David A. Dunlap Department of Astronomy & Astrophysics
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Lost Stars, Found Insights:

Extra-Tidal Stars as Probes of Stellar, Cluster and Milky Way Evolution

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University of Toronto

IAU Symposium 395 (November 18, 2024)

Collaborators: Jeremy Webb, Joshua Speagle, James Lane and Nathan Leigh

Globular clusters can lose mass in a variety of ways.

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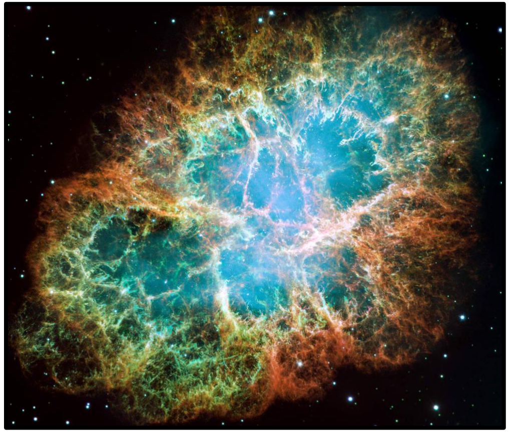
Massive star evolution
(dominated ~1 Gyr after formation)



NASA (Arizona State University)

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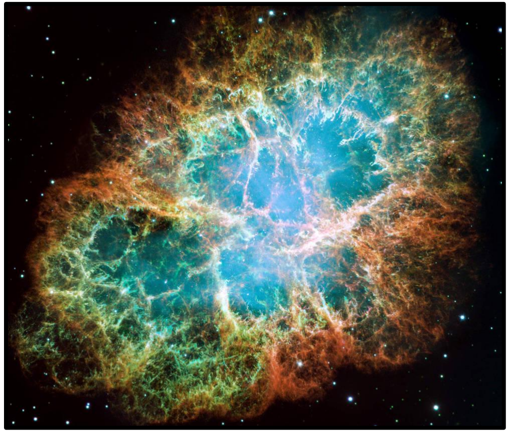

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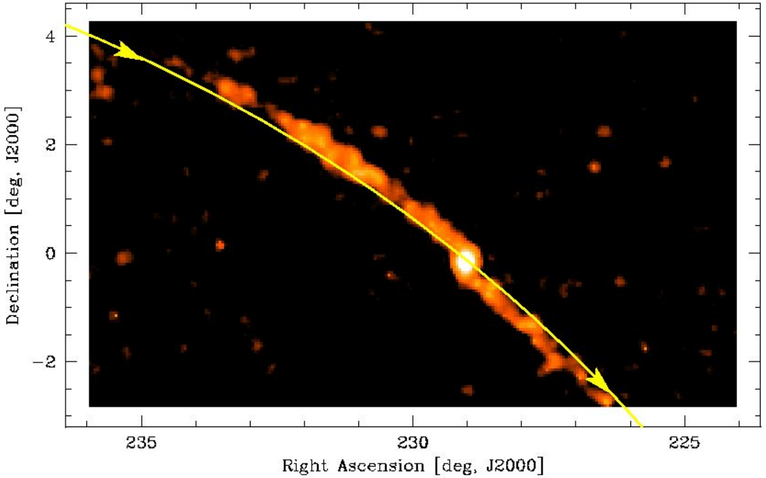
Two-body relaxation → tidal stripping
(dominant mass-loss channel)



Odenkirchen et al. (2003)

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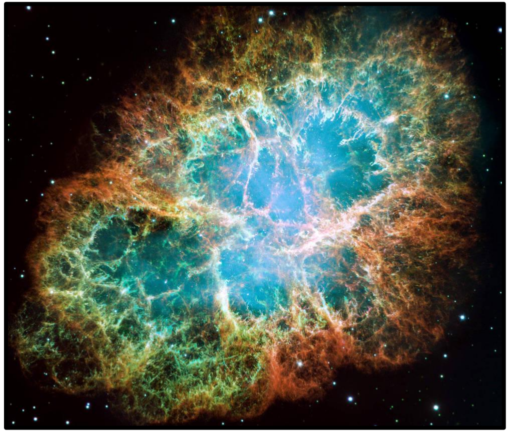

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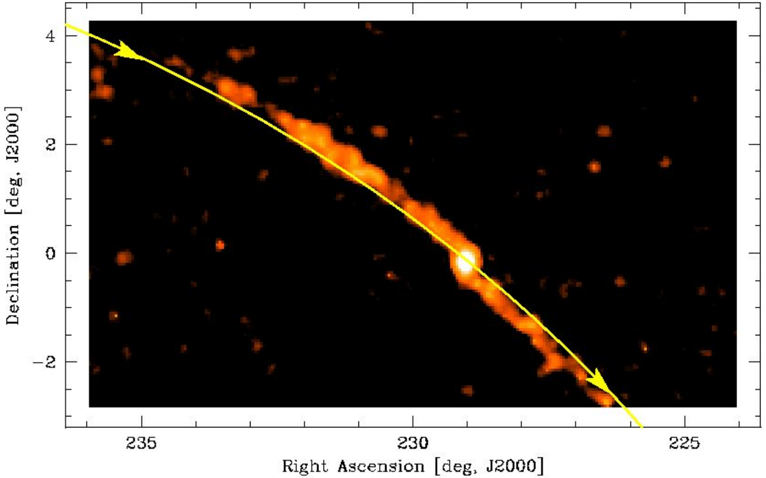
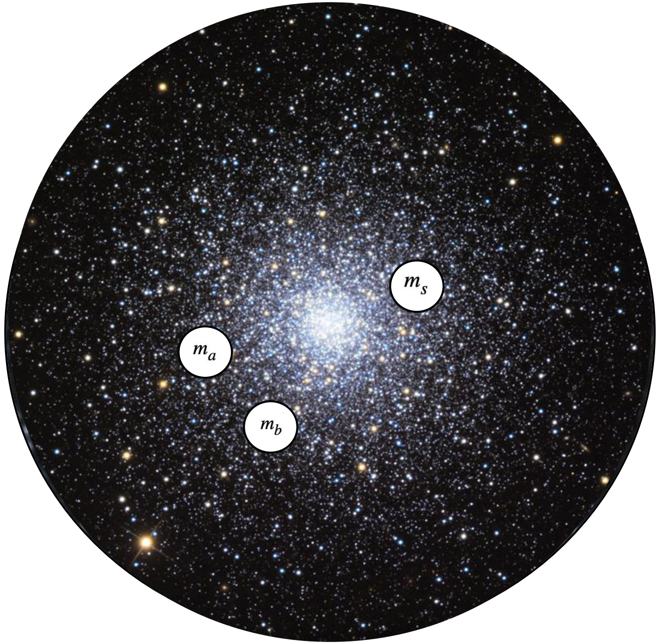


Odenkirchen et al. (2003)

GCs are dense. What about interactions between stars in the core?

Binary-single interactions in GC cores are responsible for ejecting binaries and compact objects.



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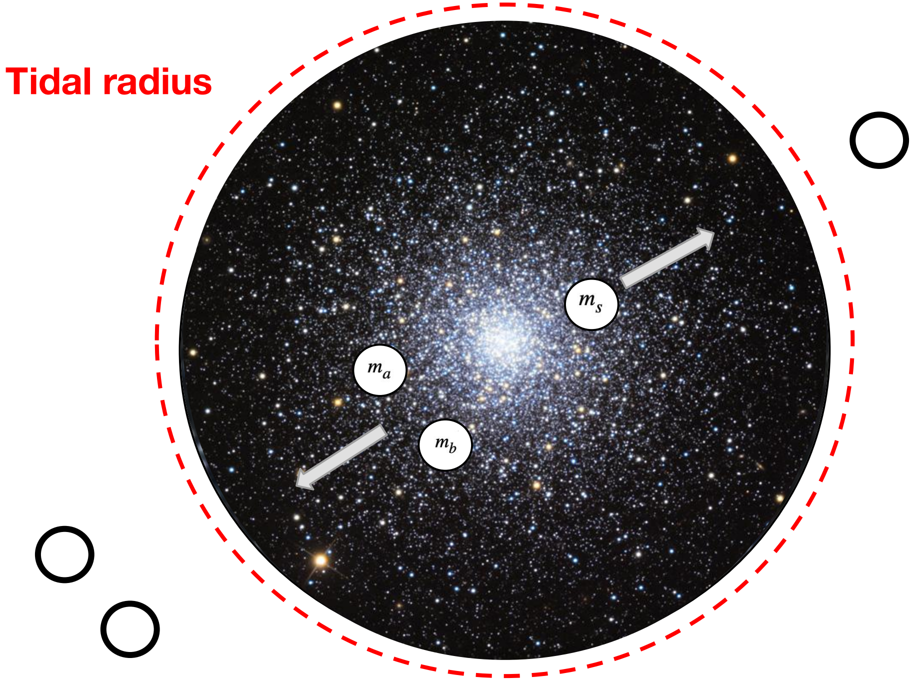

These are extra-tidal stars/binaries.

Dynamically ejected stars populate the Galactic halo, form exotic binaries, etc.

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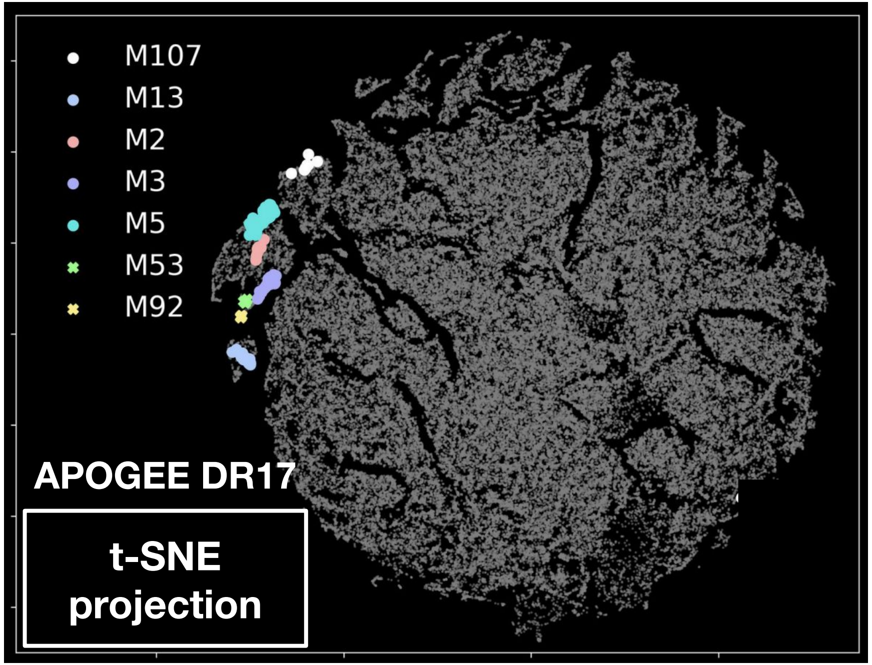
Often, we exploit the fact that GCs are chemically distinct from one another and use "chemo-dynamical" tagging to link field stars with clusters.



Credit: Yuan-Sen Ting

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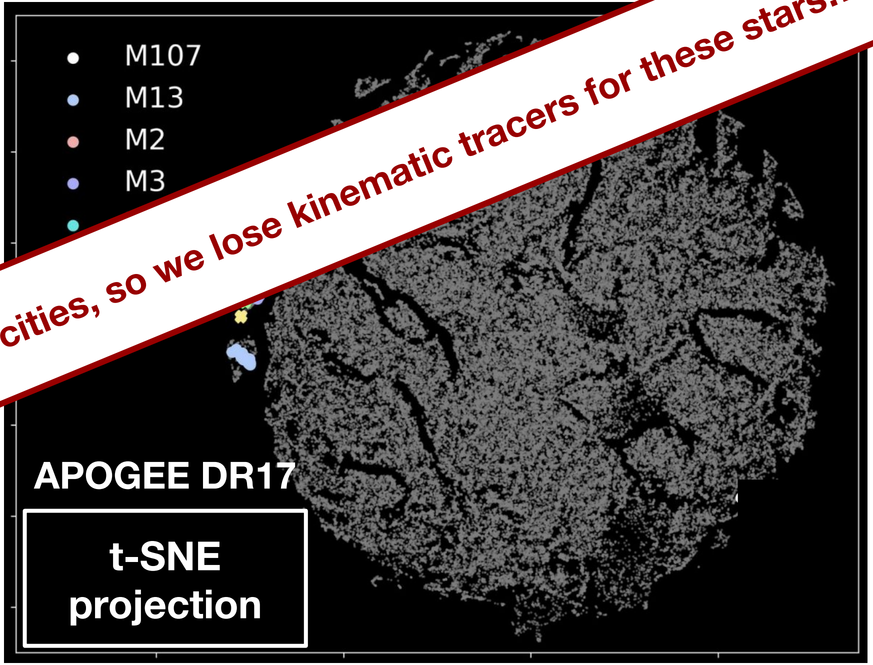

Credit: Yuan-Sen Ting

Dynamical interactions could change radial velocities, so we lose kinematic tracers for these stars…

Simulations can provide dynamical information for comparison.
However, modelling dynamical escape from a GC's core is difficult…

N-body integrators (e.g. `Nbody6`, Aarseth 2003) and Monte Carlo methods (e.g. CMC, Rodriguez+ 2020) directly model gravitational encounters between cluster stars.

BUT simulating the evolution of GCs is computationally expensive due to the **large particle numbers** and **old ages.**

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BUT simulating the evolution of GCs is computationally expensive due to the **large particle numbers** and **old ages.**

A tool that quickly samples and integrates orbits for extra-tidal stars and binaries would be extremely useful to explore full high-N distributions of dynamical escapers.

Enter: `Corespray`

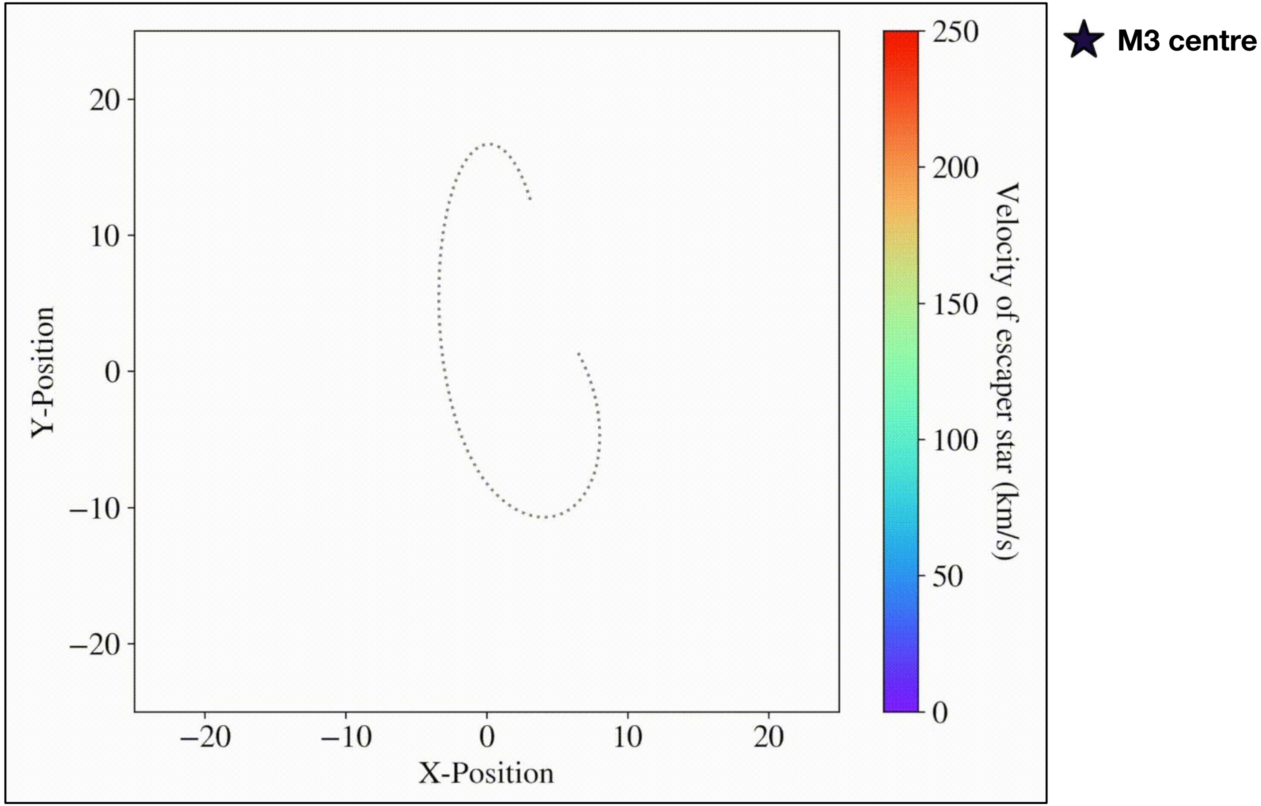
A Python-based **particle spray code** that **quickly samples** three-body encounters in GC cores until N escapers are generated.

Grondin et al. (2023), arXiv: 2207.11263

Some examples of Corespray's applications include:

- The production of hypervelocity stars from GCs (Evans, **Grondin** et al., submitted to MNRAS)
- The migration of binary pulsars from star clusters (Leigh, Ye, **Grondin** et al. 2024)
- The identification of single-binary pairs from open clusters (Herrera-Urquieta incl. **Grondin** et al., in review at A&A)

`Corespray` excels at sampling the **complete parameter spaces** for extra-tidal stars/binaries ejected from GCs **(N=1000)**.



M3 centre

Runtime ~ 15 min

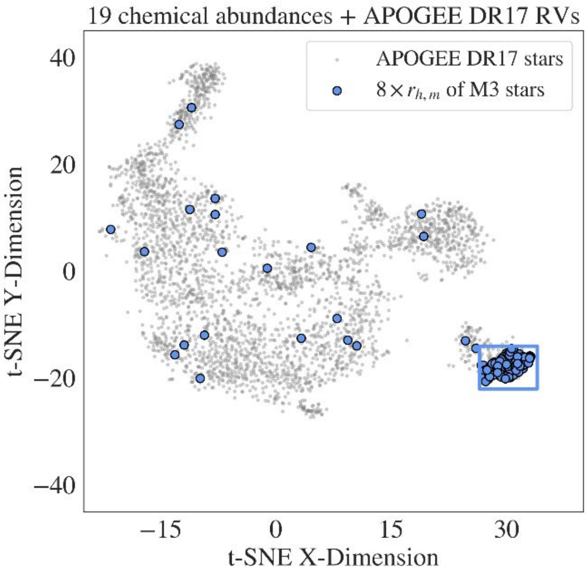
Grondin et al. (2023)

The goal:

Combine machine learning, chemical tagging and large Corespray simulations to identify extra-tidal stars and binaries of Milky Way star clusters.

Case Study: M3

We first run t-SNE on a dataset of 19 chemical abundances* + radial velocities.
(allows us to identify APOGEE DR17 stars that are similar to M3 cluster stars for a control group.)

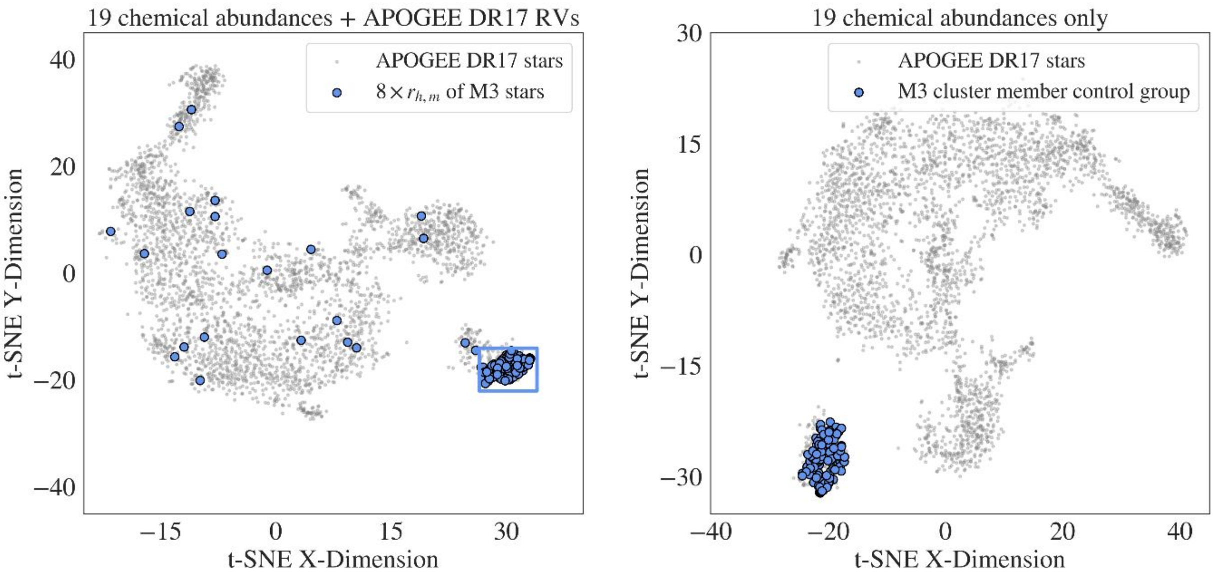


Grondin et al. (2023)

Case Study: M3

We then run t-SNE again on the dataset with only the abundances*.

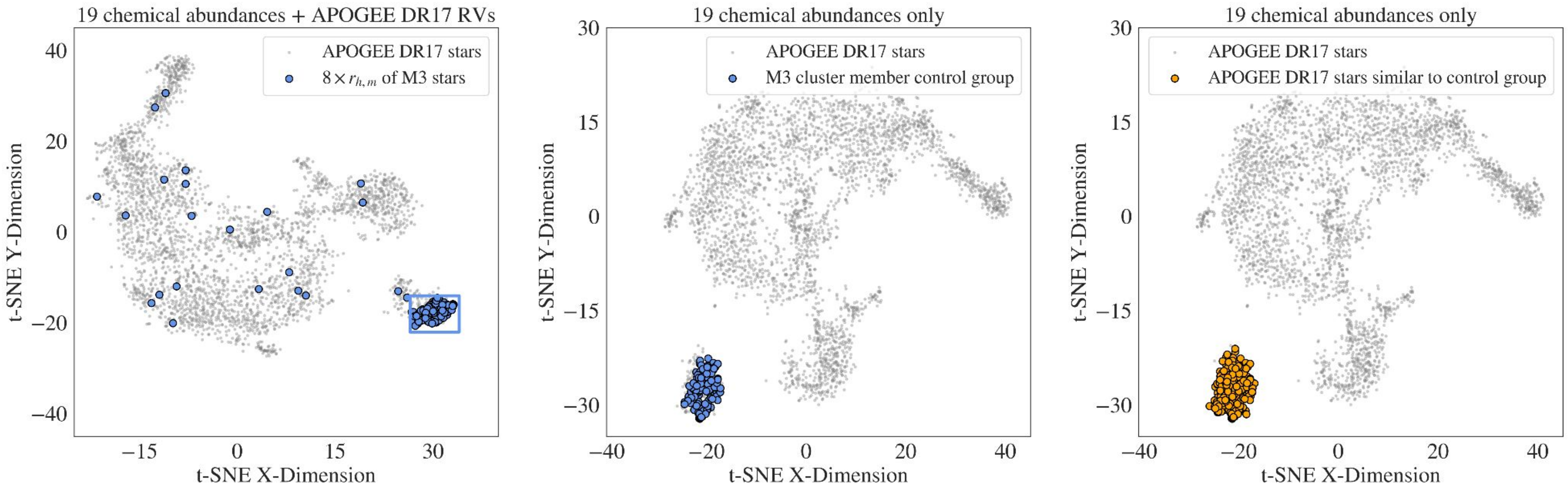
(extra-tidal stars don't necessarily have the same RVs as the cluster stars)



Grondin et al. (2023)

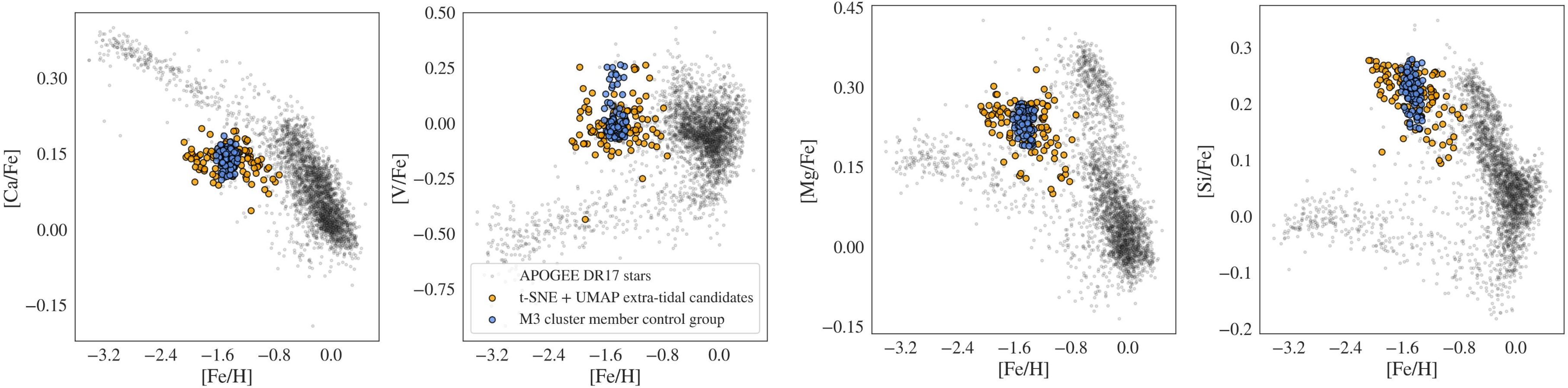
Case Study: M3

Finally, we select **stars similar to the cluster stars** in t-SNE abundance-only space to obtain a sample of extra-tidal candidates. This identifies **103 extra-tidal candidates.**



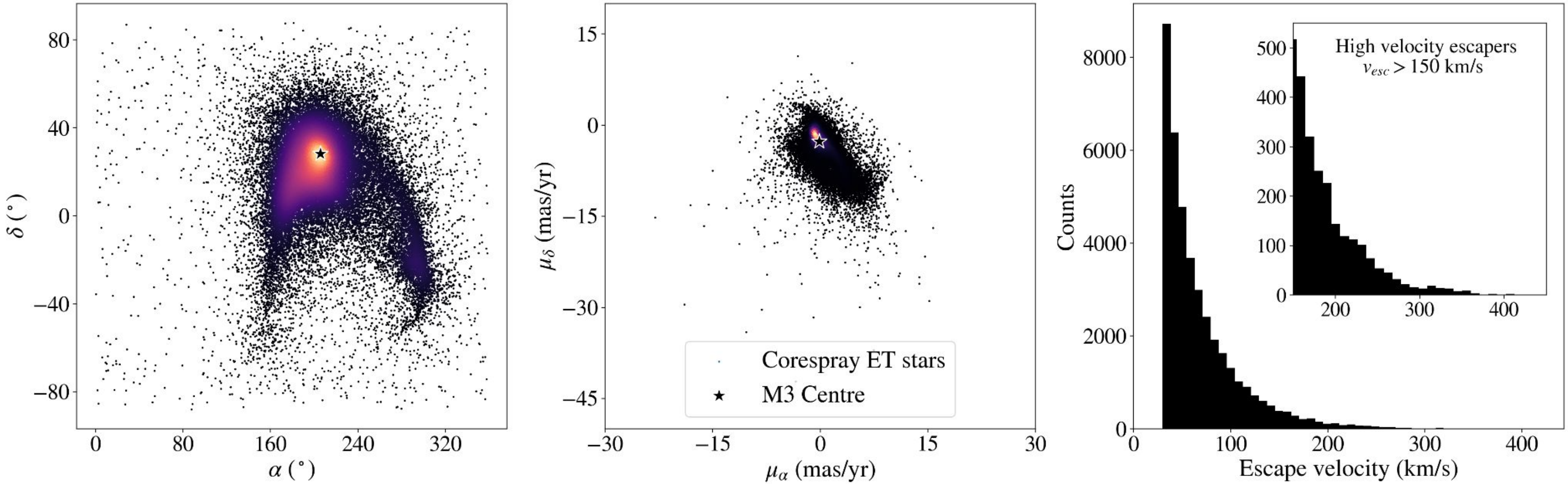
Grondin et al. (2023)

These chemically-similar extra-tidal candidates align with the M3 control group in abundance spaces.



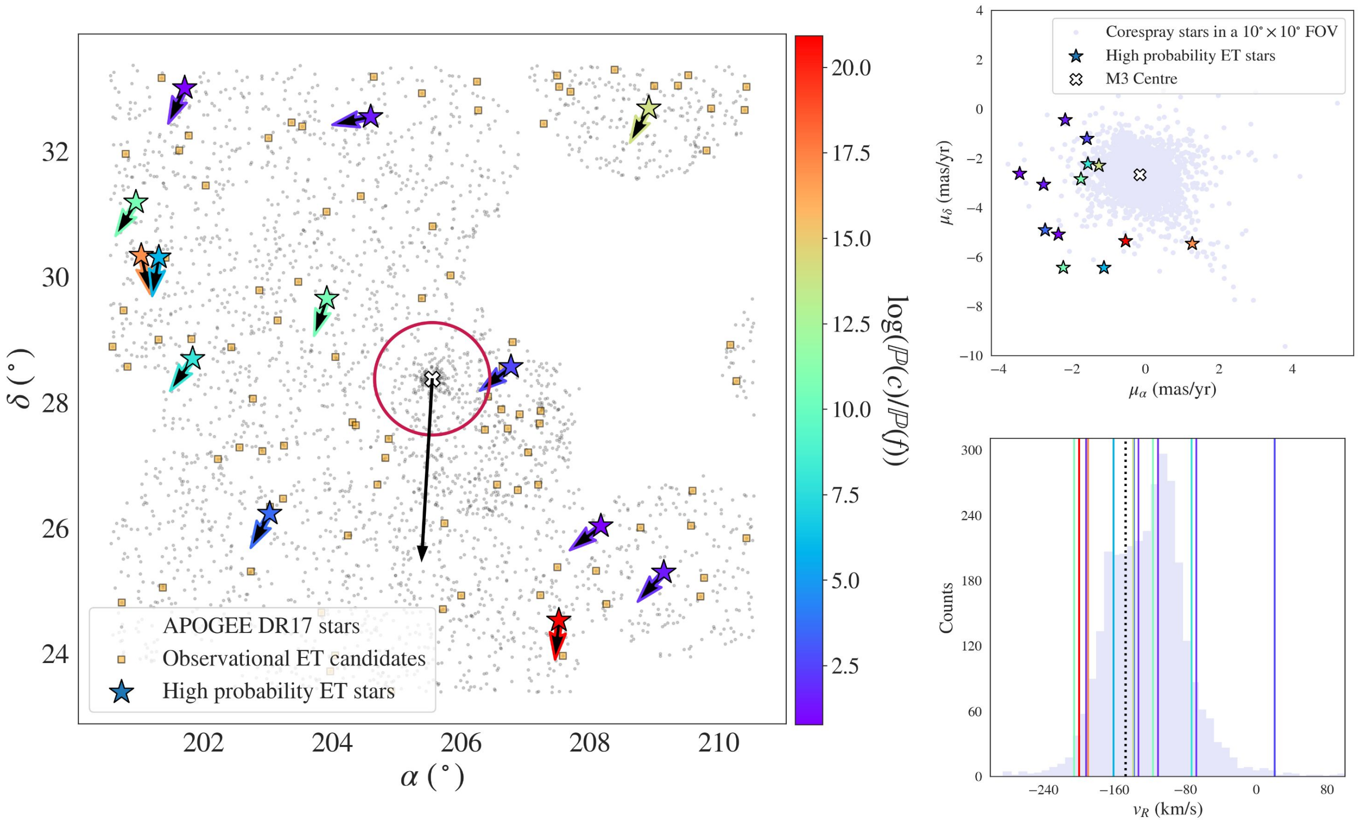
Grondin et al. (2023)

Corespray provides spatial locations, kinematics and escape velocities of 40,000 simulated extra-tidal stars of M3



Grondin et al. (2023)

Chemo-dynamical tagging and `Corespray` identified **10 new high-probability extra-tidal stars of M3.**



Grondin et al. (2023)

M3 is only one globular cluster in the Milky Way.

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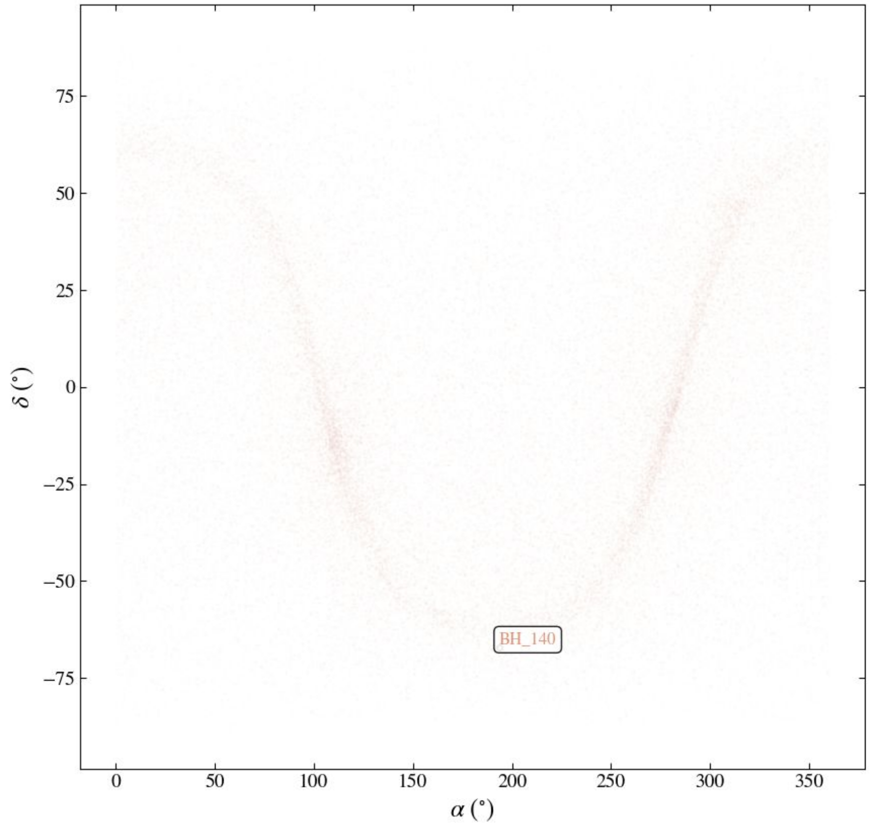
We can use Corespray to produce extra-tidal star and binary distributions for all 160+ Milky Way GCs.

Catalogue of Galactic GEMS: Globular cluster Extra-tidal Mock Stars

Grondin et al. (2024a)

The spatial distributions of extra-tidal stars can vary in shape and size.



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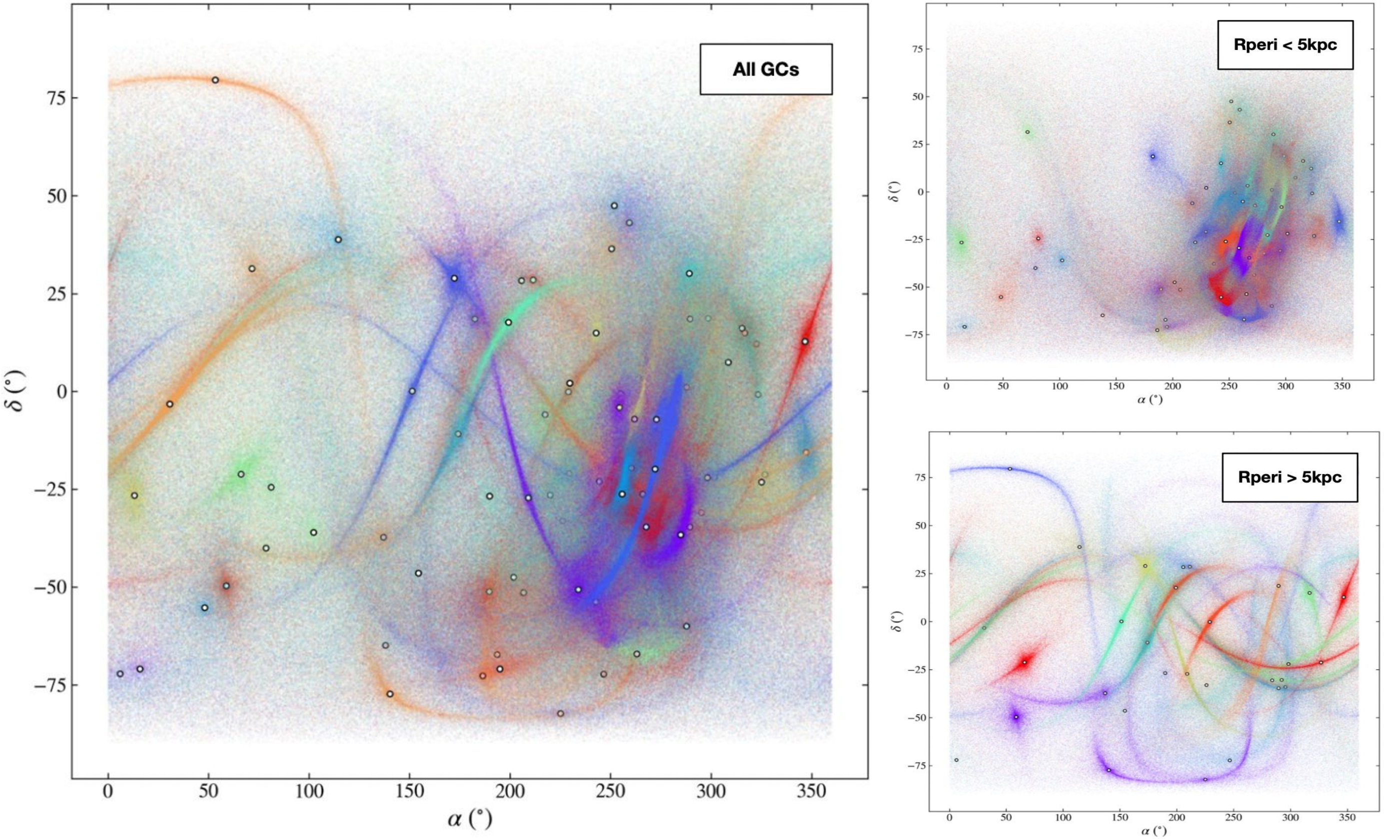

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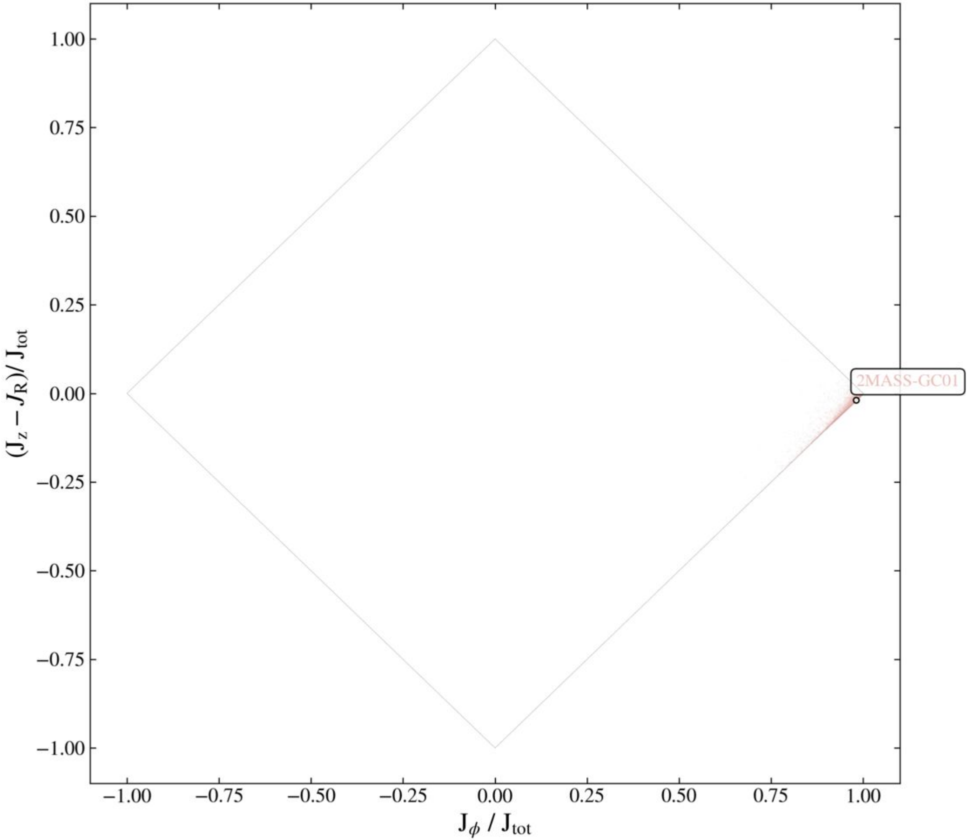
The action distributions of extra-tidal stars are ~ unique for each GC.



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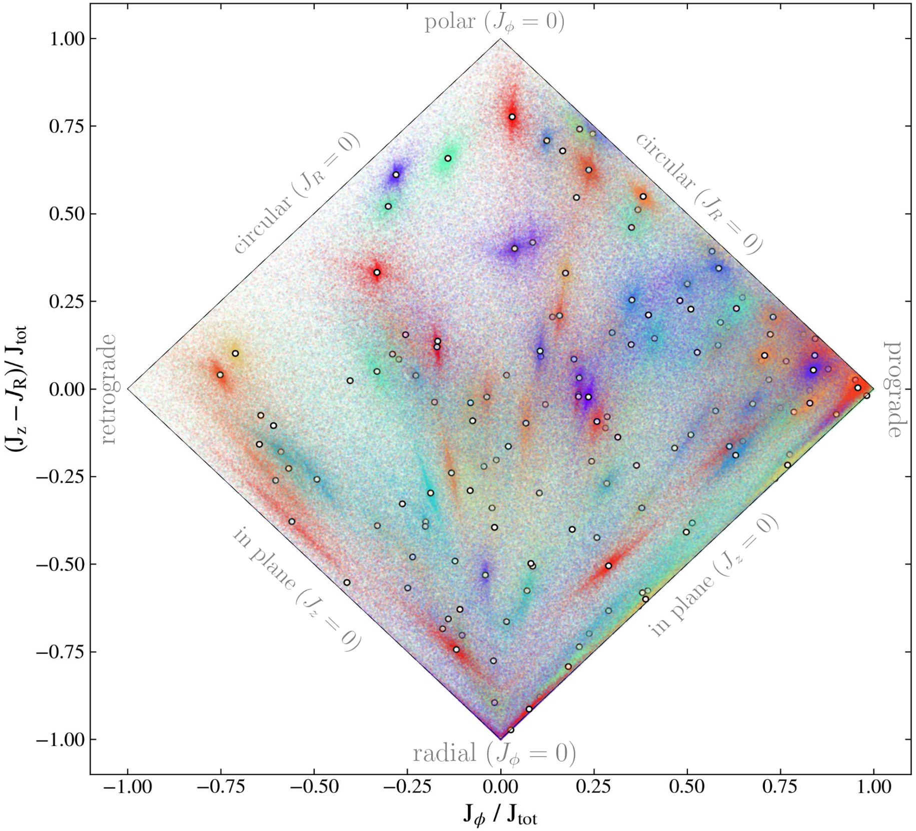

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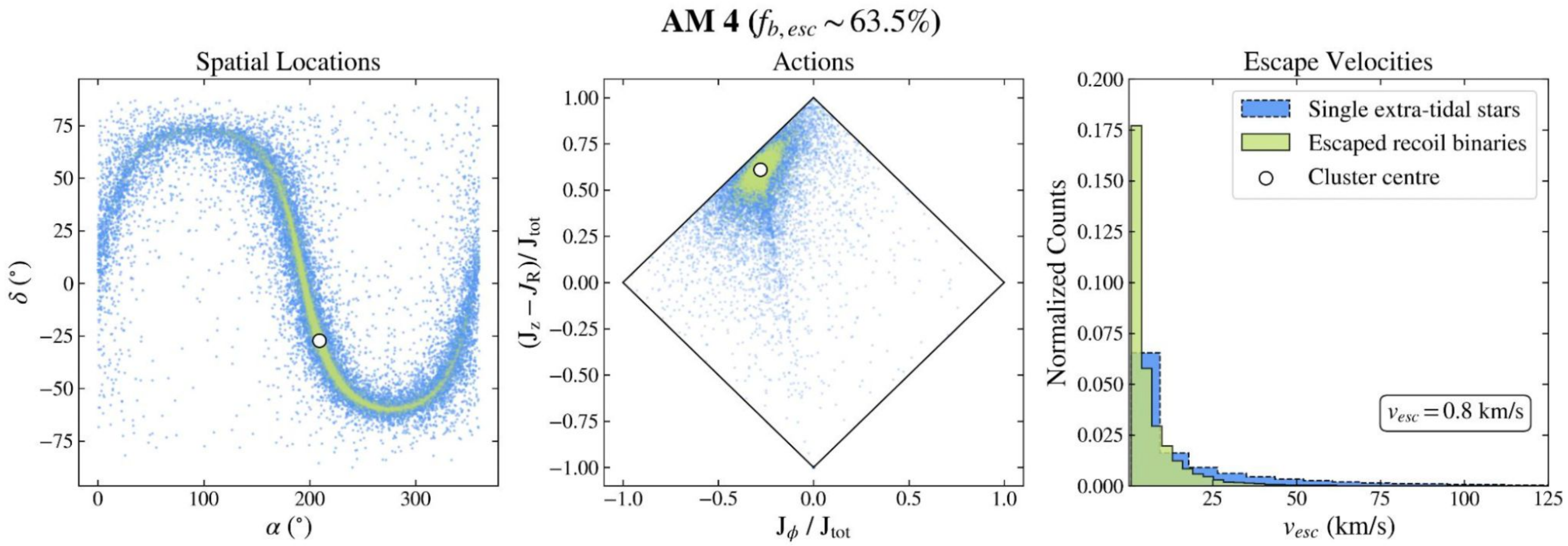
Extra-tidal binaries are more concentrated near the GC's centre than single escapers.



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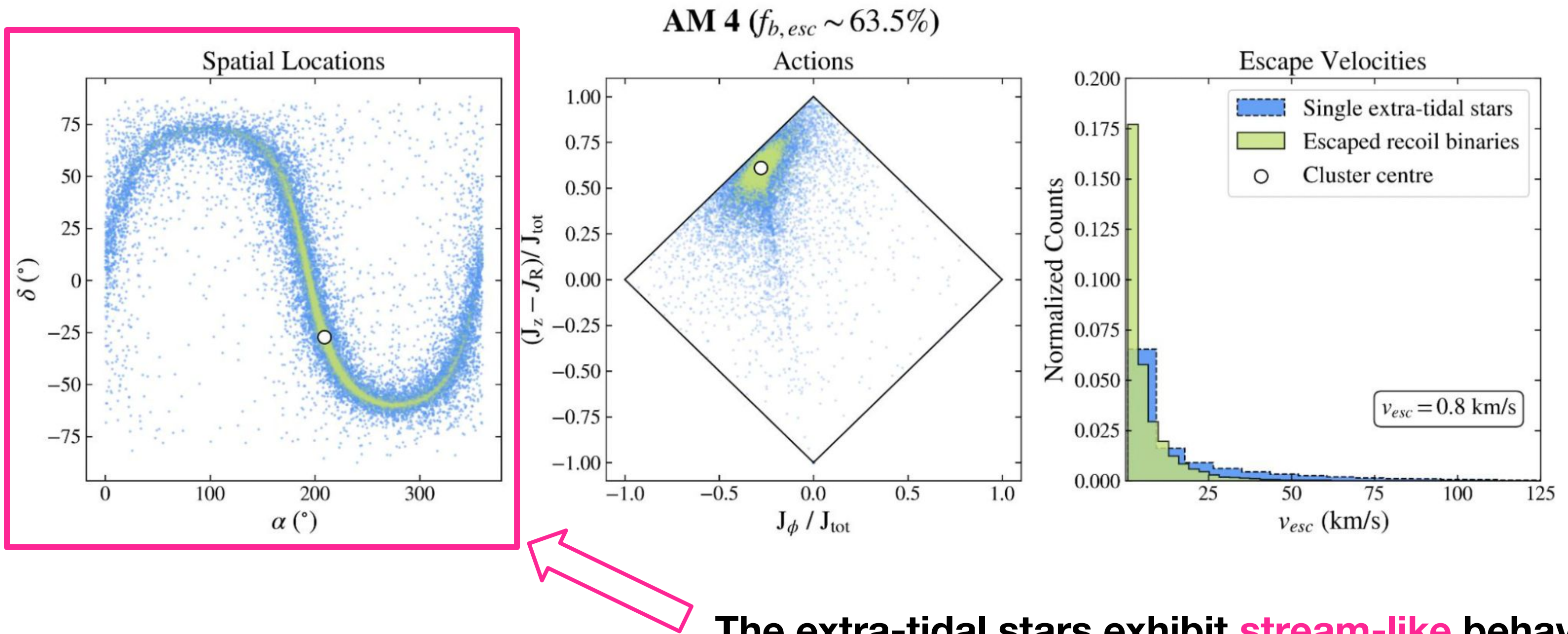
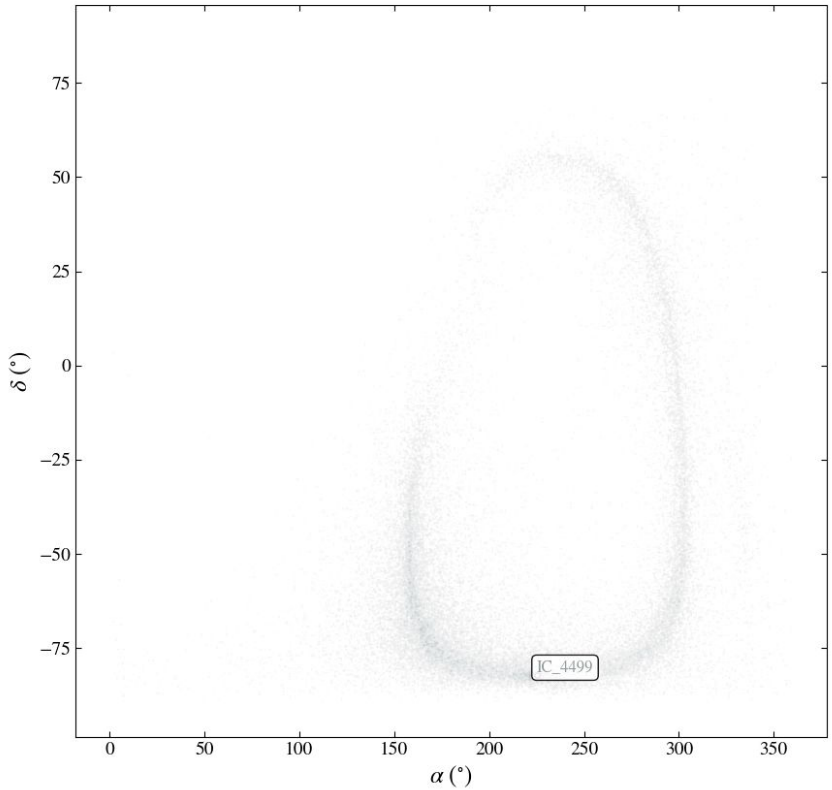


The extra-tidal stars exhibit stream-like behaviour?

Grondin et al. (2024a)

GEMS Application: Can stars and binaries from GC cores contaminate stellar streams?



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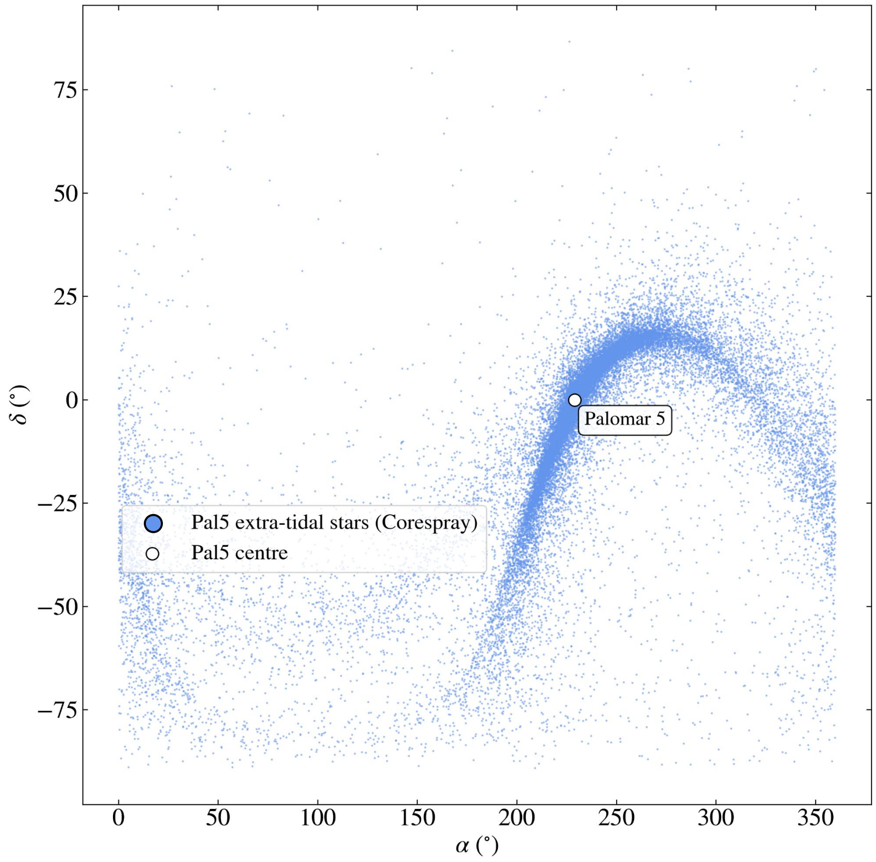

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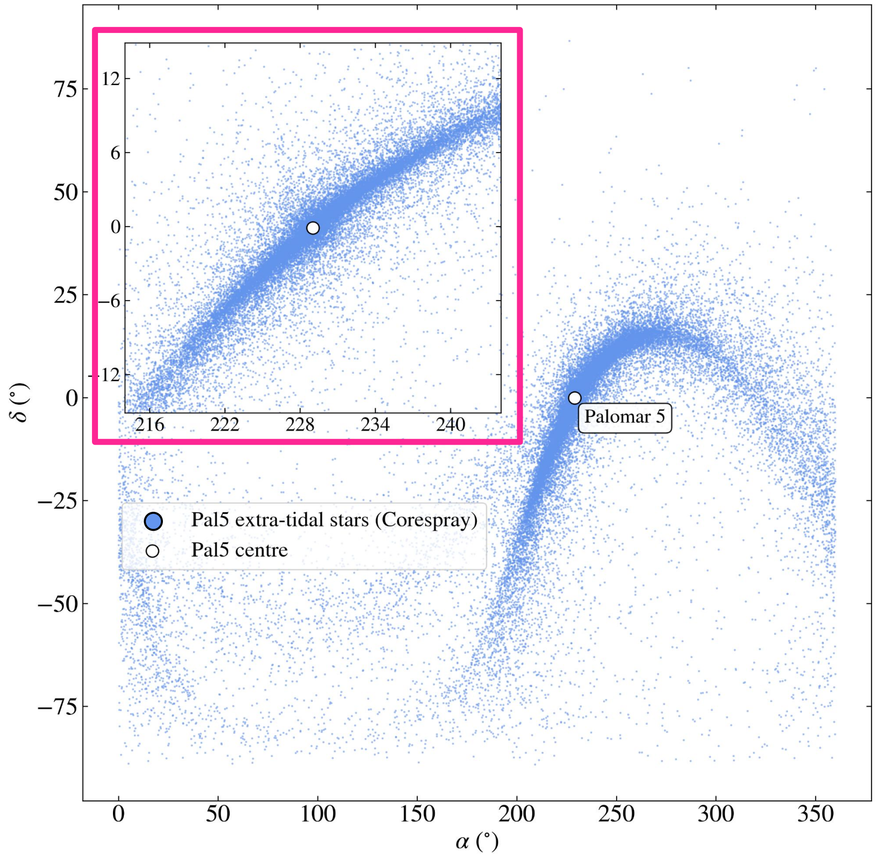

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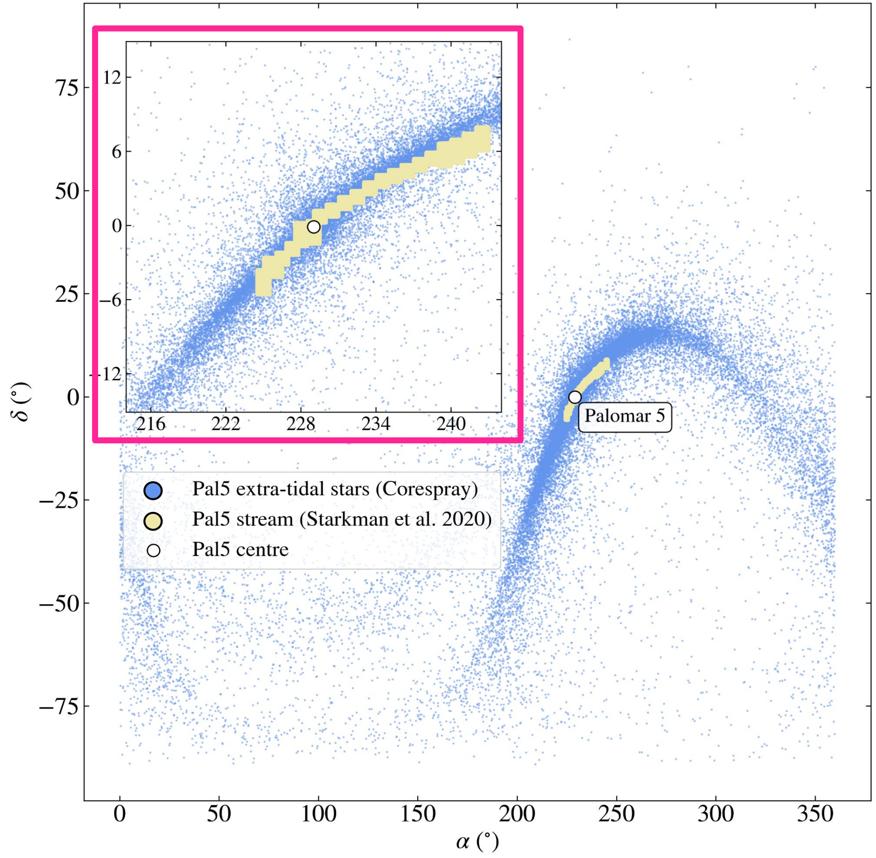

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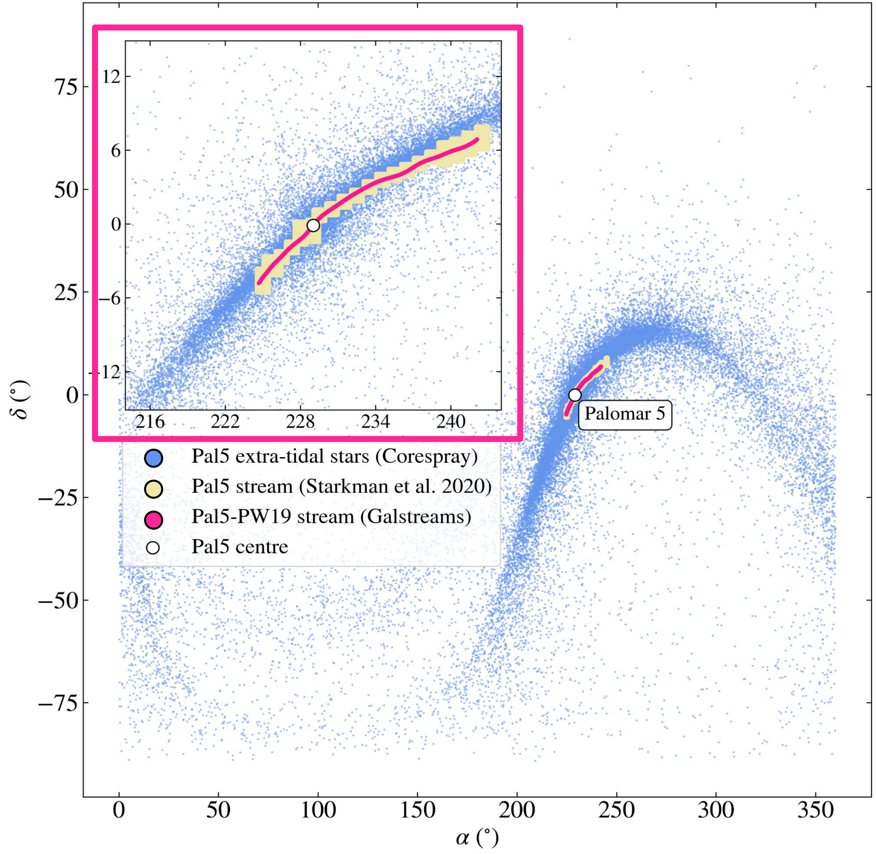
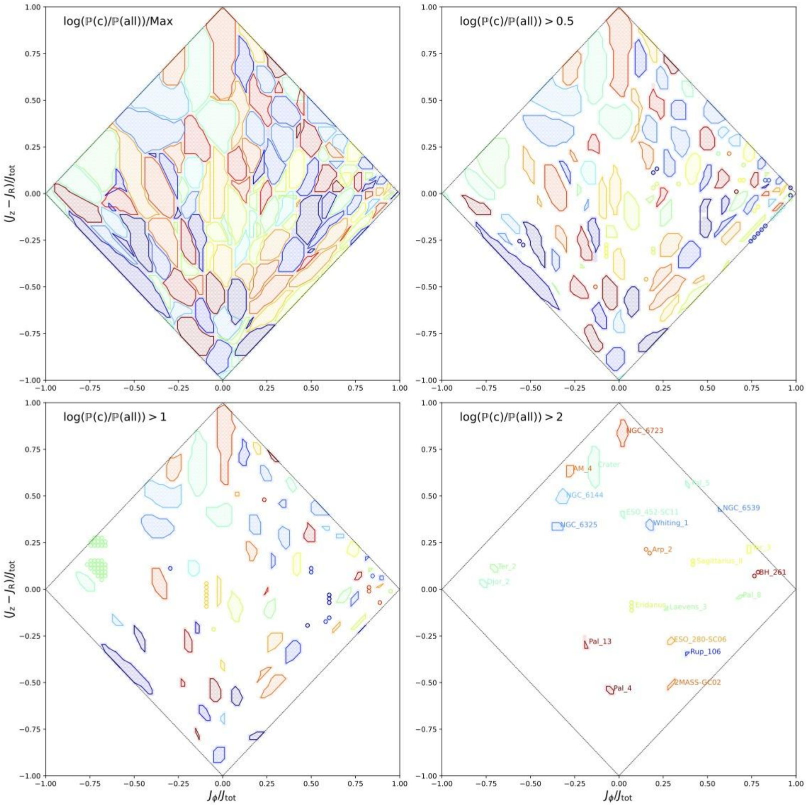


Grondin et al. (2024a)

Lost and Found: Discovering more observational extra-tidal candidates with GEMS!



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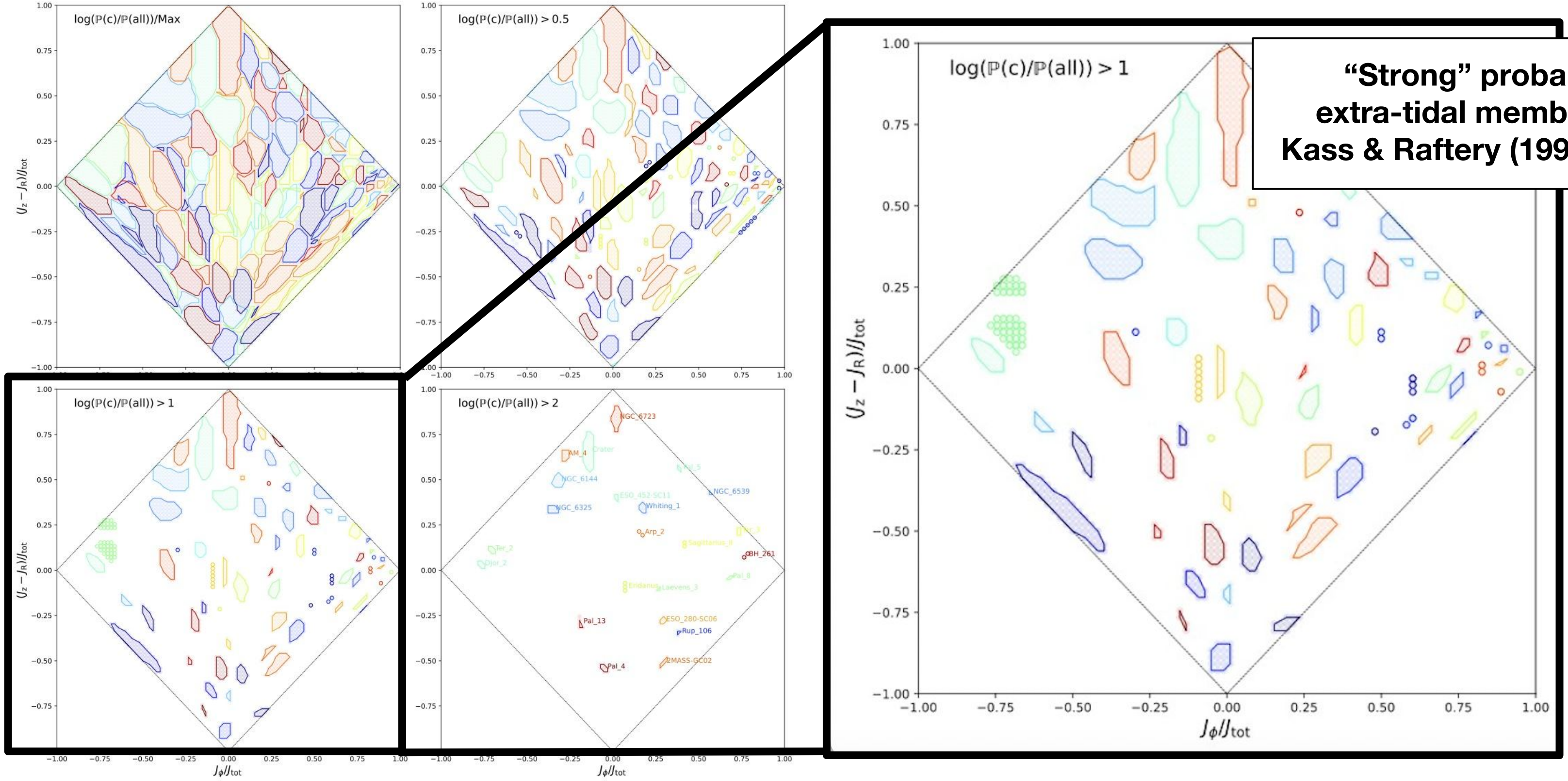


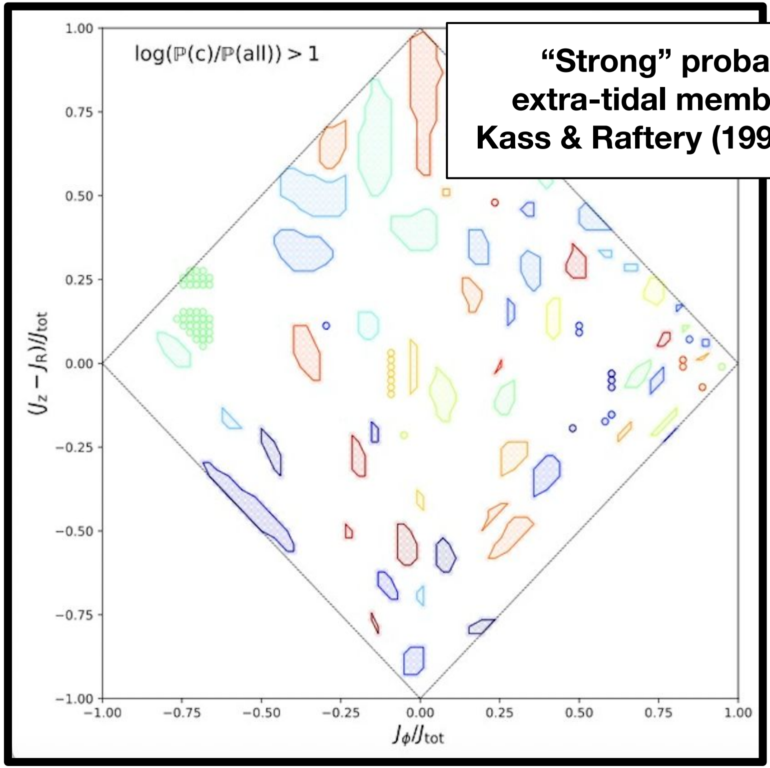
"Strong" probability extra-tidal members via Kass & Raftery (1995) metric

Grondin et al. (2024a)

Lost and Found: Discovering more observational extra-tidal candidates with GEMS!

Chemo-dynamical tagging applied to stars in APOGEE DR17 identifies **~100s of new observational extra-tidal candidates in ~25 GCs.**

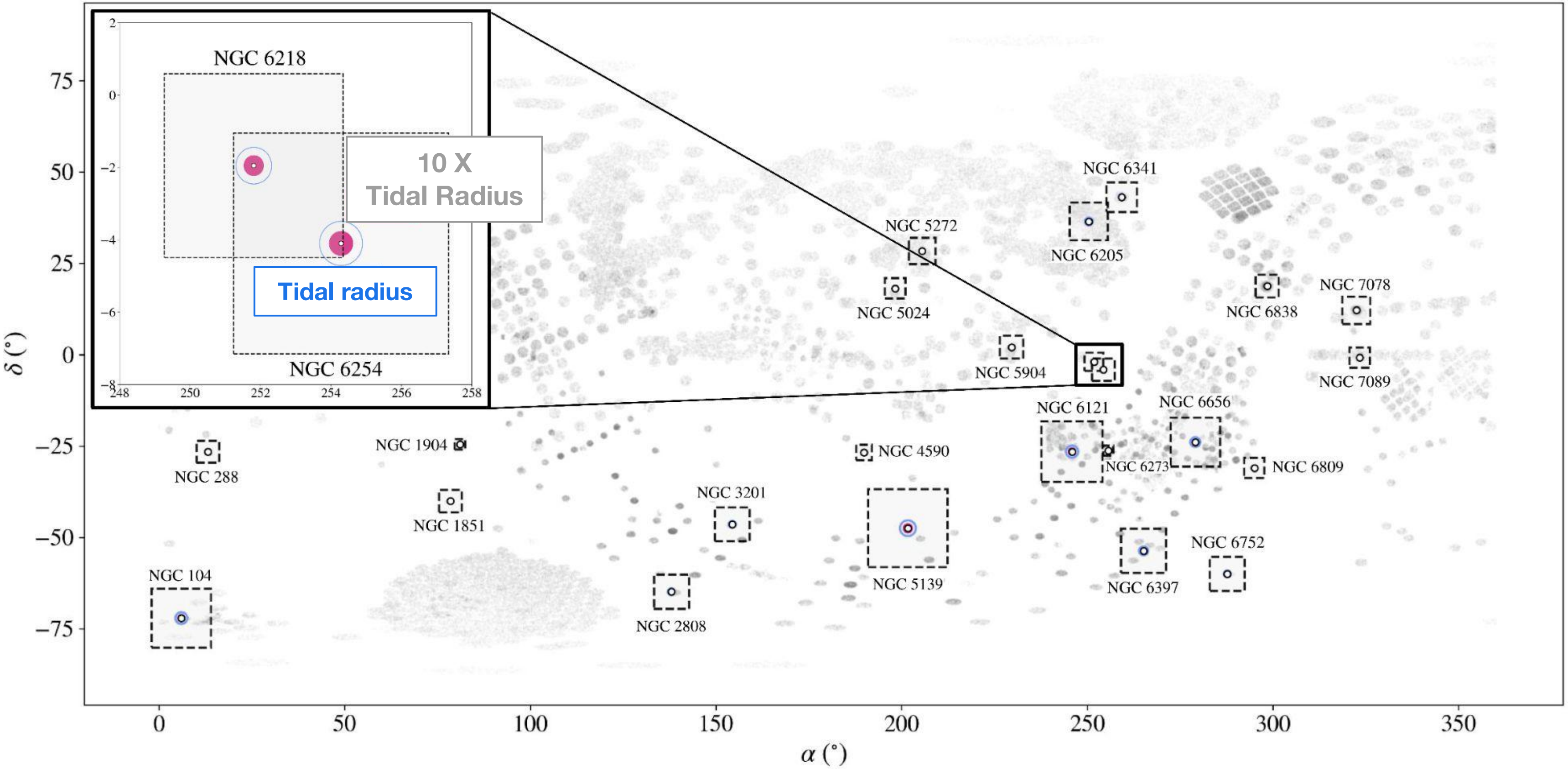
Confirm cluster origin with GEMS!



"Strong" probability extra-tidal members via Kass & Raftery (1995) metric

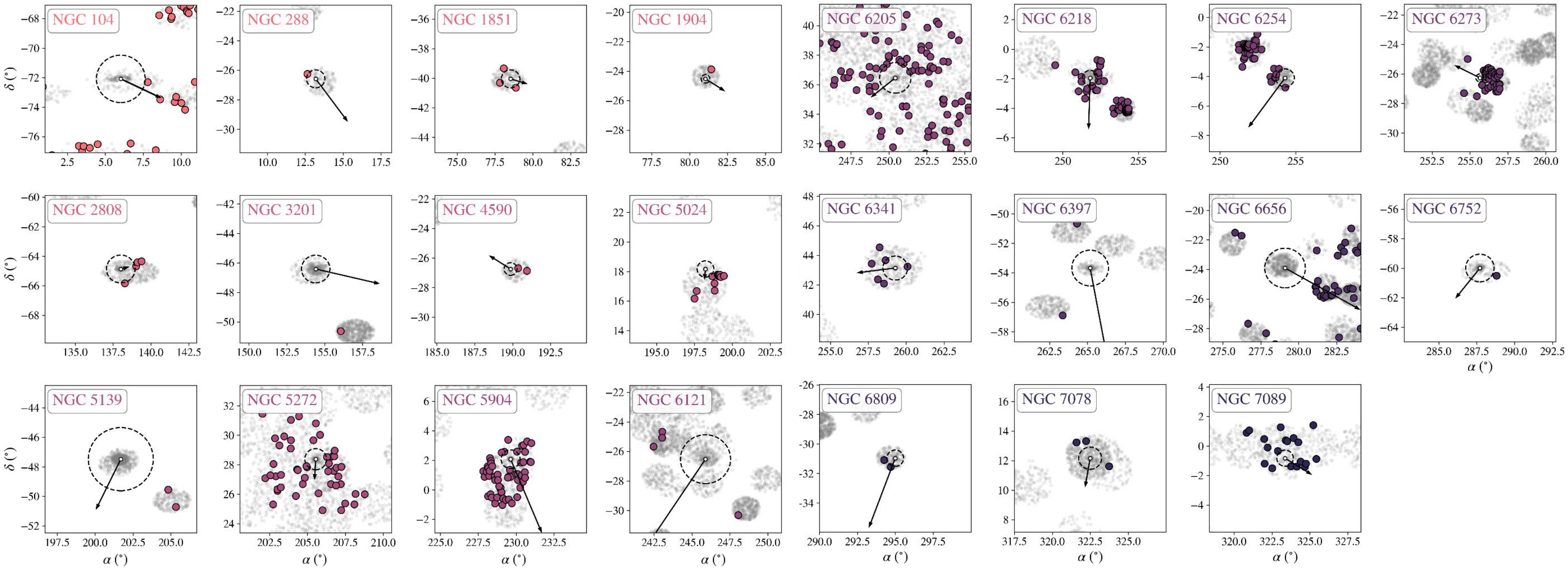
Grondin, Wang, et al., in prep.

Searching for extra-tidal stars of 25 Milky Way GCs within 10X the cluster's tidal radius.



Grondin, Wang, et al., in prep.

Chemical tagging yields hundreds of extra-tidal candidates.



Currently confirming whether these stars were dynamically ejected (GEMS catalogue) or tidally stripped (e-TidalGCs Project; Ferrone et al. 2023).

Grondin, Wang, et al., in prep.

Come and chat if you're interested in machine learning for star cluster science, the Corespray software, utilizing the GEMS catalogue, etc.!

Jupyter notebook: Machine Learning Techniques for Star Cluster Science

Corespray software

Full GEMS Catalogue

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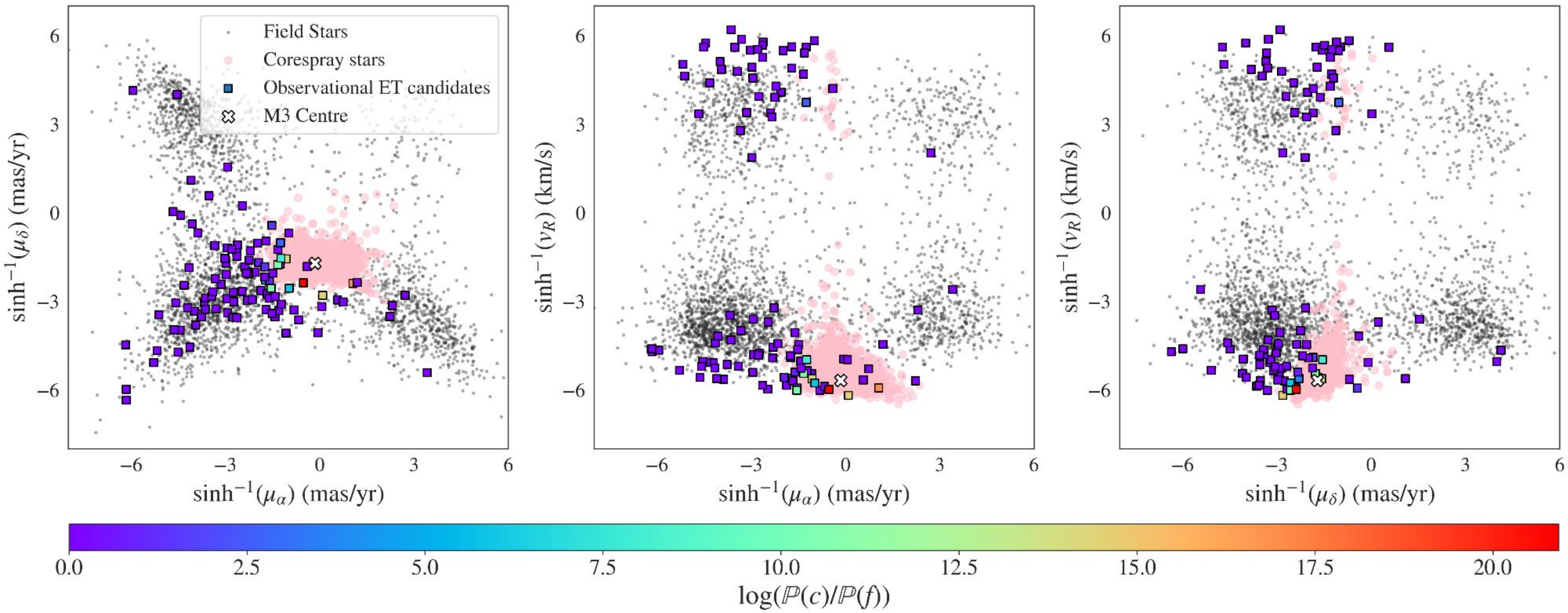
Supplemental Slides

Using Gaia EDR3 proper motions and APOGEE DR17 RVs, we apply a **multivariate Gaussian model** (`scikit-learn`) and an **extreme deconvolution** (`astroML`) to compute the probabilities that each extra-tidal candidate belongs to the `Corespray` or field star distribution of M3.



We identify 14 extra-tidal candidates with log(Pc/Pf) > 0!

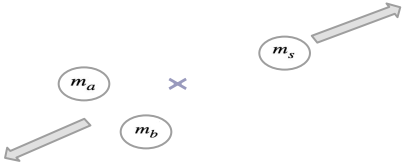
How does Corespray work?

Corespray samples 3D positions, velocities, actions, proper motions, escape times/velocities and masses of extra-tidal stars and recoil binaries.

Input GC conditions
e.g. $M_{GC}, \sigma_0, \rho_{core}$...

Define initial positions, velocities for stars along orbit of GC.*

*orbits defined using galpy. (Bovy 2015)



Sample masses of 3-body system from IMF.

Compute prob. of 3-body escape.

$$P_s = \frac{m_s^{-3}}{m_s^{-3} + m_a^{-3} + m_b^{-3}}$$

Compute escape velocity.
If vesc_s > vesc_GC, star/binary escapes.

Integrate stars in Galactic + King potential to the present day.

Extra-tidal stars simulated!

Three-body framework from Valtonen & Karttunen (2006)

How does Corespray work?

GC/Galaxy inputs

- Mass
- Core density
- Velocity dispersion
- Tidal radius
- Escape velocity
- Galactic potential
- etc.

2+1 encounters

Extra-tidal star/binary outputs

- 3D positions
- 3D velocities
- Proper motions
- Actions
- Escape times
- Escape velocities
- etc.

Corespray produces extra-tidal star and binary distributions FAST.

Example: Want to simulate the outcomes of three-body interactions from Palomar 5.

Nbody6

Runtime:

~1 month to produce **~100s** of 3-body interactions – not all will be ejected.

Realistic, but small-N population.

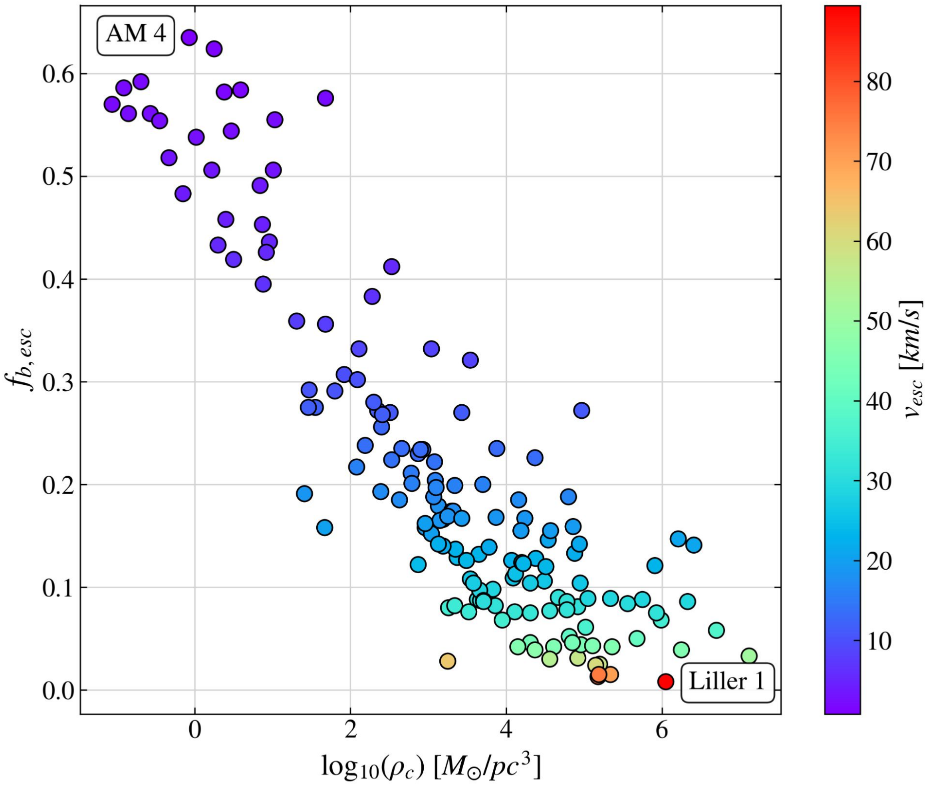
Corespray

Runtime:

~2 hours to produce **~10,000s** of 3-body interactions leading to extra-tidal stars/binaries.

Sampled, but high-N population.

Binary escape: strong correlation between vesc, core density and escape fraction.



Steffani Grondin | University of Toronto

Grondin et al. (2023b), in prep.

The GEMS catalogue initial conditions

We initialize Corespray to produce **N=50,000 over 5 orbital periods** to produce extra-tidal stars of **every Galactic GC** from the following conditions:

- **7 different models of the Milky Way gravitational potential**
    - **Baseline:** a simple static tidal field with `MWPot2014` (`galpy`, Bovy 2015)
    - **Time-dependent:** Rotating bar + spiral arms; LMC infall
    - **Time-independent:** heavy DM halo (McMillan 2017), DM halo triaxiality (oblate, spherical and prolate halos)

- **Encounter radii:**
    - Between the binary semi-major axis and 2X mean separation of stars in GC's core

- **Initial mass function:**
    - Kroupa IMF (10^6 stars) evolved for 12 Gyr to approximate IMF at present.