The star clusters of the Milky Way

Emily L. Hunt | March 4th, 2024 | University of Vienna

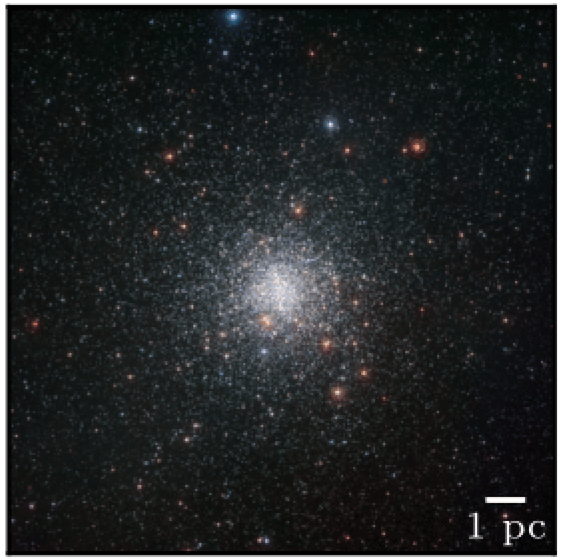
Nomenclature: the Milky Way's star clusters

Open clusters

Bound, $\lesssim 10^4$ $M_{\rm Sun}$, young

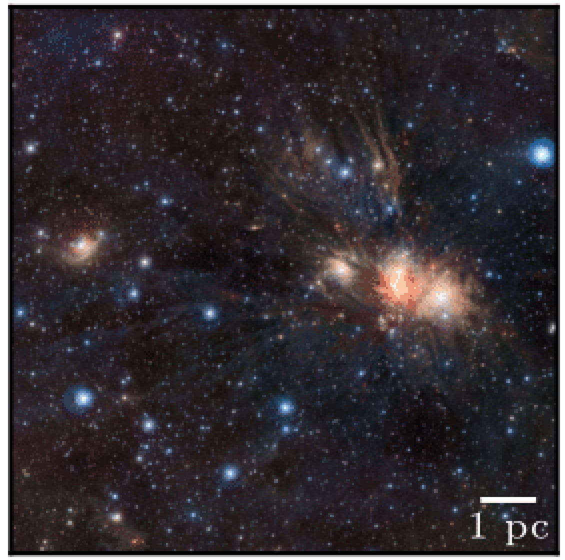
Globular clusters

Bound, $\gtrsim 10^4$ $M_{\rm Sun}$, old

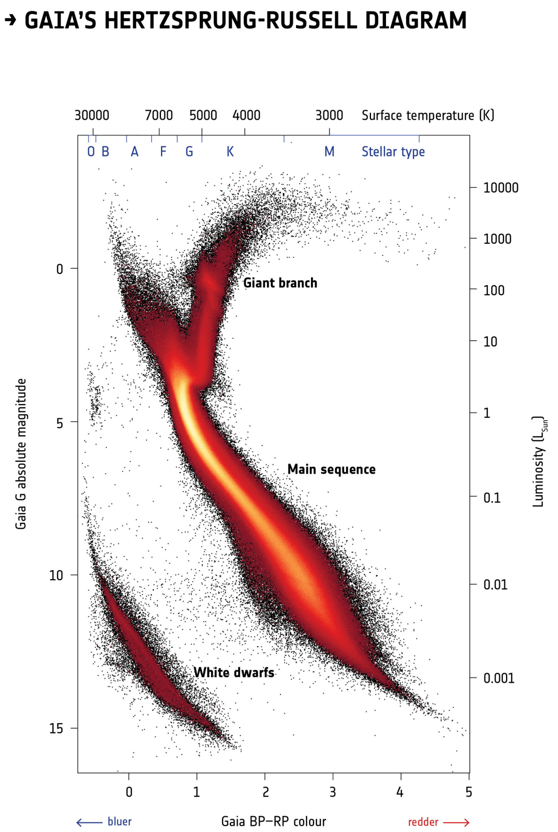


Associations / moving groups

Unbound, $\lesssim 10^3$ $M_{\rm Sun}$, young

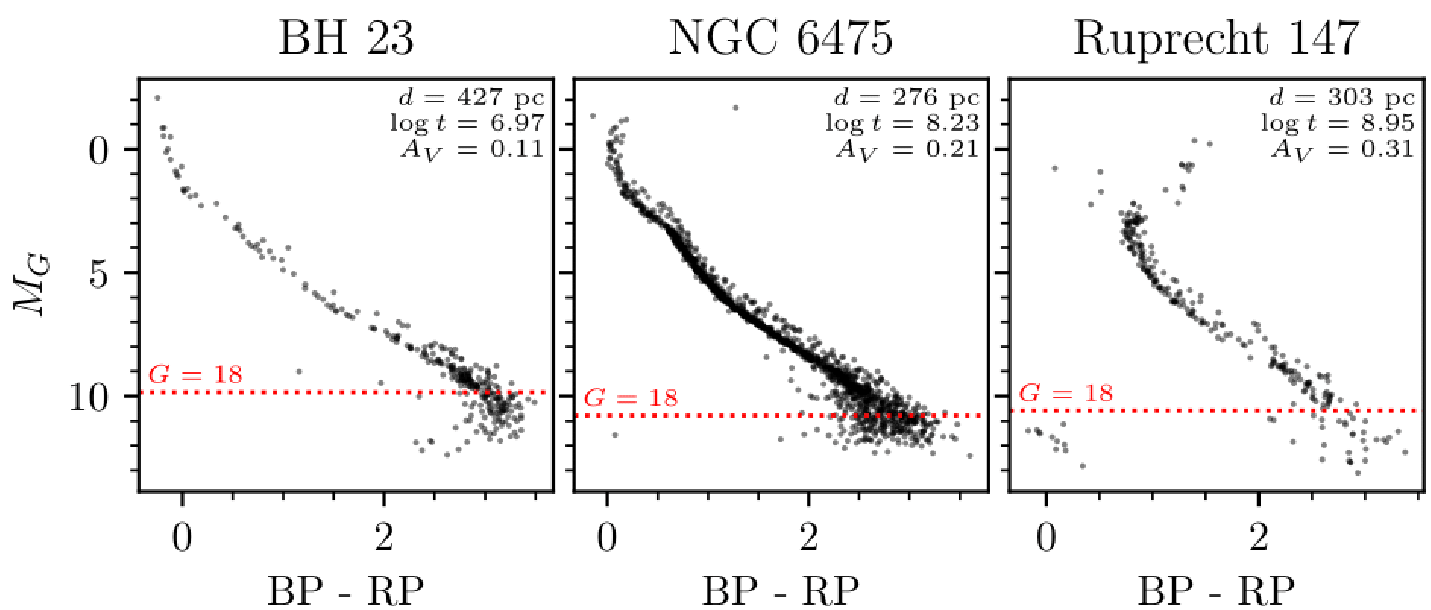


Why they're extremely useful



Gaia DR2 Hertzsprung-Russell diagram (Credit: Gaia Collaboration+18)

Stars in clusters formed at the **same time** from the **same material**



The Milky Way Cepheid Leavitt law based on Gaia DR2 parallaxes of companion stars and host open cluster populations

Louise Breuval[1], Pierre Kervella[1], Richard I. Anderson[2], Adam G. Riess[3,4], Frédéric Arenou[5], Boris Trahin[1], Antoine Mérand[2], Alexandre Gallenne[6,7,8,9], Wolfgang Gieren[7], Jesper Storm[10], Giuseppe Bono[11,12], Grzegorz Pietrzyński[7,8], Nicolas Nardetto[6], Behnam Javanmardi[1], Vincent Hocdé[6]

How Do Disks and Planetary Systems in High-mass Open Clusters Differ from Those around Field Stars?

Kirsten Vincke and Susanne Pfalzner

Don't just take my word for it...

Painting a portrait of the Galactic disc with its stellar clusters ★

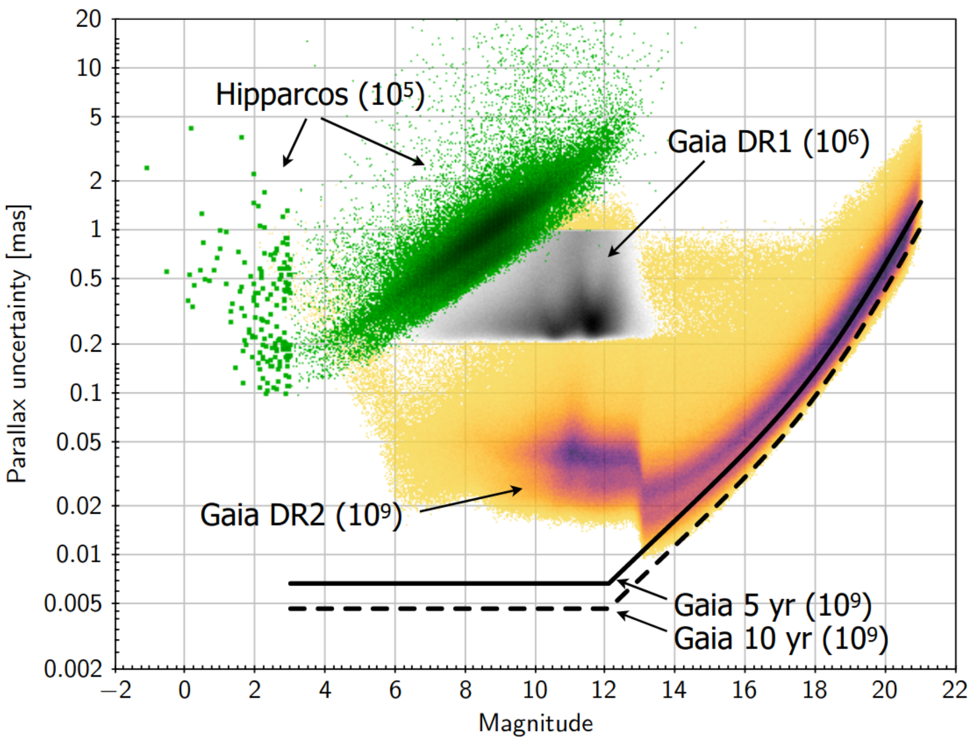
T. Cantat-Gaudin[1], F. Anders[1], A. Castro-Ginard[1], C. Jordi[1], M. Romero-Gómez[1], C. Soubiran[2], L. Casamiquela[2], Y. Tarricq[2], A. Moitinho[3], A. Vallenari[4], A. Bragaglia[5], A. Krone-Martins[3,6], and M. Kounkel[7]

The Gaia-ESO survey: Calibrating a relationship between Age and the [C/N] abundance ratio with open clusters★

G. Casali[1,2], L. Magrini[2], E. Tognelli[3,4], R. Jackson[5], R. D. Jeffries[5], N. Lagarde[6], G. Tautvaišienė[7], T. Masseron[8,9], S. Degl'Innocenti[3,4], P. G. Prada Moroni[3,4], G. Kordopatis[10], E. Pancino[2,11], S. Randich[2], S. Feltzing[12], C. Sahlholdt[12], L. Spina[13], E. Friel[14], V. Roccatagliata[2,4], N. Sanna[2], A. Bragaglia[15], A. Drazdauskas[7], Š. Mikolaitis[7], R. Minkevičiūtė[7], E. Stonkutė[7], Y. Chorniy[7], V. Bagdonas[7], F. Jimenez-Esteban[16], S. Martell[17,18], M. Van der Swaelmen[2], G. Gilmore[19], A. Vallenari[20], T. Bensby[12], S. E. Koposov[21], A. Korn[22], C. Worley[19], R. Smiljanic[23], M. Bergemann[24], G. Carraro[25], F. Damiani[26], L. Prisinzano[26], R. Bonito[26], E. Franciosini[2], A. Gonneau[19], A. Hourihane[19], P. Jofre[27], J. Lewis[19], L. Morbidelli[2], G. Sacco[2], S. G. Sousa[28], S. Zaggia[20], A. C. Lanzafame[29], U. Heiter[30], A. Frasca[31], A. Bayo[32]

Gaia's impact

Launched in 2013, Gaia is measuring **astrometry** and **photometry** for stars in the Milky Way.



Credit: Lindegren+18

Its accuracy is really incredible!

- ~10^9 stars
- At least 40$\times$ the accuracy
- Down to magnitude ~21

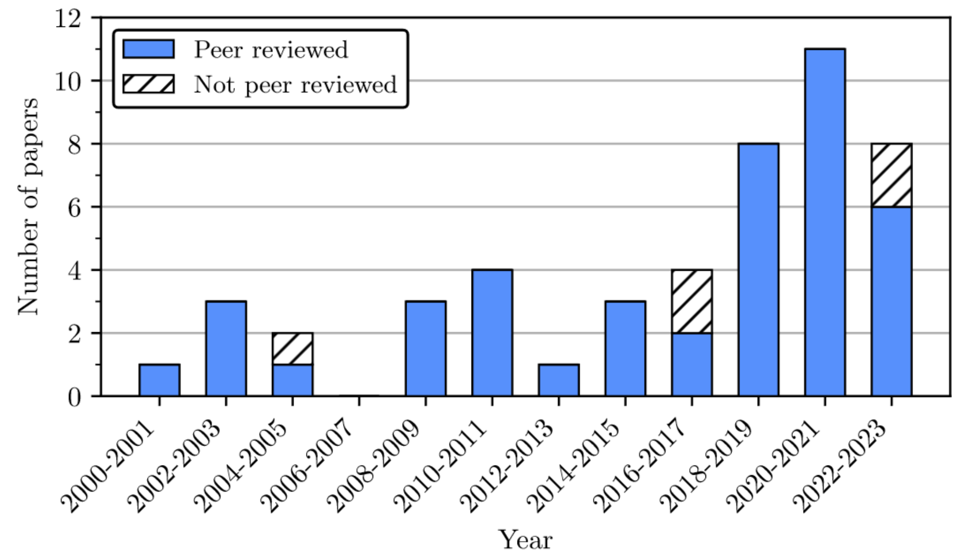
How many stars is that?

How many stars is that?

But there's a catch...

There are many **difficulties** when trying to work with star clusters:

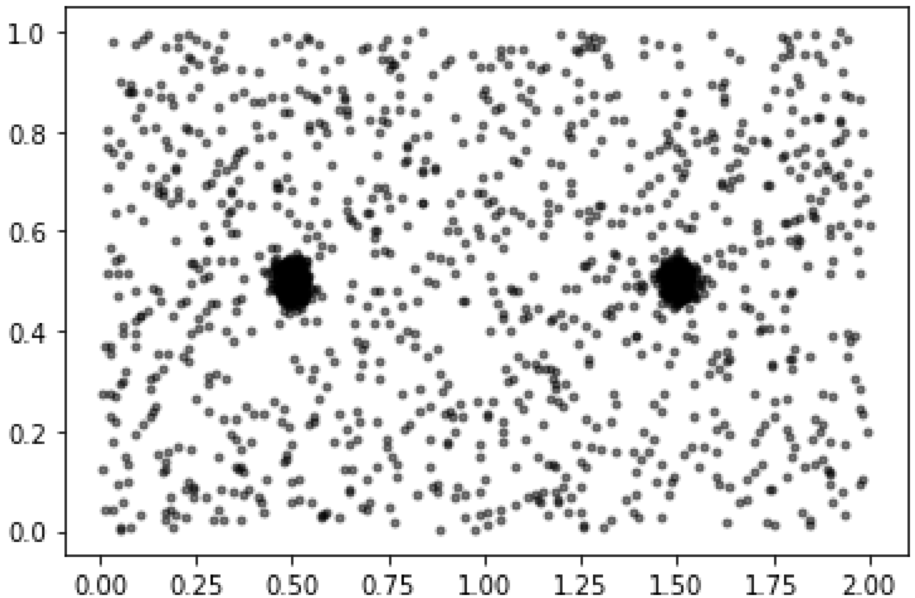
1. No perfect algorithm to recover clusters
2. "Invisible" clusters from **before** Gaia
   ~50% of clusters are missing!
3. Clusters reported **with** Gaia
   many duplicates + how many are real?
4. The completeness of the census
5. How to even **define** an open cluster!



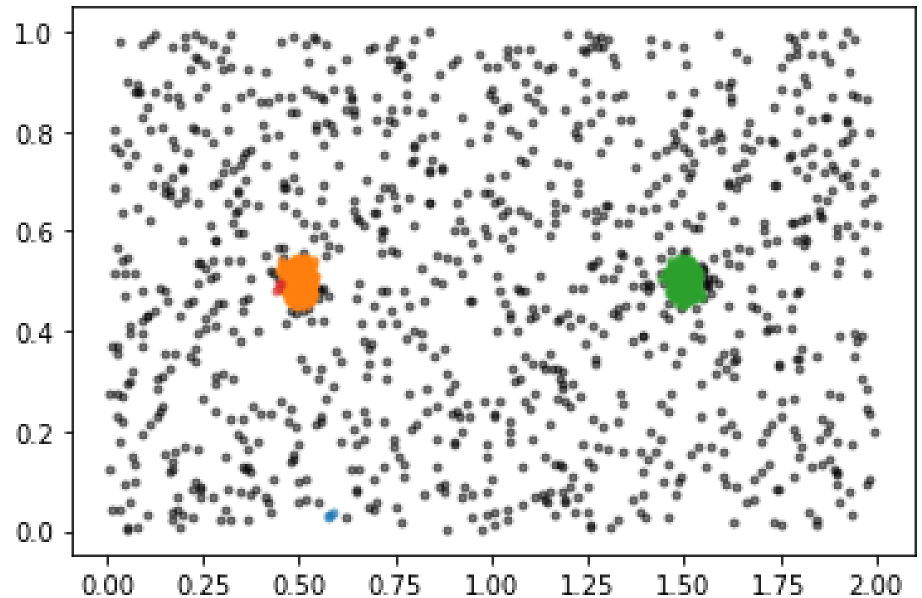
Papers reporting new open clusters. Gaia DR2 was released in 2018.

Clustering algorithms

Clustering algorithms use **user-defined parameters** to extract **clusters** from data. There are many of them!



A 'toy' 2D dataset



After applying DBSCAN

HDBSCAN was best!

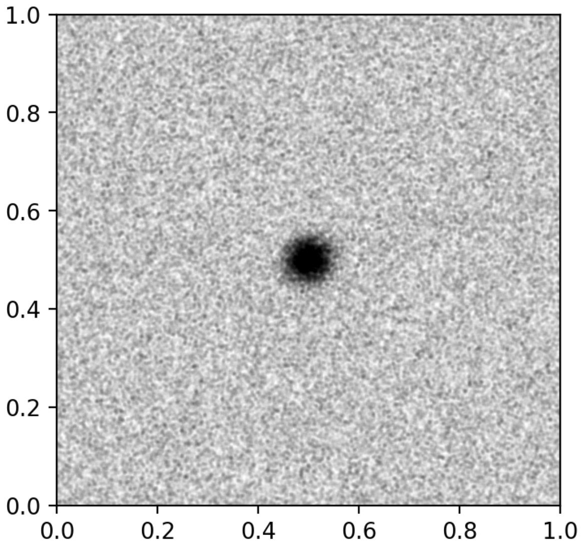
I tried multiple different algorithms

HDBSCAN was the most **sensitive**

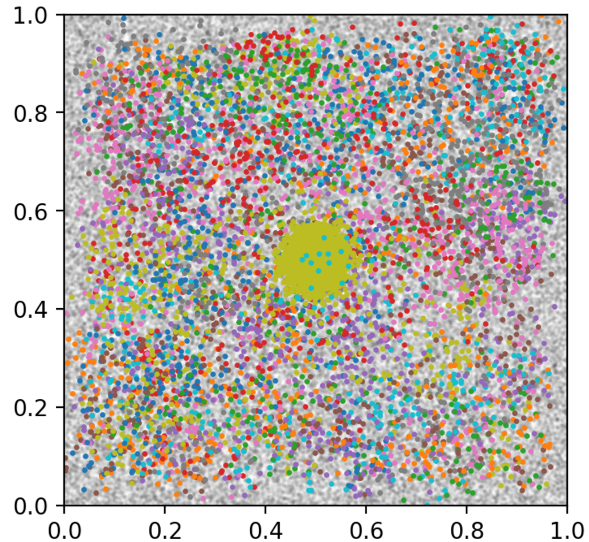
Sadly, it also reported the most false positives...

The false positive problem

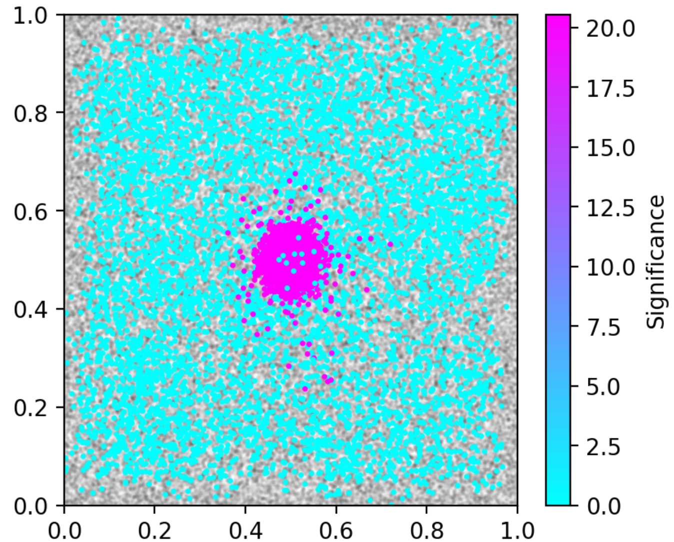
However, HDBSCAN is **unusable** without an extra step to remove false positives:



Toy 3D dataset



After applying HDBSCAN clustering



With cluster significance test shading

Creating an all-sky catalogue

Recall: unknown how many literature clusters are real & census has unknown completeness

The solution? **An all-sky catalogue!**

HDBSCAN most sensitive $\Longrightarrow$ should get good results!

The setup

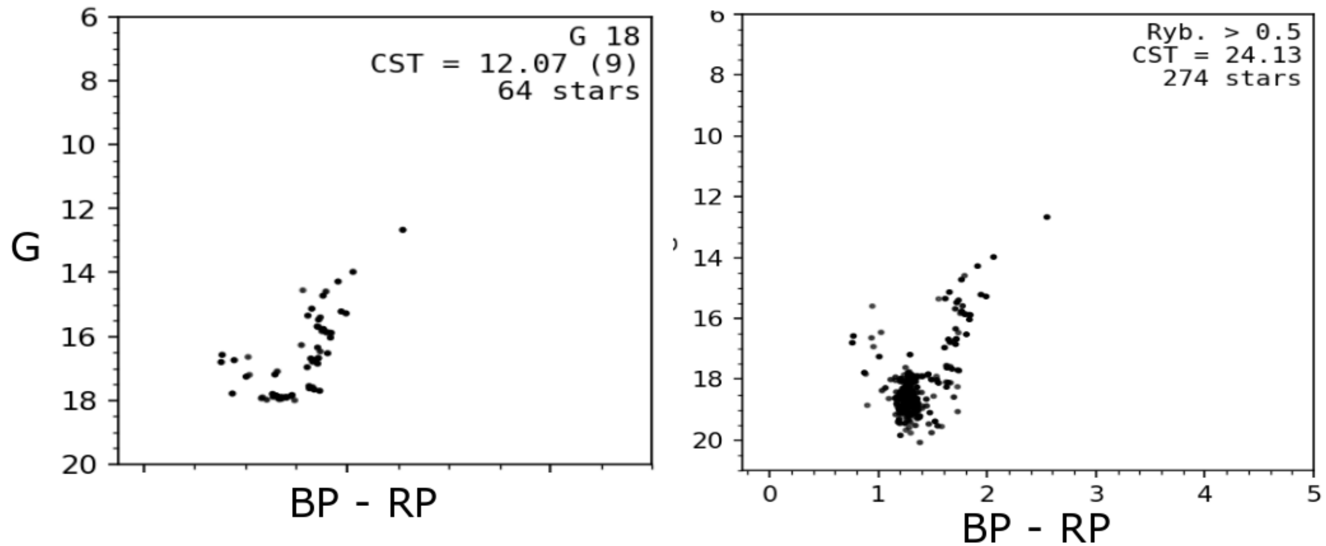
Performed clustering in three different distance ranges, totalling almost **13000** different fields

The goal: recover **greater than 99%** of clusters with signal to noise ratios over 3σ

Add-on: more stars

Many stars in Gaia fainter than G=18 are still usable - I included all stars with Rybizcki+21 classification over 0.5

Total of **729 million** stars (largest ever Gaia clustering analysis)

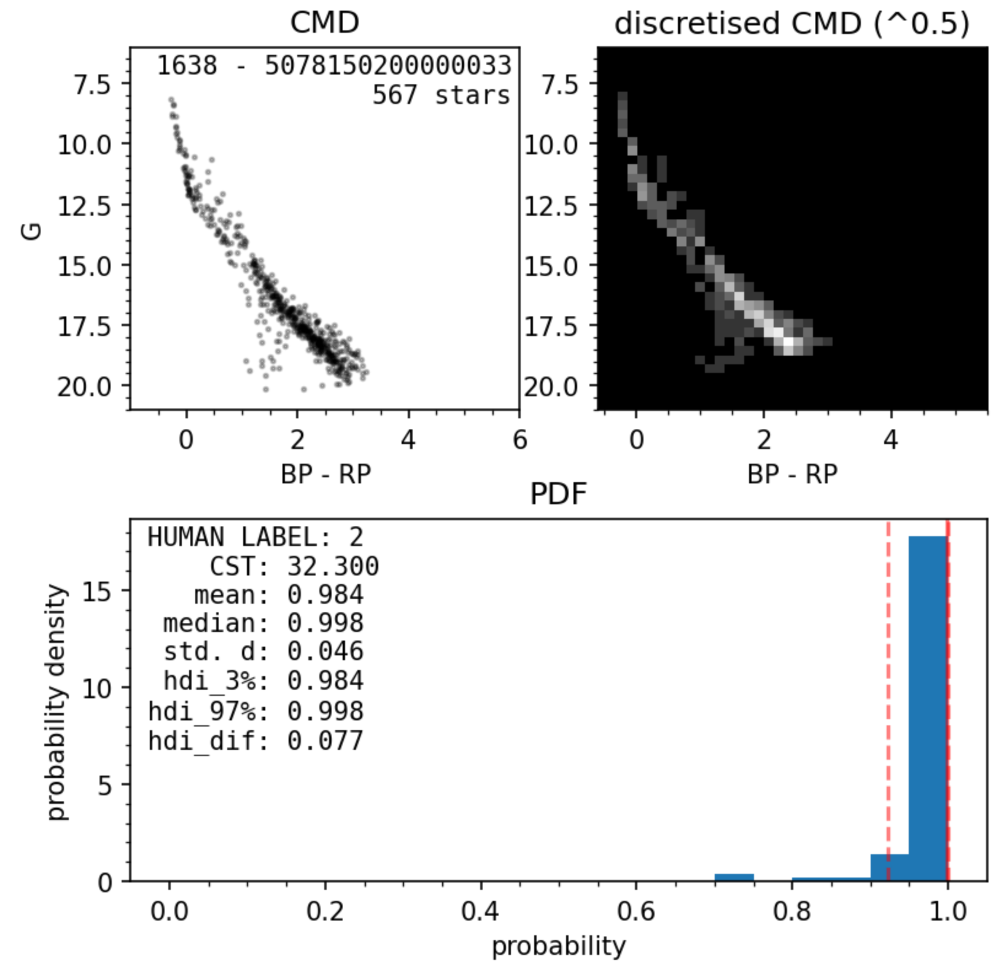


King 9, without (left) and with (right) these extra stars

Add-on: cluster classifications

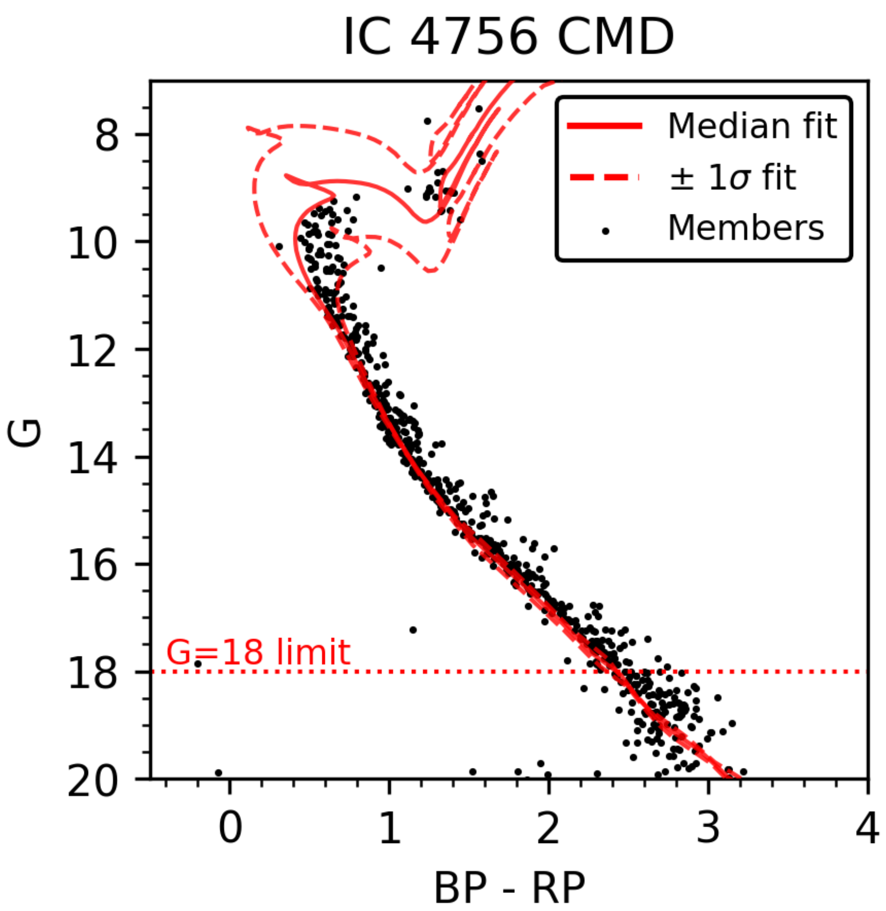
Cluster **colour-magnitude diagrams** (CMDs) are a useful indicator of the quality of a cluster

I used an **approximate Bayesian neural network** to classify cluster CMDs



CMD classification for a candidate cluster

Add-on: cluster photometric parameters



Isochrone fit for to IC 4756

I also made a similar network to infer **photometric parameters** (age, extinction, photometric distance)


All in all: we go from this...

... to this!

- **7169 clusters** (4105 highly reliable)
- **2387 new clusters** (739 highly reliable)
- Plus many extras…

We accidentally detected tidal tails!

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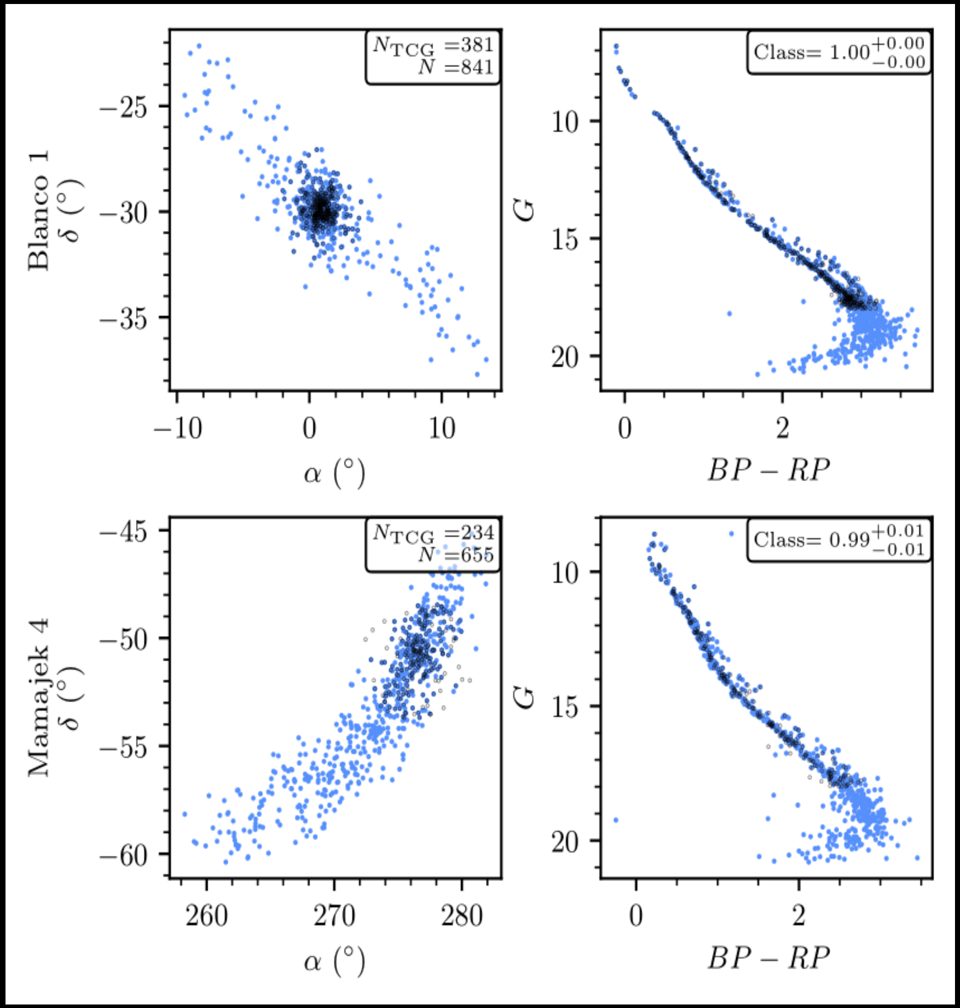
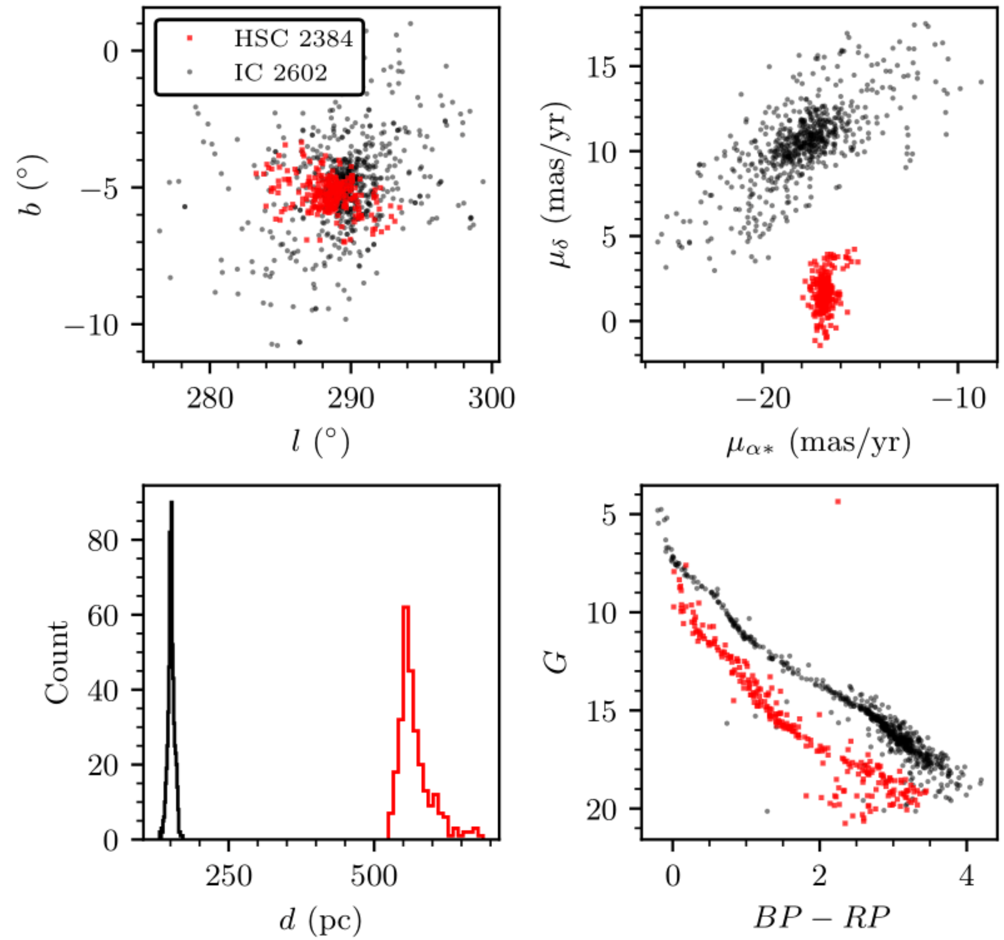


On new clusters

There are clearly big advantages to a single blind search!

There are some **very obvious clusters** that were missed previously



HSC 2384, a new open cluster that was hidden behind IC 2602

How many pre-reported clusters do we find?

A big blind search makes it possible to say **lots** about literature clusters, e.g.:

- Recover **just 51.6%** of clusters in biggest pre-Gaia catalogue, Kharchenko+13.
  ~1000 missing clusters that we would find if real - hence, probably not
- Recover **only 18.1%** of clusters in Kounkel+20
  Unlikely that many of their clusters real - we use same algorithm + better data
- Some **Gaia-era papers:** recover almost all objects; others: not as many...

Are all of the clusters we detect bound?

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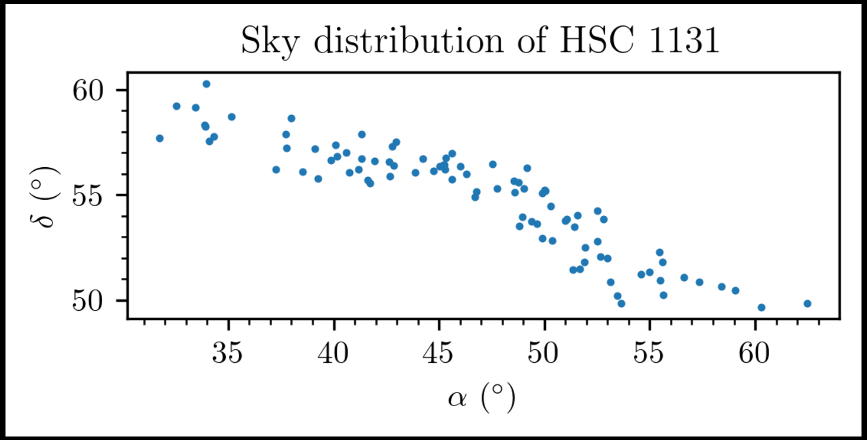
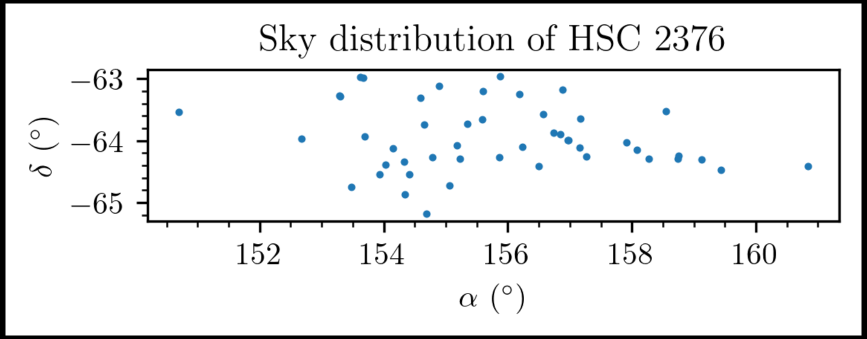
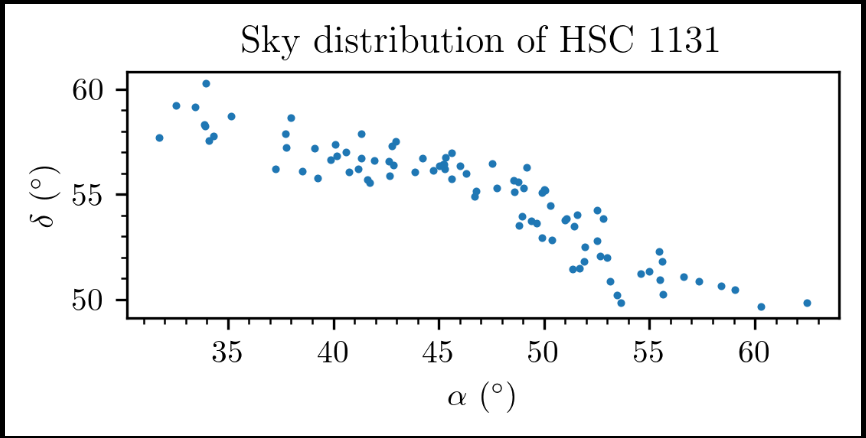
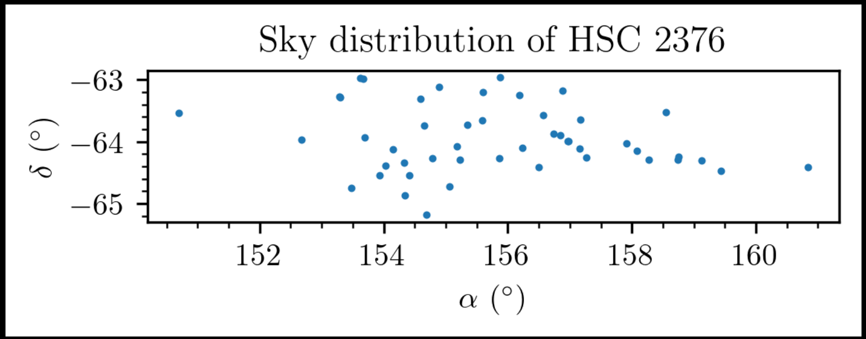
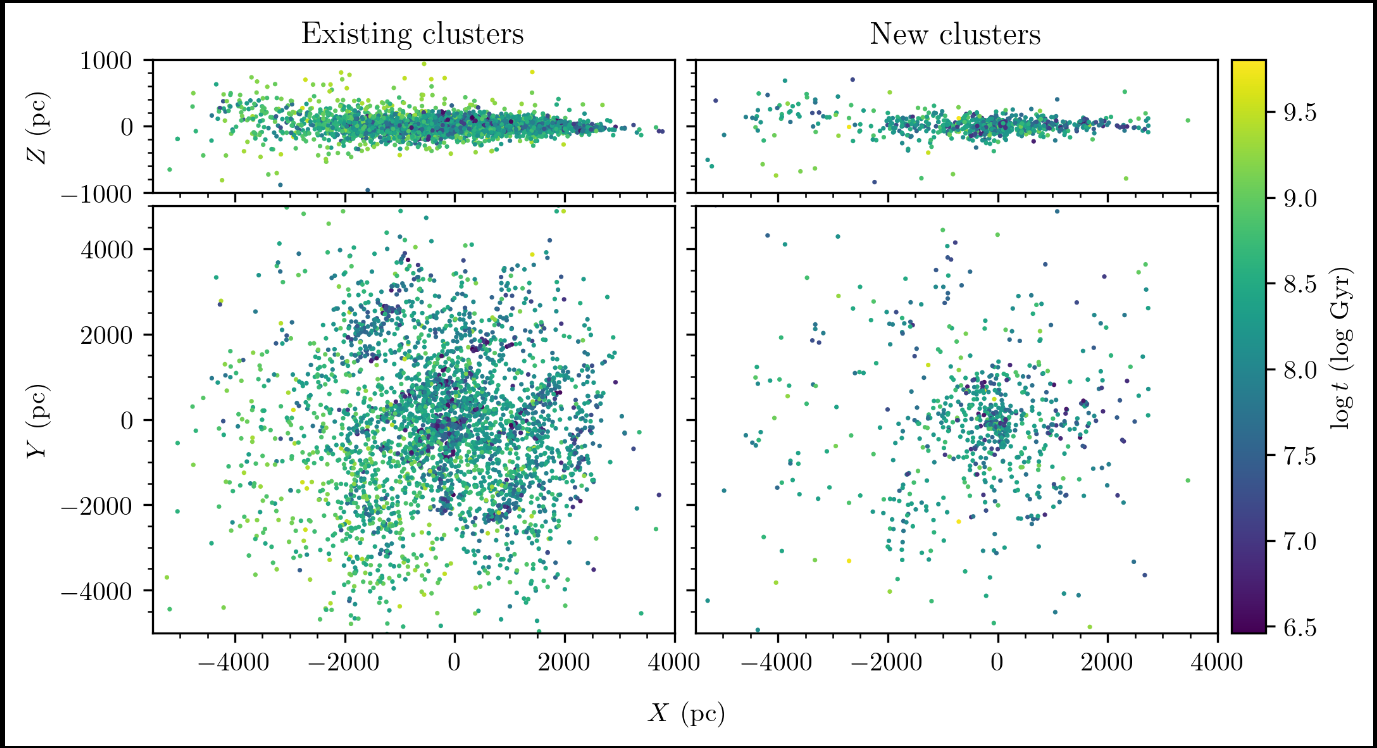




Are all of the clusters we detect bound?







Existing vs. new clusters.

Distinguishing between bound & unbound clusters

It's clear I needed to separate open clusters from unbound moving groups.

But how?

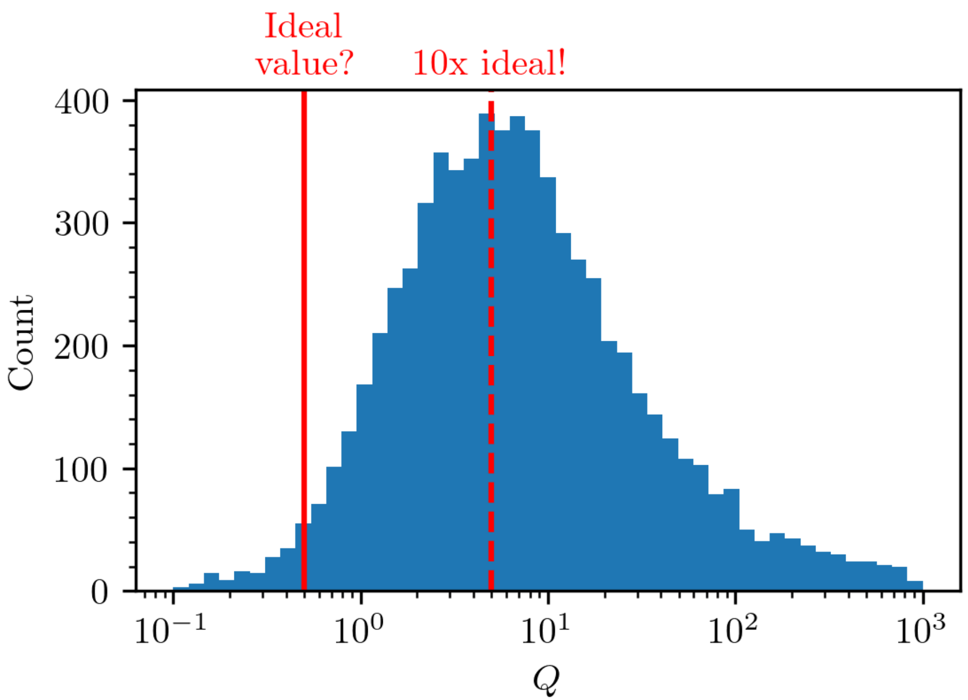
Logically: Virial theorem time?

The **virial theorem** states that an object in **gravitational equilibrium** should have $2T = |U|$

For star clusters, we can express this as:

$$Q = \frac{T}{V} = \frac{\eta r_{50} \sigma^2}{2GM} \approx \frac{1}{2} \quad \text{for a bound cluster.}$$

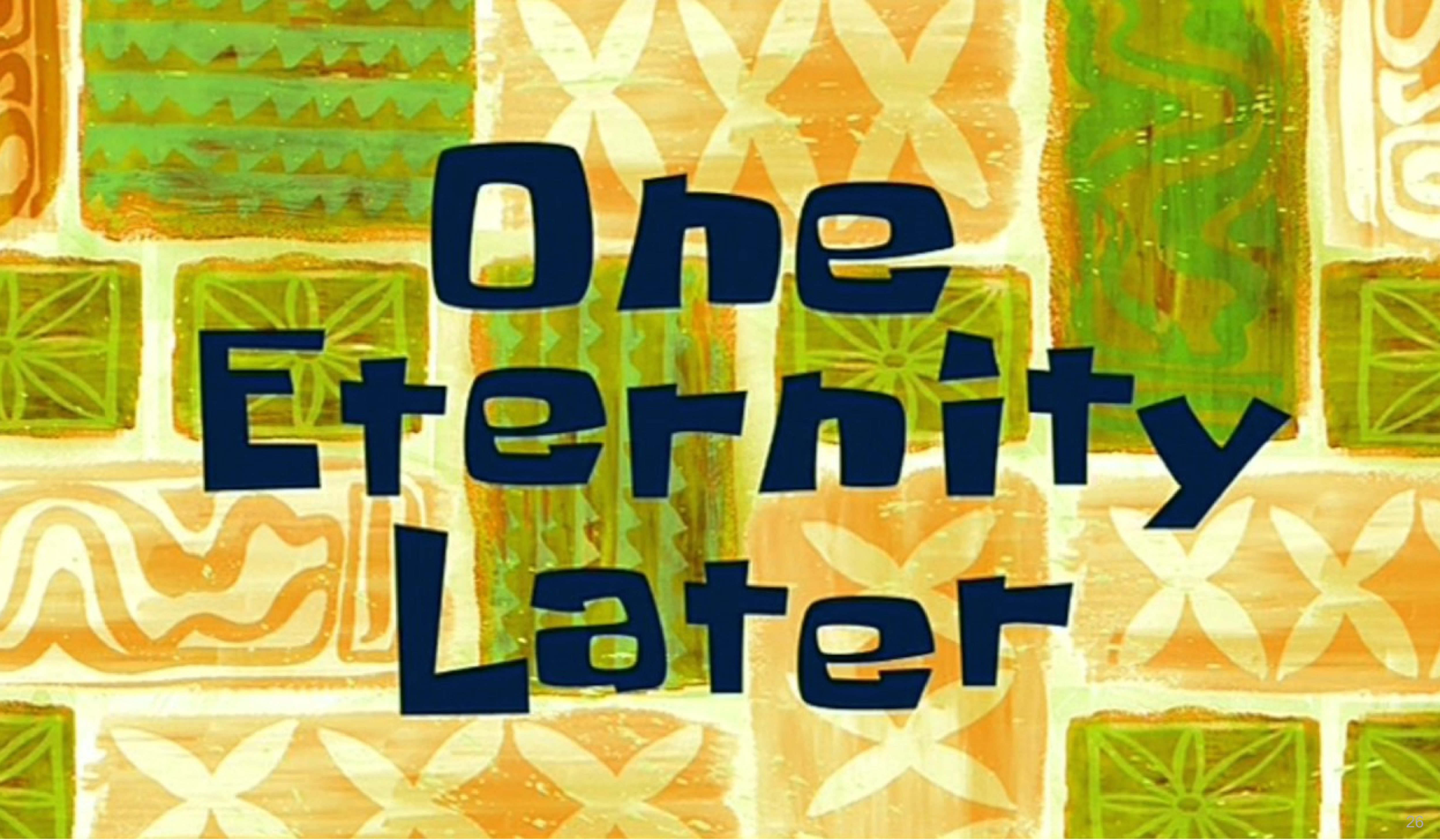
But it didn't work...



Virial ratios for clusters in the catalogue.

They were consistently too large by a factor of ~10.

The issue: **binary stars** messing up velocity dispersion measurements


One
Eternity
Later

Jacobi radii to the rescue!

I spent a while looking for a solution.

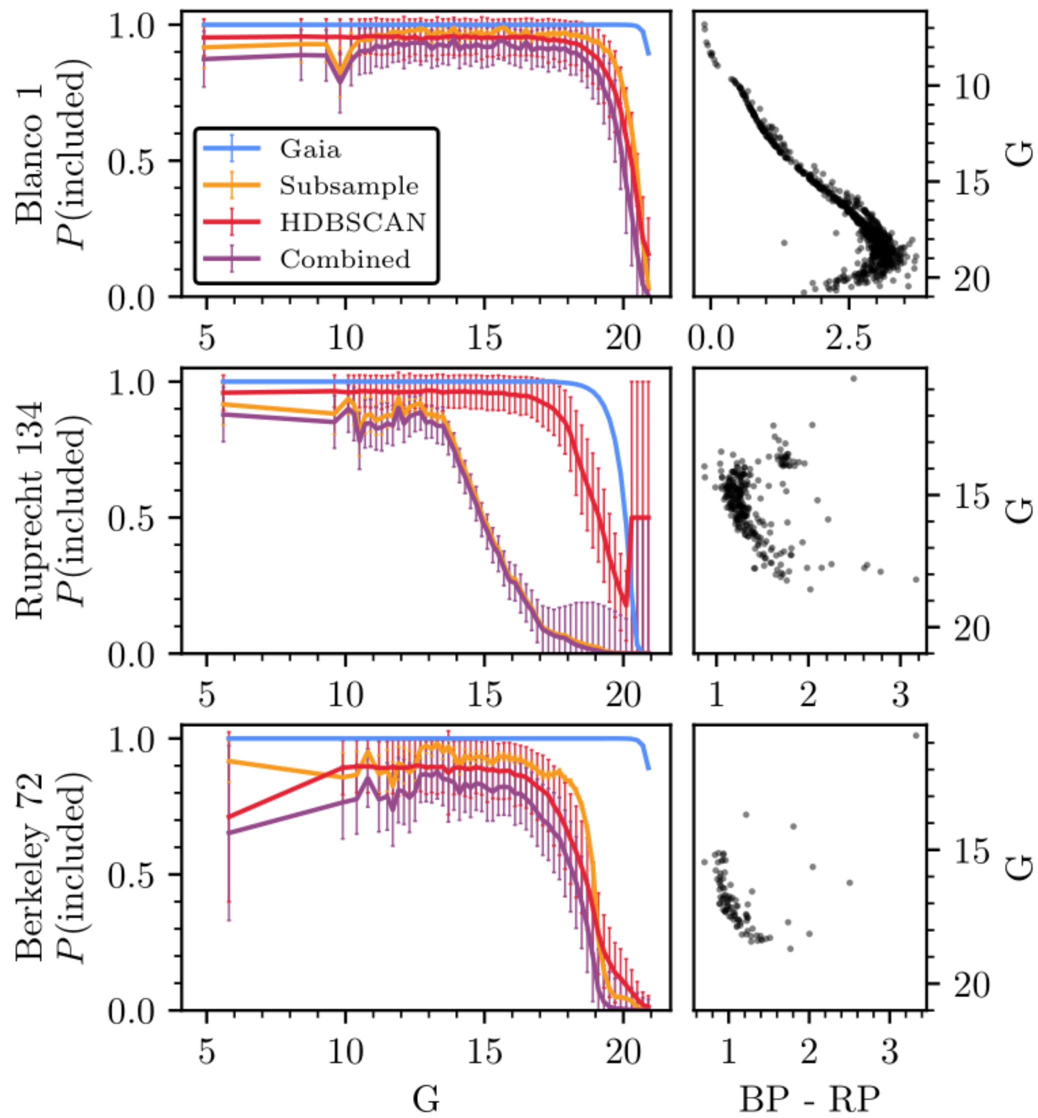
A bound cluster will have a radius r_J (the Jacobi radius) at which its potential is stronger than its host galaxy:

$$r_J = \left(\frac{M}{4\Omega^2 - k^2} \right)^{\frac{1}{3}}$$

Measuring accurate cluster masses

Problem: cluster masses not widely measured for Milky Way clusters

To do this more accurately: I developed method for **selection effect** corrections

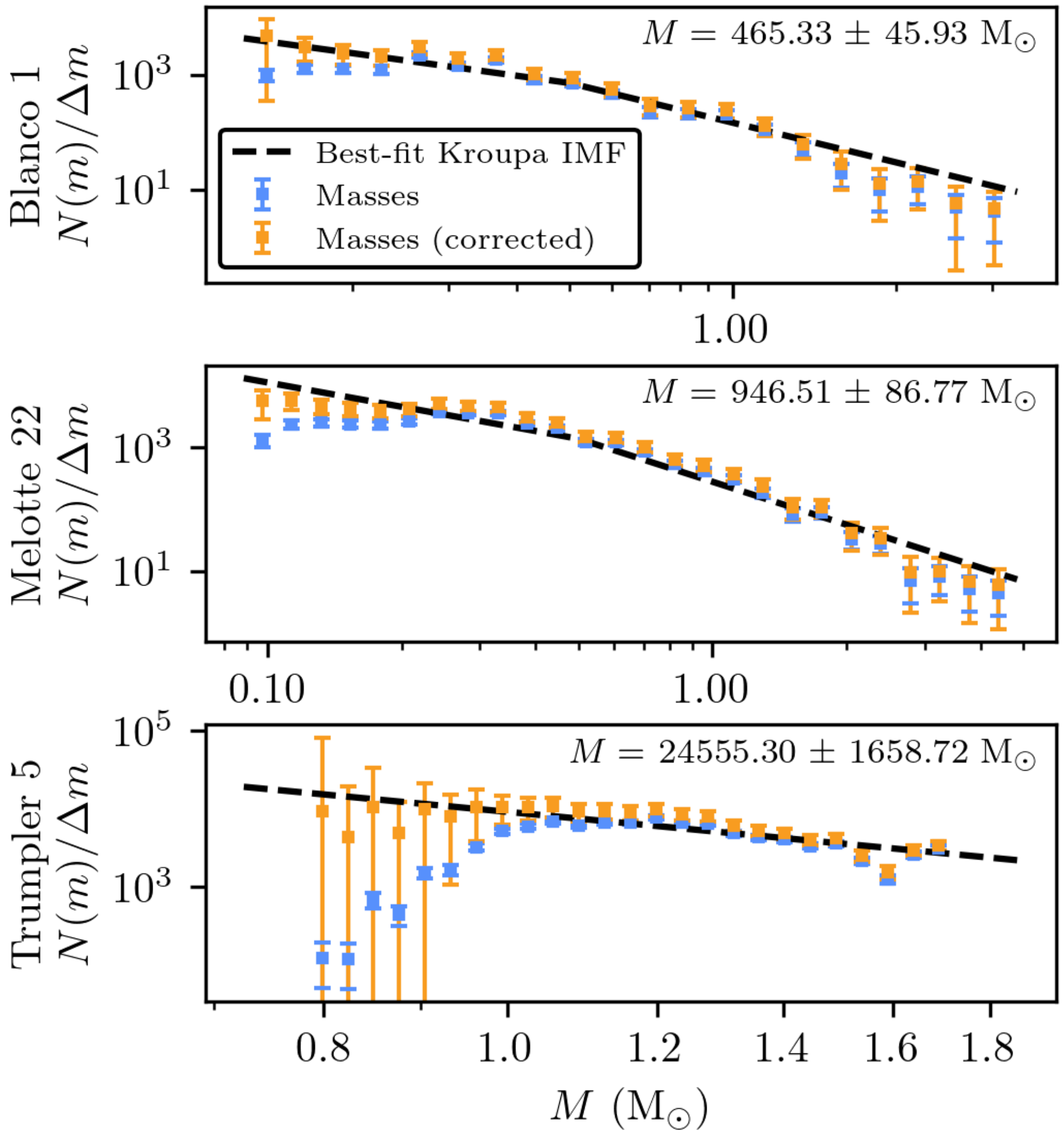


The magnitude-dependent selection function of three clusters

Measuring accurate cluster masses II

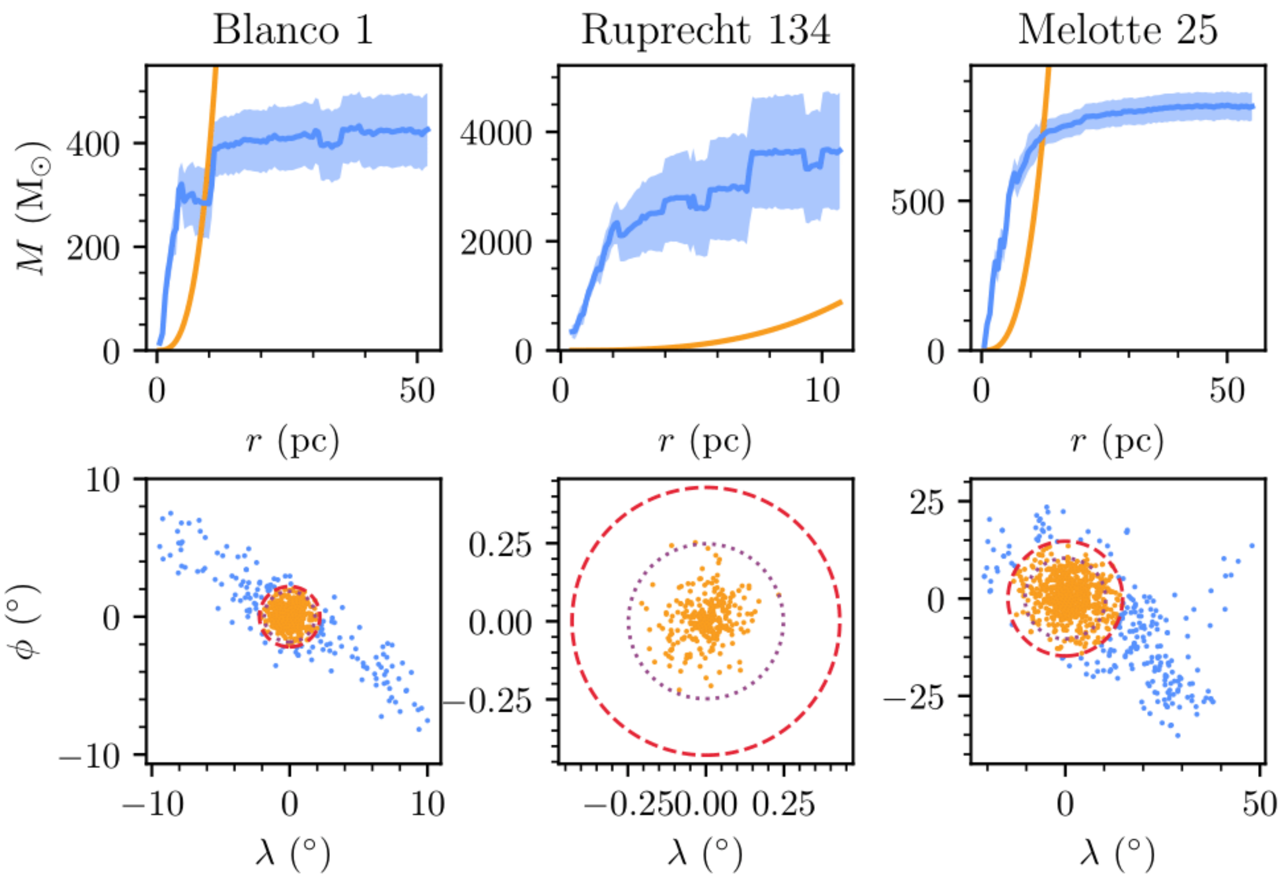
- Stellar masses from **isochrone interpolation**
- Additional correction for **unresolved binary stars** applied
- **Kroupa IMF fitted**

Corrections are **important!**



Uncorrected and corrected cluster mass functions

Onto Jacobi radii: for three reliable clusters

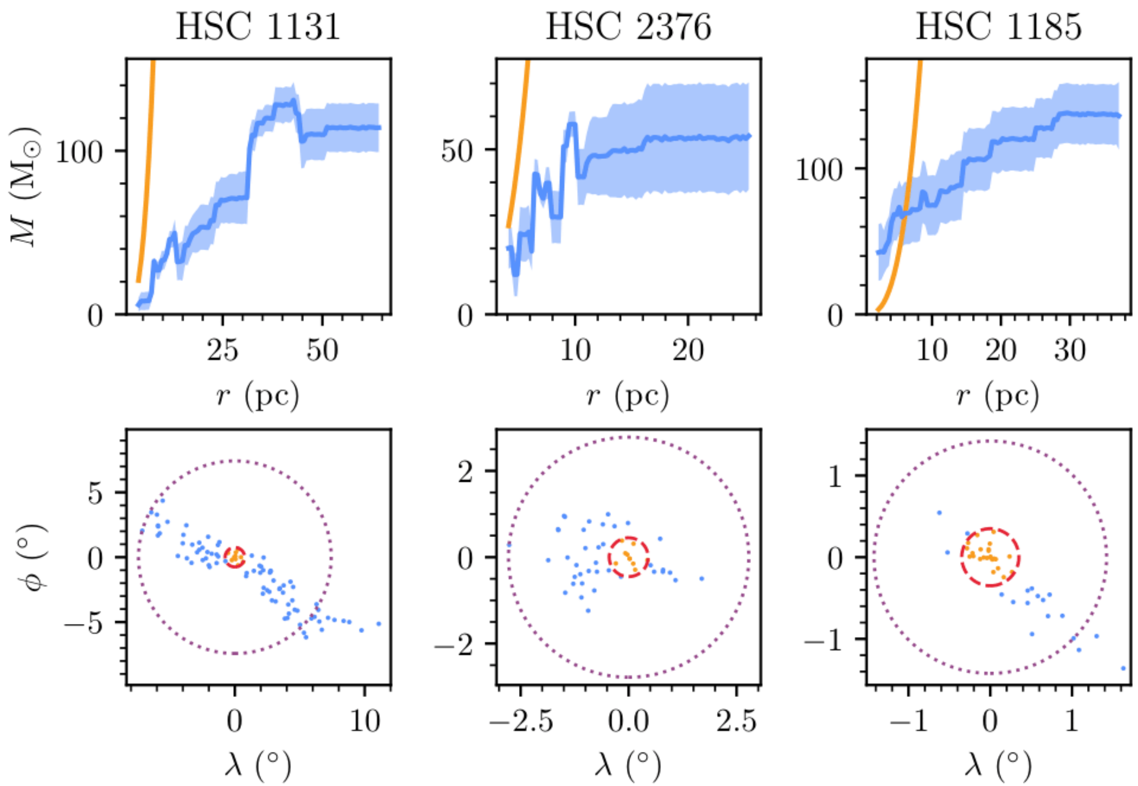


Jacobi radius determination for three reliable clusters

Intersection = r_J

All three are clear bound open clusters

But what about the 'weird' clusters?



Jacobi radius determination for three suspect clusters

- **HSC 1131:** not bound (disk stream?)
- **HSC 2376:** not bound (expanding association?)
- **HSC 1131:** bound! (small, ~60 solar masses)

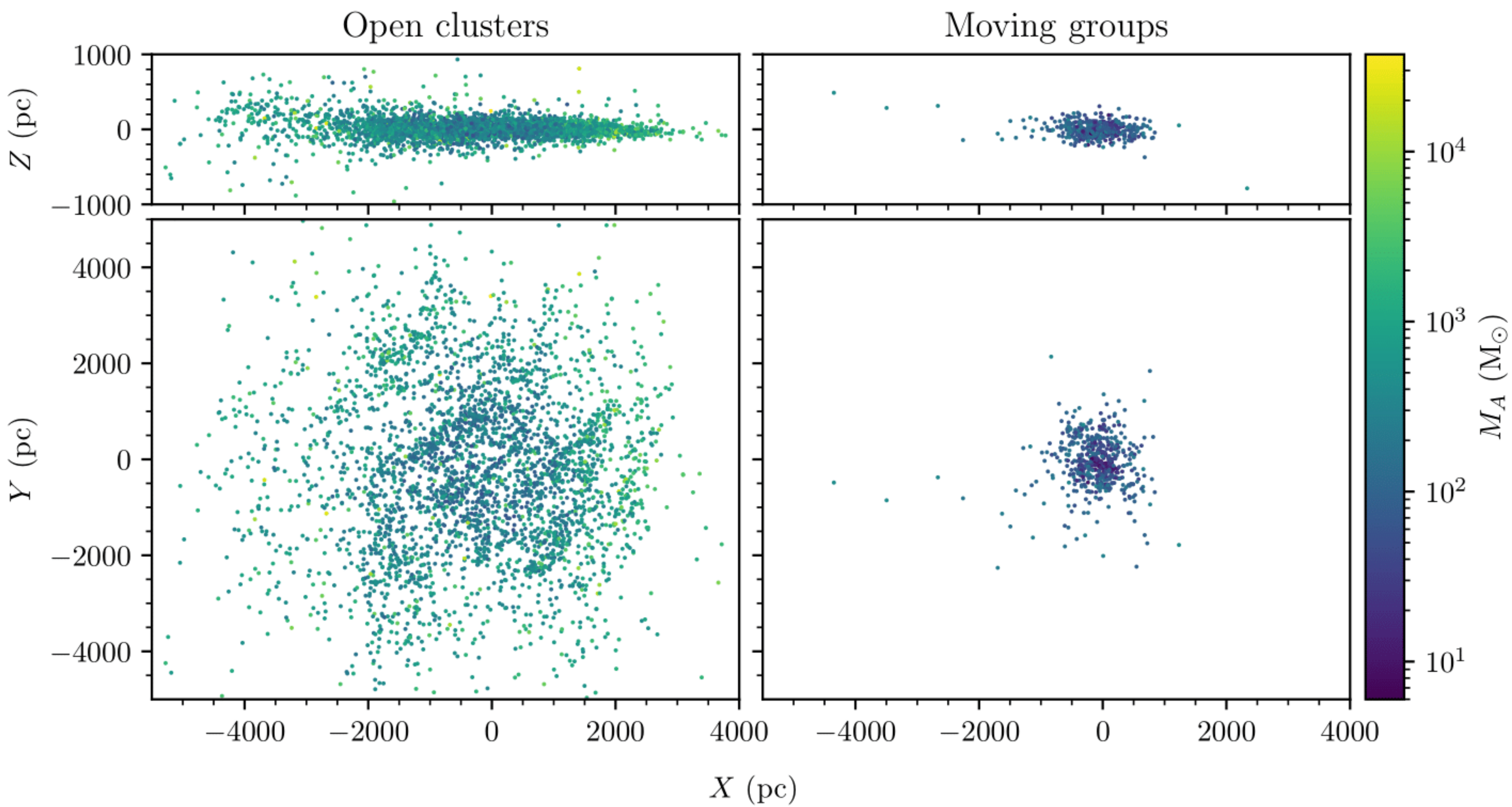
Some limitations

Method is not perfect:

- Have to assume spherical clusters
- Have to assume circular orbits
- Not good for clusters below ~40 MSun

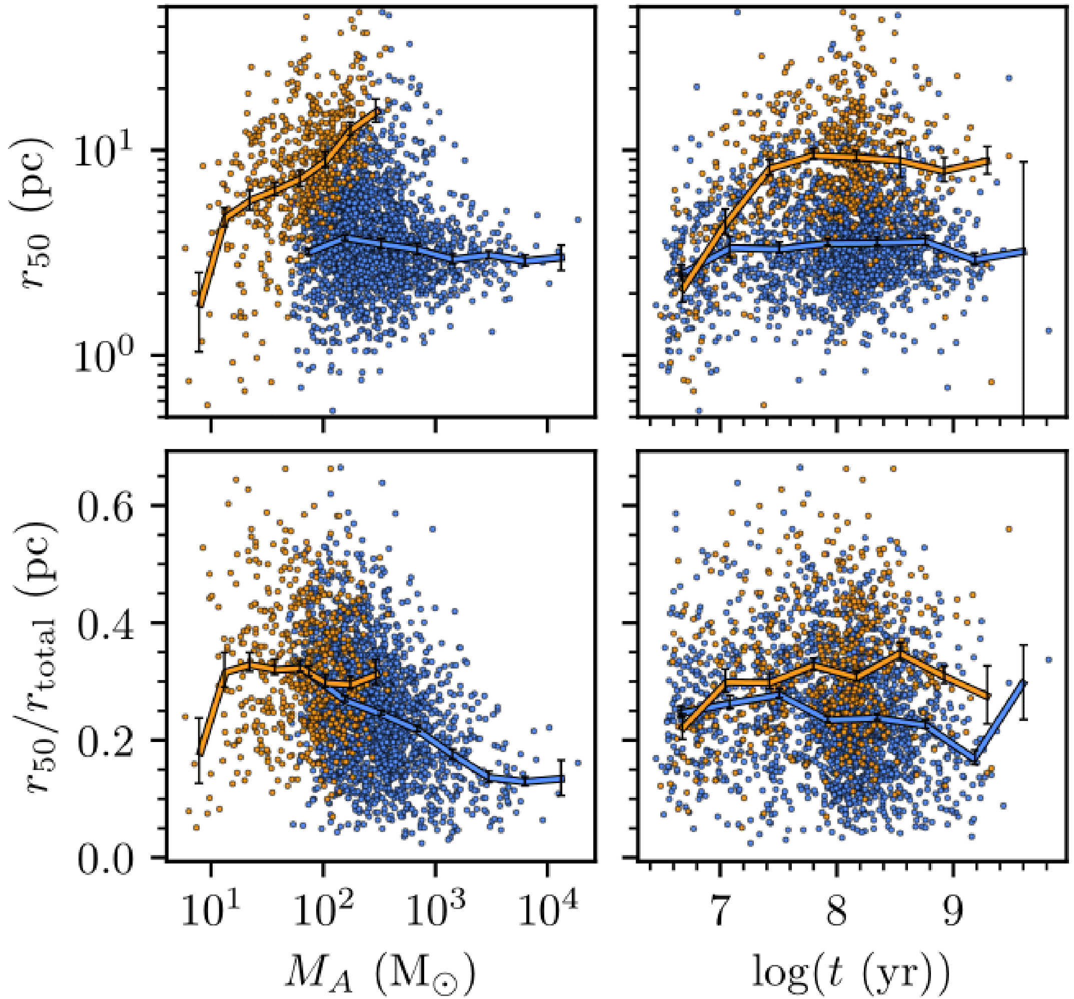
But I think it's still **much** better than using nothing!

How does it change the catalogue's distribution?



The catalogue divided into clusters with (left) and without (right) a valid Jacobi radius.

What are the differences between them?

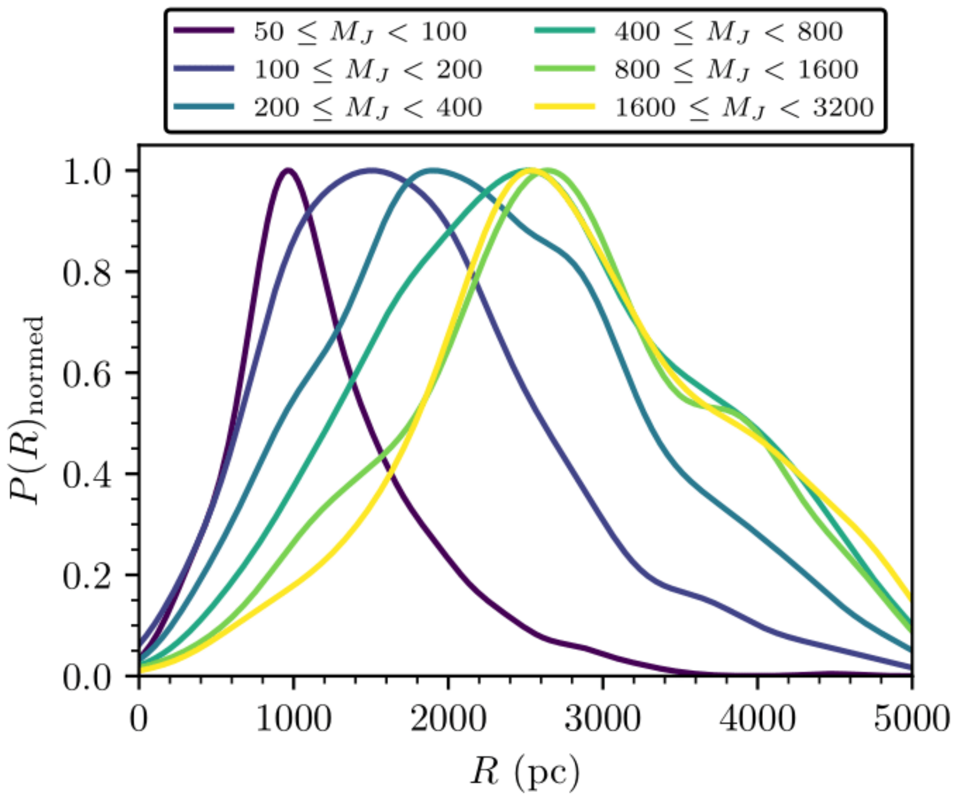


Radius and concentration of clusters vs. mass and age

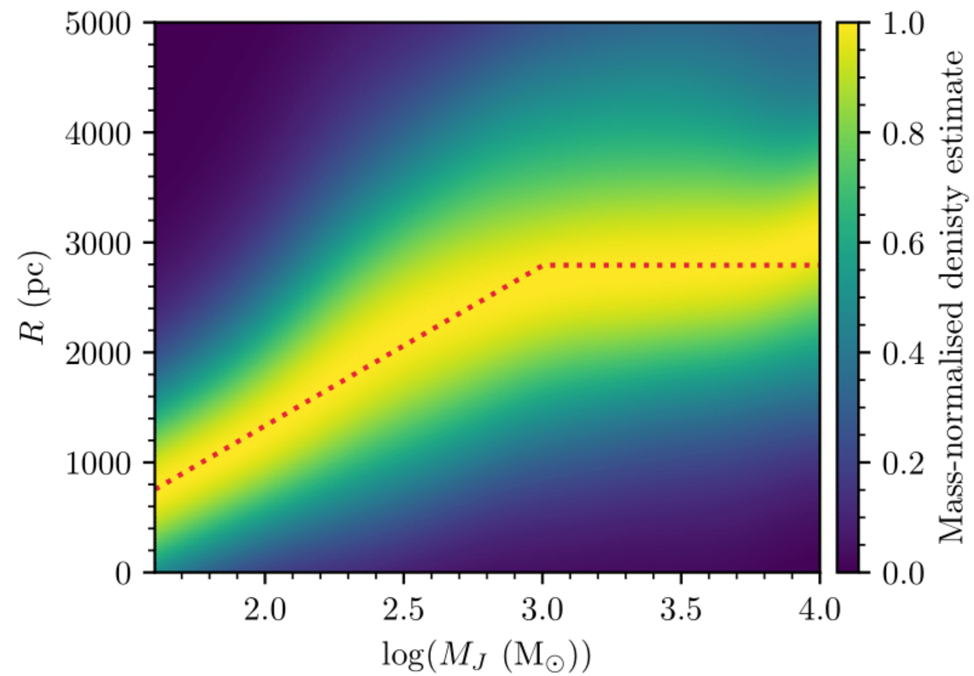
- Moving groups **expand** with time; open clusters do not
- High-mass open clusters are **very concentrated**
- Low-mass open clusters and moving groups **less concentrated**

The power of cluster masses

The catalogue's completeness depends **strongly** on mass

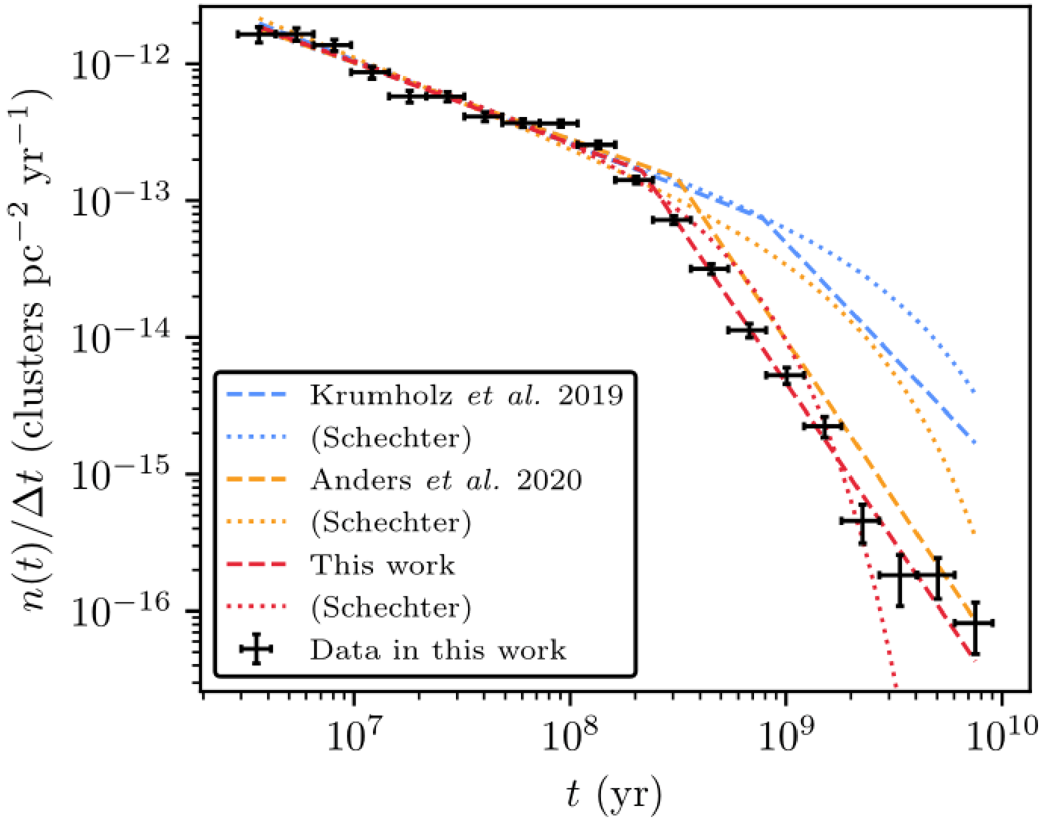


Kernel density estimate of cluster distance distribution in mass bins.



Full KDE estimate of cluster mass-distance distribution.

Cluster age function

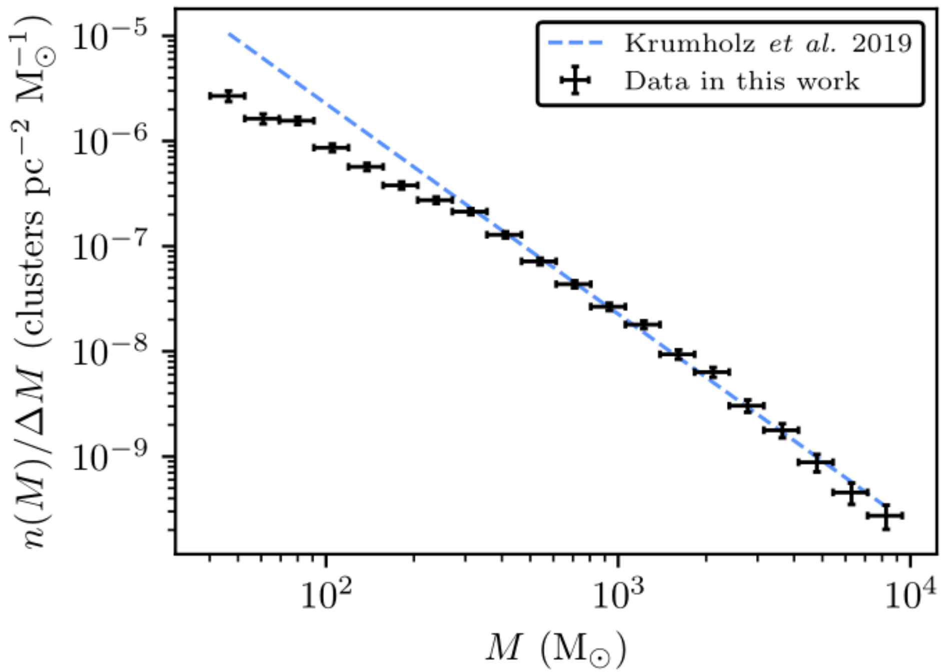


The cluster age function for OCs in the catalogue.

Open cluster catalogues in Gaia era have **fewer old clusters**

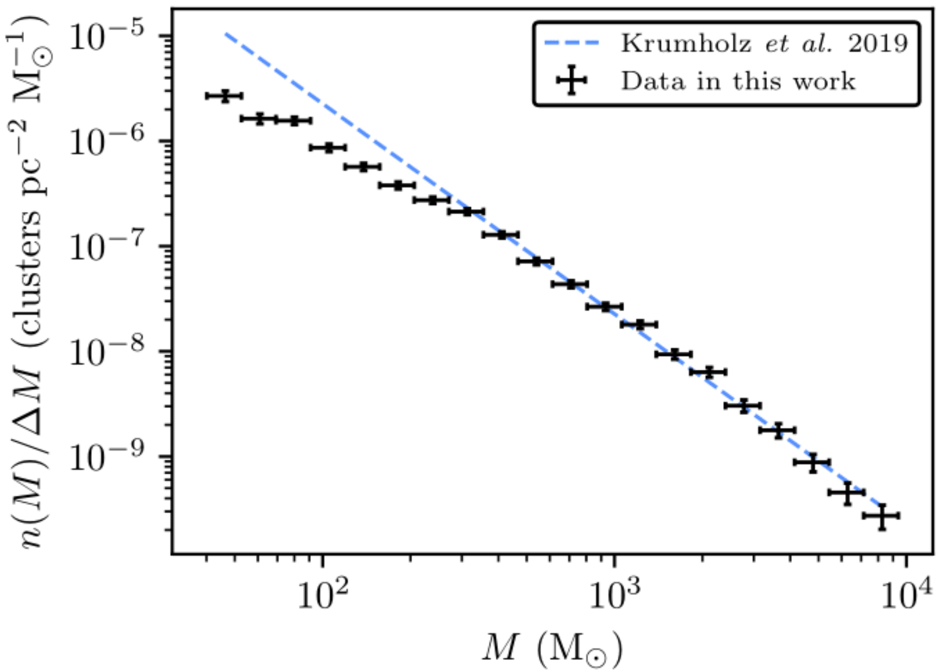
(likely due to removal of erroneous old objects)

The first ever Gaia cluster mass function

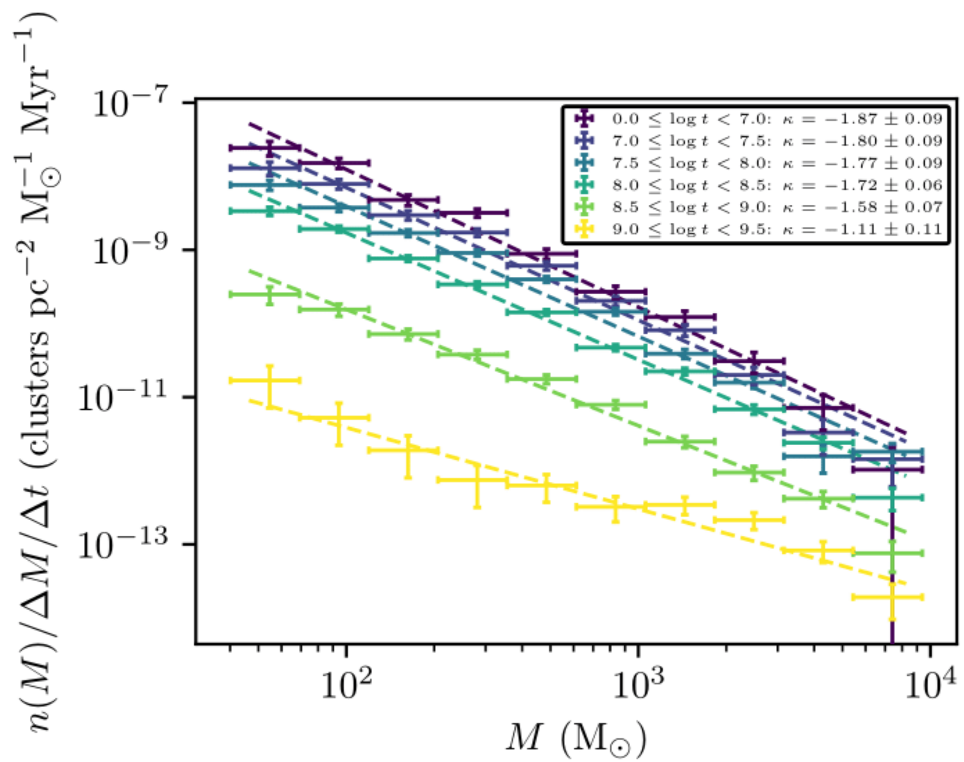


The cluster mass function for OCs in the catalogue

Low-mass clusters are destroyed faster

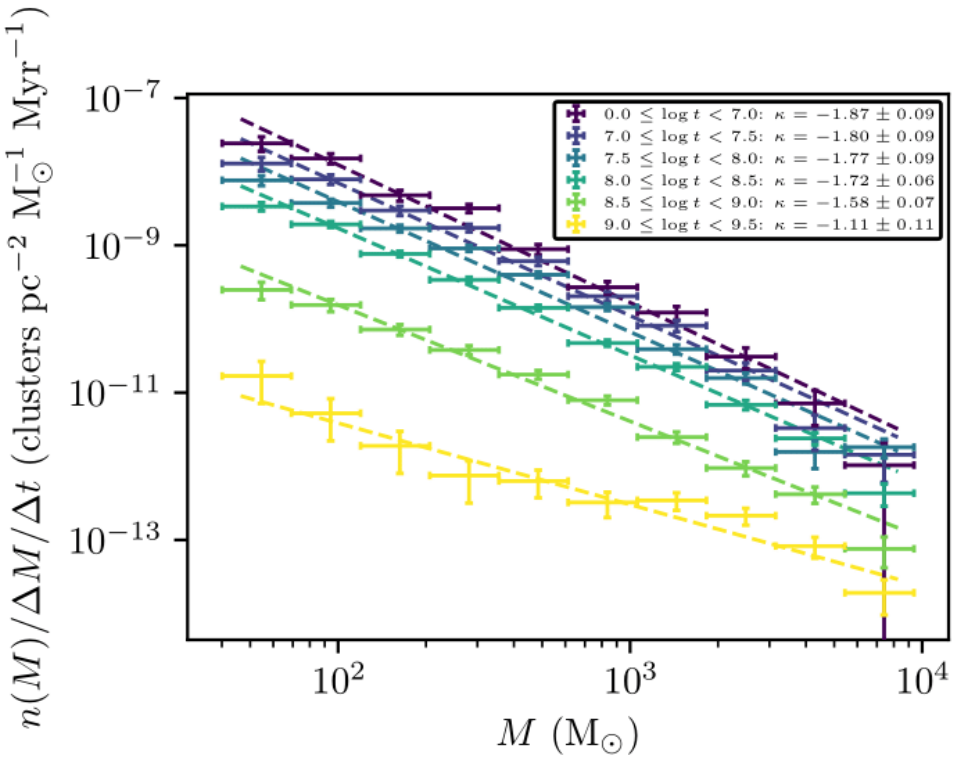


The cluster mass function for OCs in the catalogue



The cluster mass function divided into age bins

Low-mass clusters are destroyed faster



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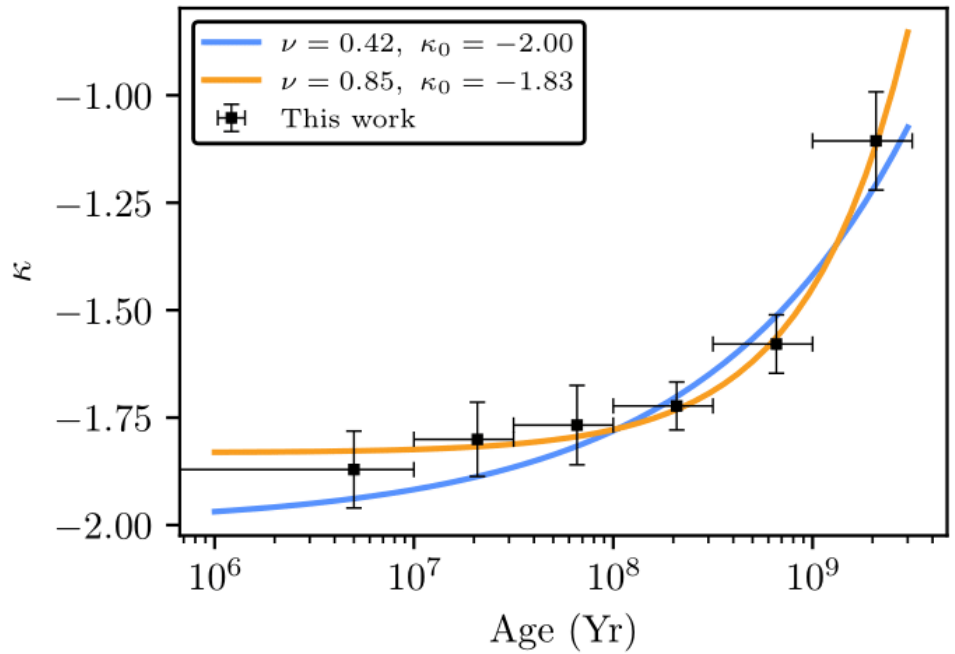


The slope of the cluster mass function, with age

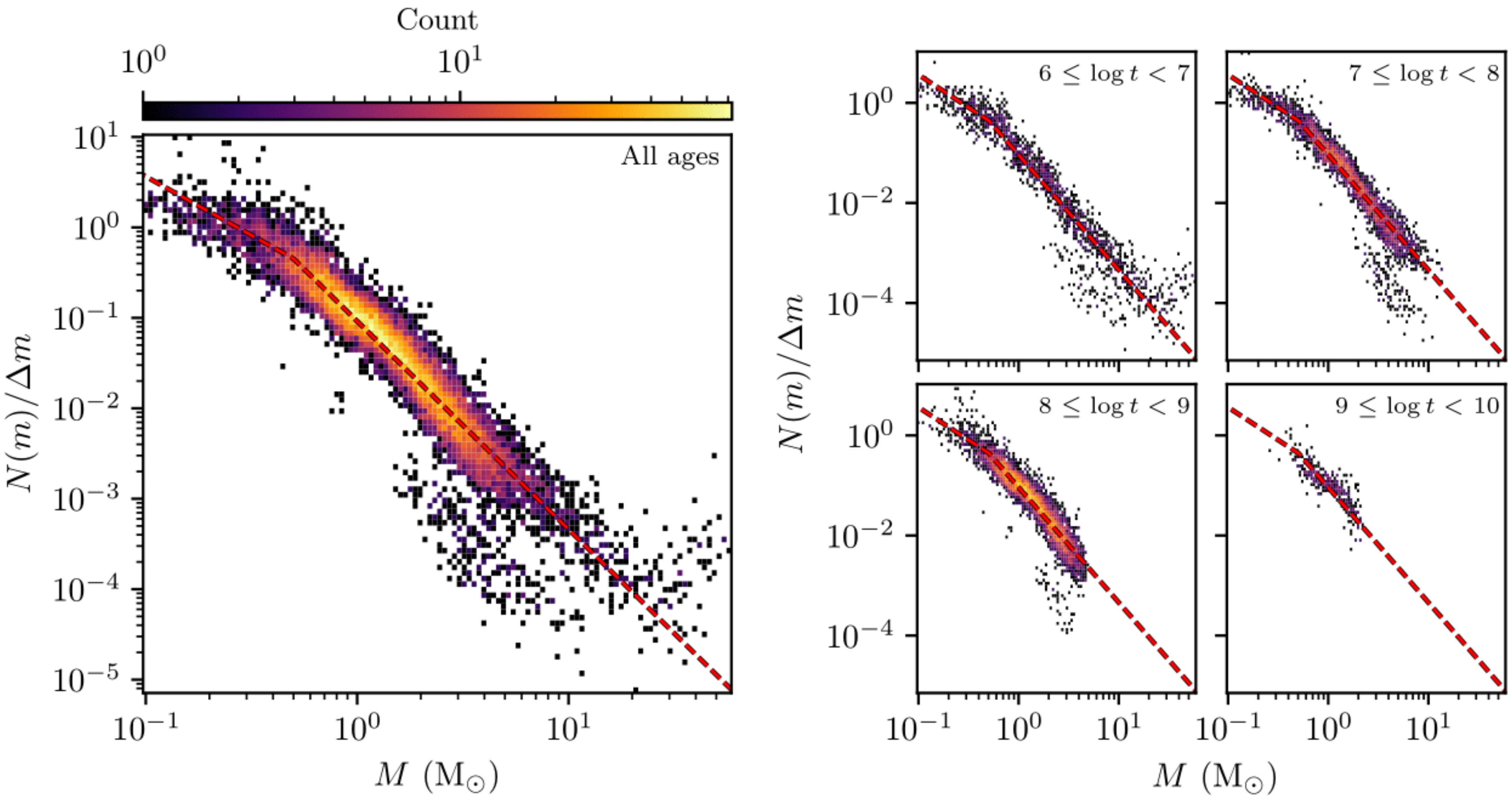
Connecting to theory and other galaxies

Young clusters **in all galaxies** form with initial mass from power law of slope ≈ -2 (Krumholz 2019 + references therein)

New result: can constrain how this **flattens** with time, due to faster destruction of low-mass clusters

Our results will be able to constrain **rate** and **intensity** of GMC and spiral arm collisions

About individual cluster mass functions



All cluster mass function datapoints for all open clusters within 2 kpc

Conclusions

- I made the **largest ever** deduplicated Milky Way star cluster catalogue
  (Hunt & Reffert 2021, 2023)
- **Jacobi radii** and **cluster masses** can differentiate bound and unbound clusters effectively
  (Hunt & Reffert submitted)
- Large catalogue of **cluster masses** reveals new details on cluster formation and destruction processes
  (also in Hunt & Reffert submitted)

I'm currently on the job market!

web: emily.space

- Largest ever MW cluster catalogue
- Jacobi radii to distinguish bound/unbound clusters
- Many new results from these mass measurements