal	18.50000	18.45716	1.73590
__lnsigma	-2.30259	-1.44130	0.14830

Error estimates from emcee

Parameter	-2sigma	-1sigma	median	+1sigma	+2sigma
R_core	-0.2362	-0.1189	3.7280	0.1289	0.2655
N_0	-3.1197	-1.6266	32.5143	1.8994	4.0378
c	-0.0774	-0.0517	0.1026	0.0637	0.1285
R_tidal	-3.0346	-1.6051	18.4572	1.8676	4.0375
__lnsigma	-0.2695	-0.1412	-1.4413	0.1555	0.3137