EXTENDED STRUCTURE IN GLOBULAR CLUSTERS

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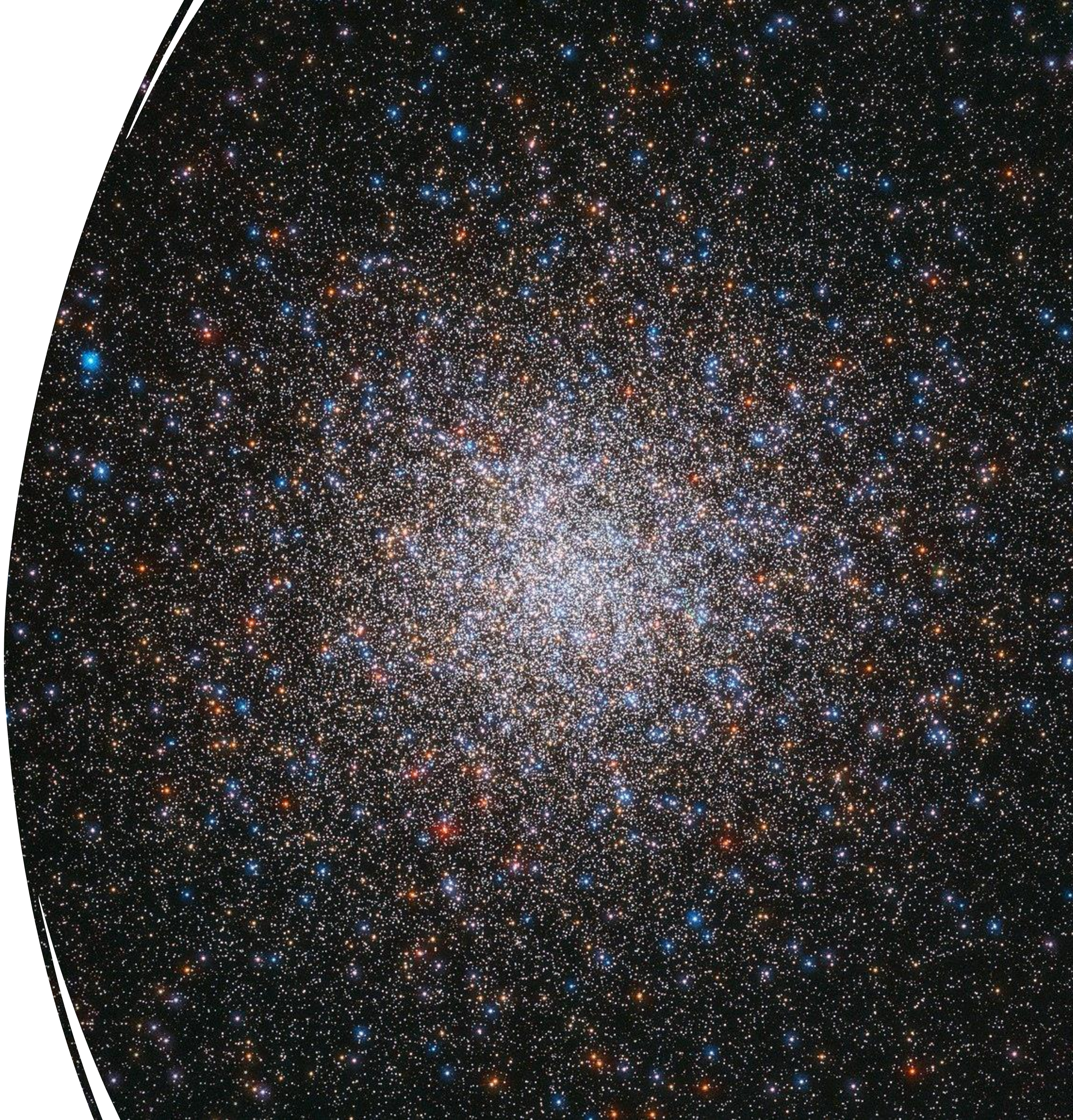
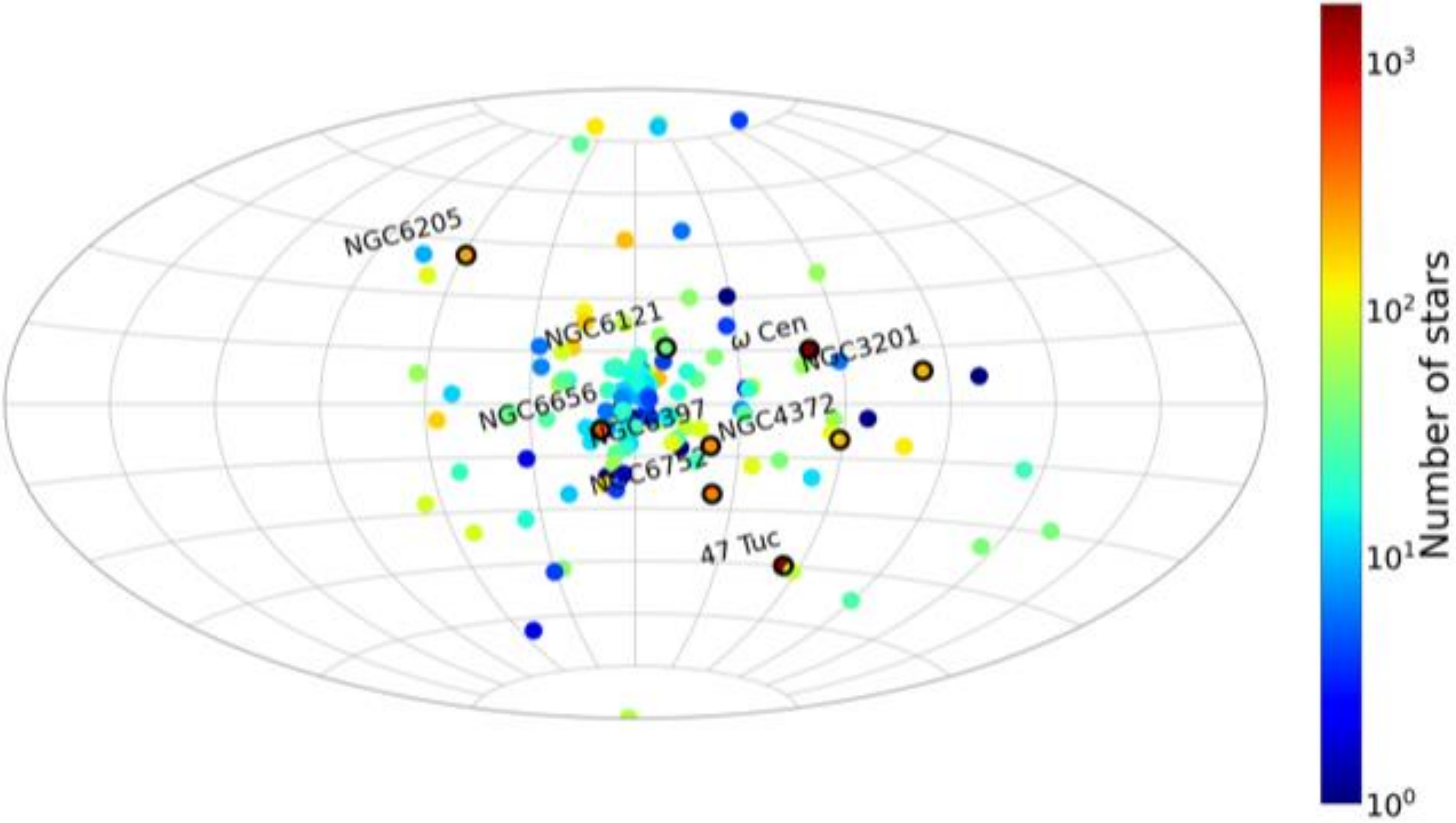


Extended Structure In Globular Clusters

- Define Globular Clusters (GC) and extended structures
- Pre-Gaia extended structure
- The Gaia Revolution
- Extended structures around Milky Way (MW) GCs
- What's coming up: next generation of instruments and Telescopes

Globular Clusters



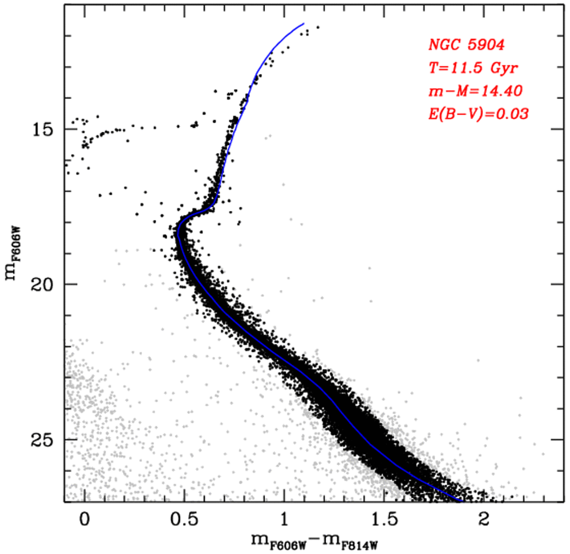
Katz et al. 2022

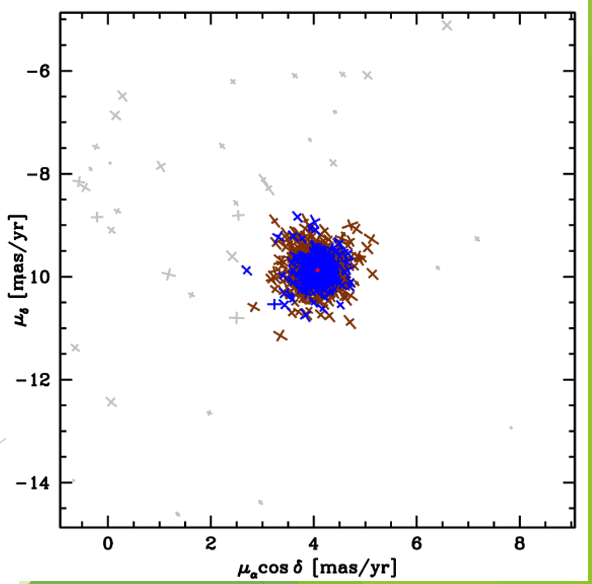
At least 164 GCs in MW (according to H. Baumgardt GC database)

Globular Clusters

- Globular clusters as old compact stellar systems.
- "Classical" view is a simple stellar population:
  - Formed at the same time
  - Under the same conditions
  - From a single molecular cloud

M5 (NGC 5904) CMD and proper motion distribution

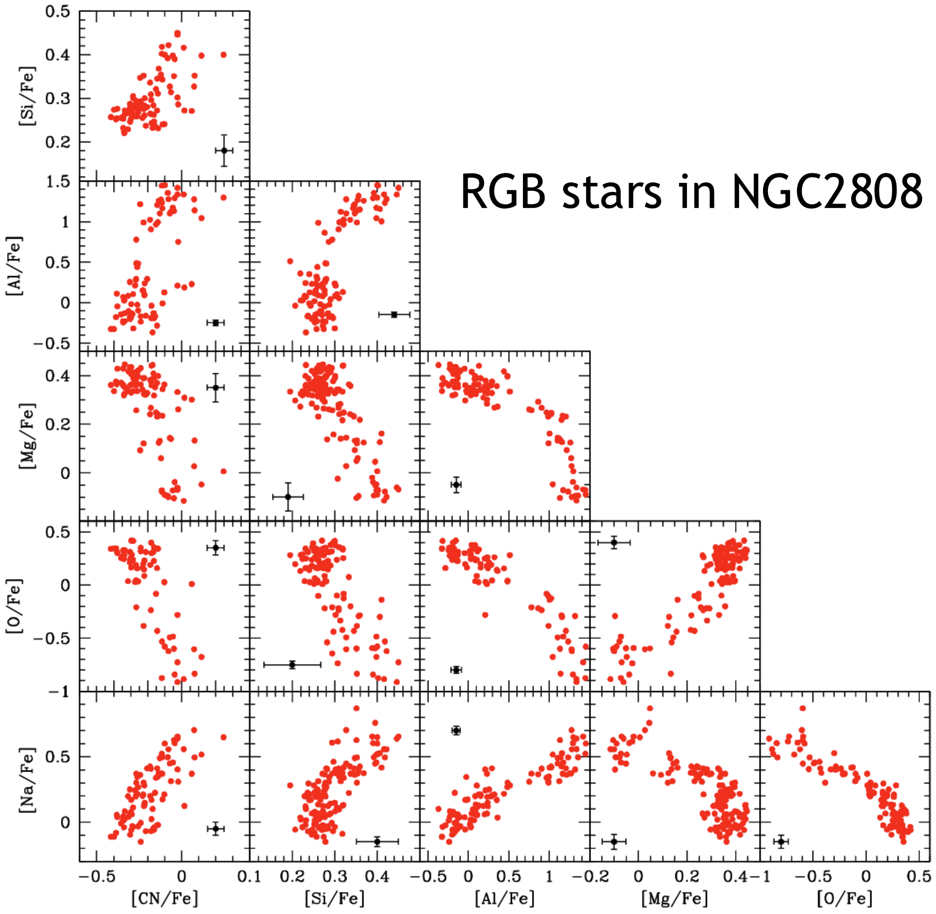




Baumgardt et. Al 2023

Globular Clusters

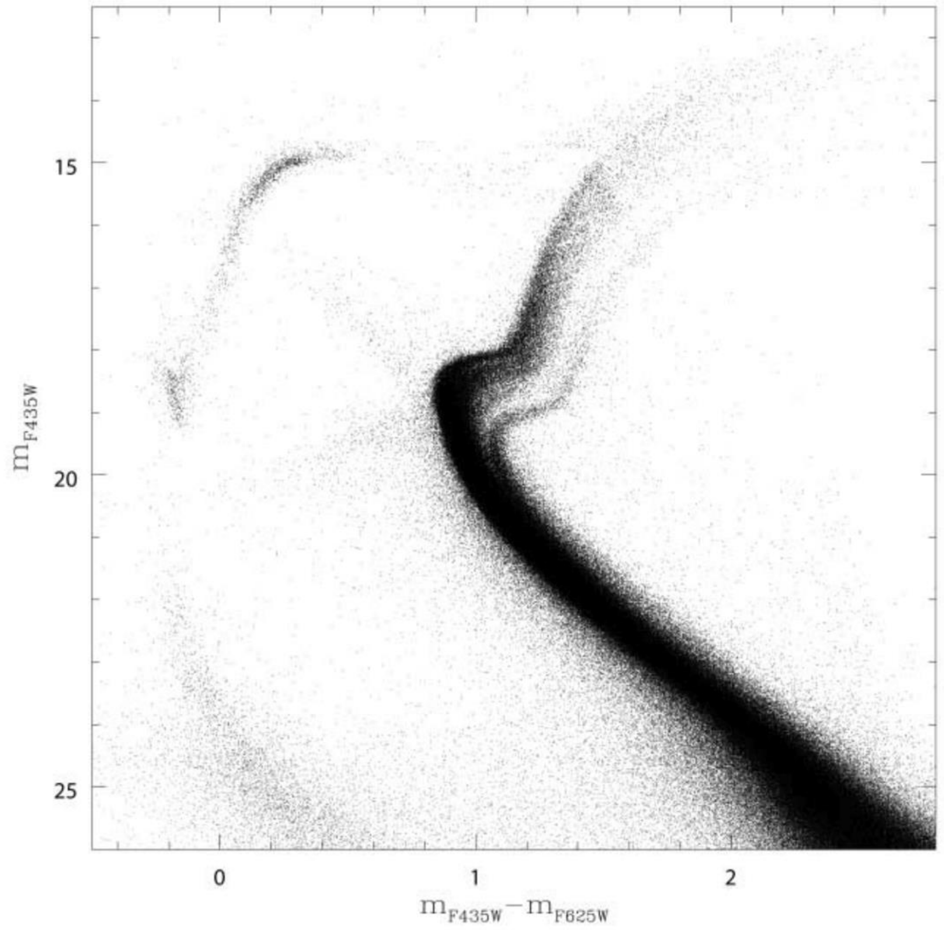
- In fact, only a few MW GCs demonstrate a single stellar population.
- Most GCs show light element variations.
  - E.g, Na-O variations.
  - E.g, Mg-Al variations.
- Origins of the light element variations generally unclear.
  - in multiple star formation events.
  - nucleosynthesis at different temperatures.



(Caretta et al. 2016; Gratton et al 2019)

Globular Clusters

- Heavy element variations are less common.
  - Multiple [Fe/H] populations
  - Unique s-process and r-process variations
- Complicated stellar populations imply a more complex formation scenario.
- Accreted GCs? Nucleated Dwarf Galaxy cores?



NGC 5139 (ω Centauri), Villanova et al. 2007

Globular Clusters

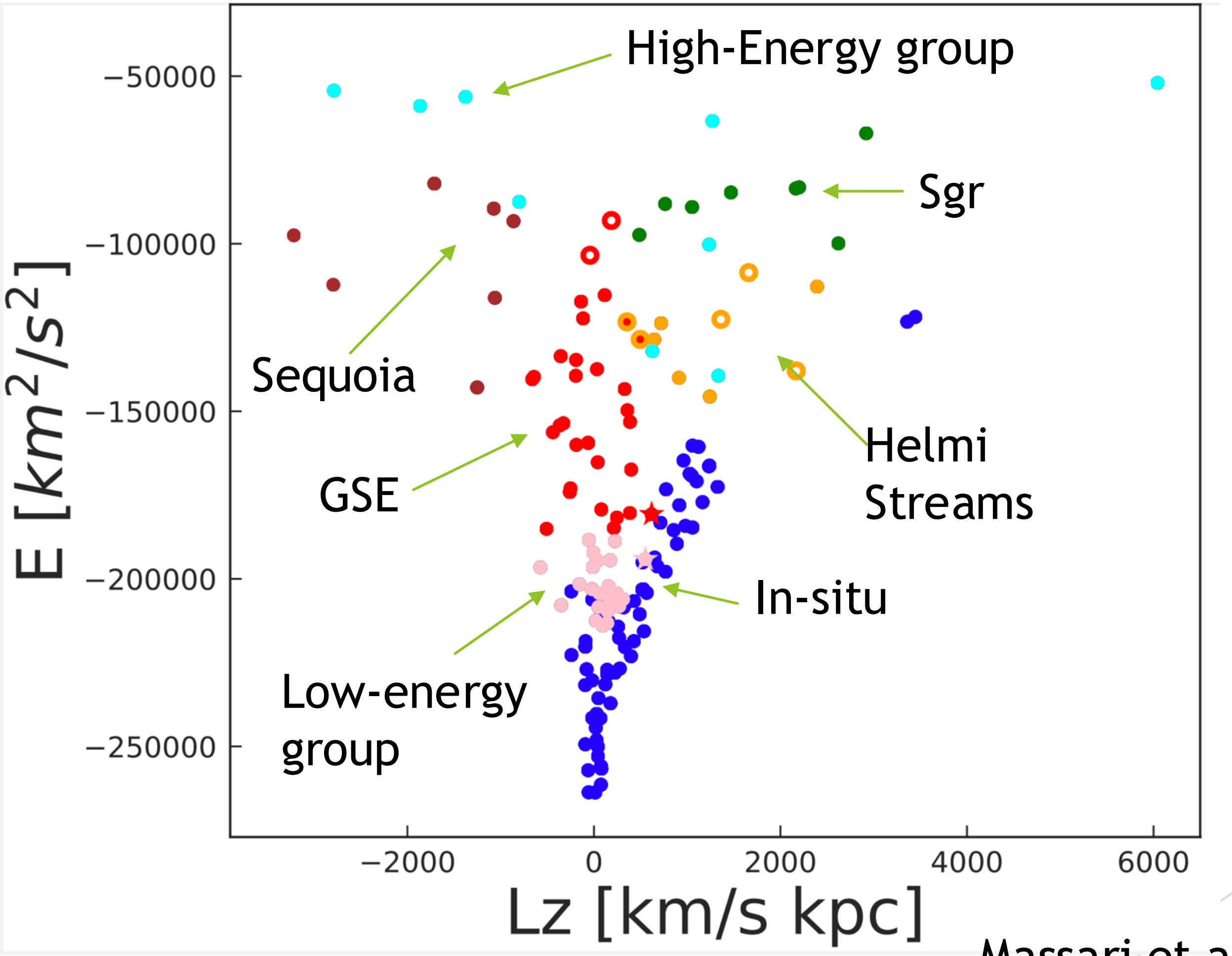
Origin of the MW GC system

- In-situ vs accreted?
  - Pre Gaia:
    - Chemistry – e.g, [Fe/H] variations.
    - Kinematics – e.g., retrograde orbits.
  - Post Gaia:
    - Action – Energy or Integral of Motion space tagging

Globular Clusters

Origin of the MW GC syst

- In-situ vs accreted?
  - Pre Gaia:
    - Chemistry – e.g,
    - Kinematics – e.g.
  - Post Gaia:
    - Action – Energy o



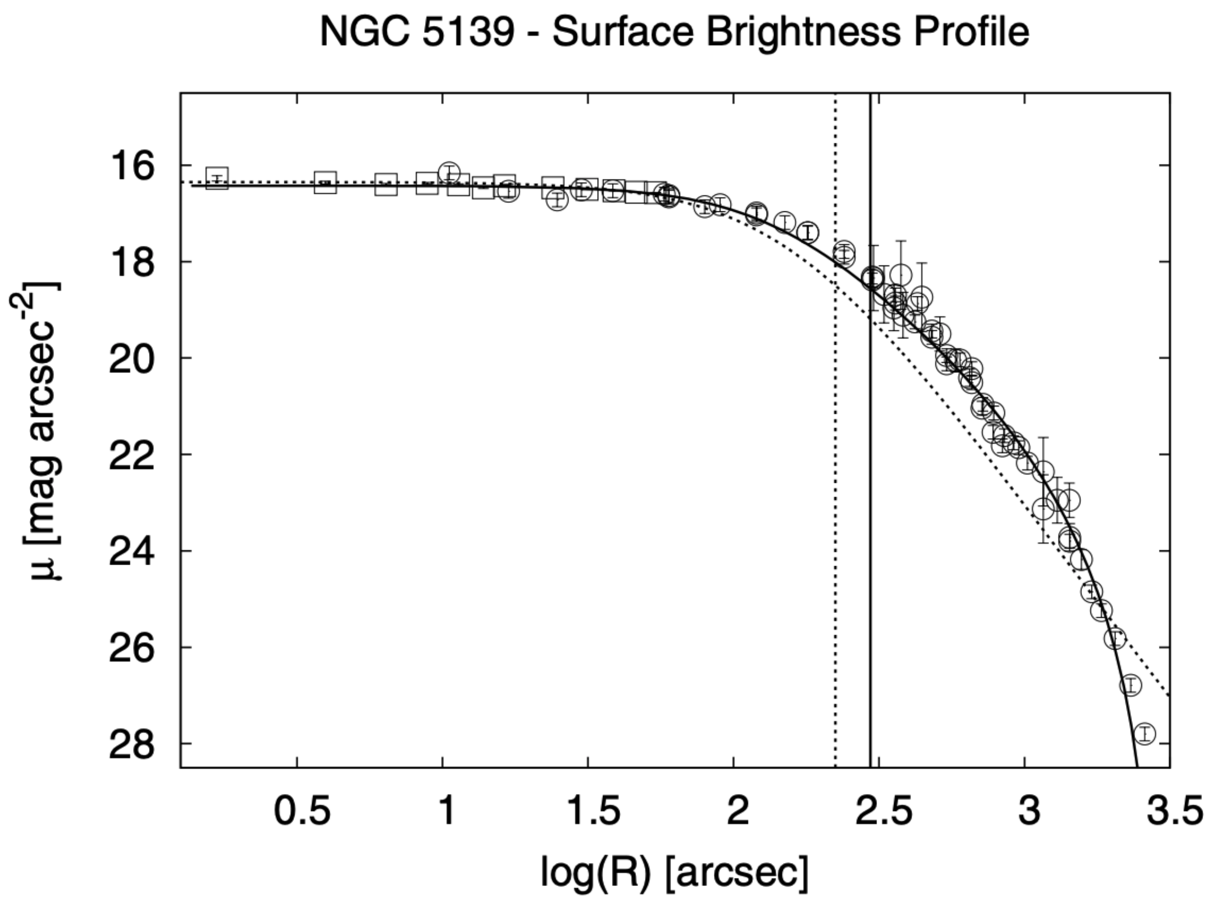
Massari et al. 2019

Note: GSE – Gaia-Sausage-Enceladus, Sgr- Sagittarius Dwarf

To the Periphery

The boundary between cluster and field is ambiguous.

- King (1962) tidal radius.

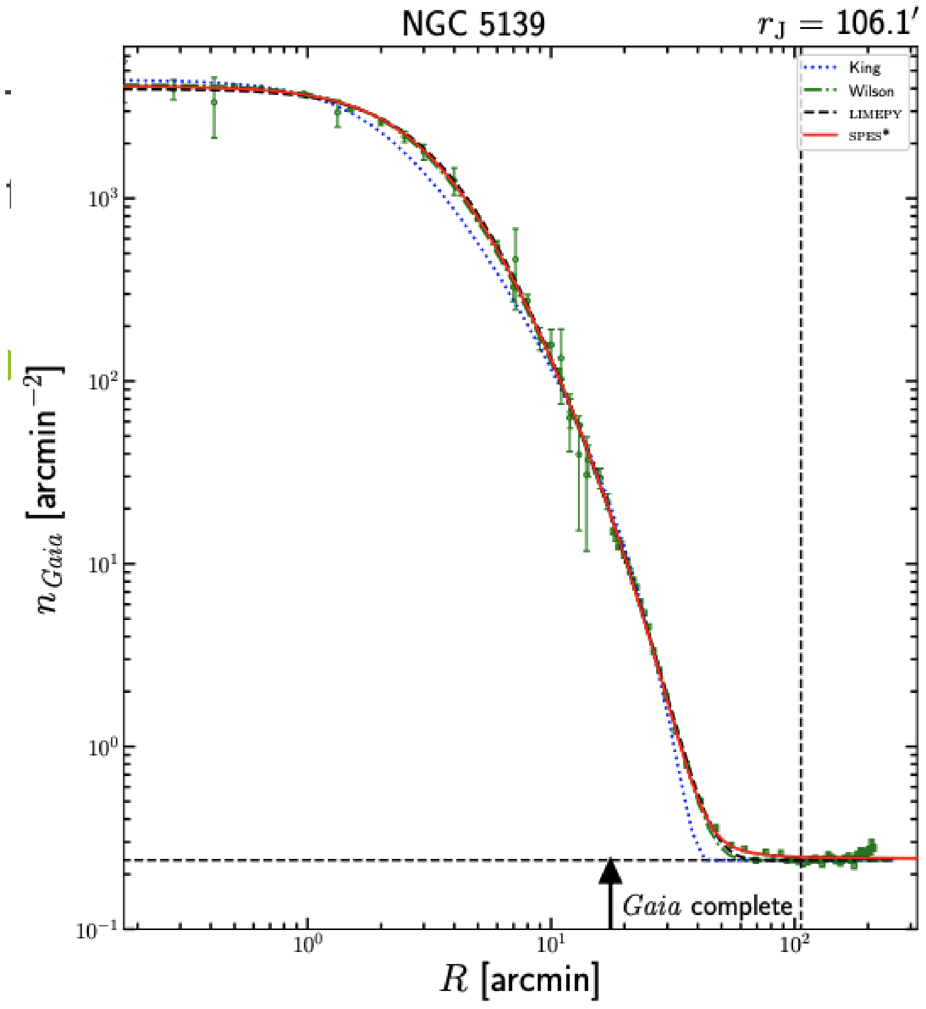


Faint stars.

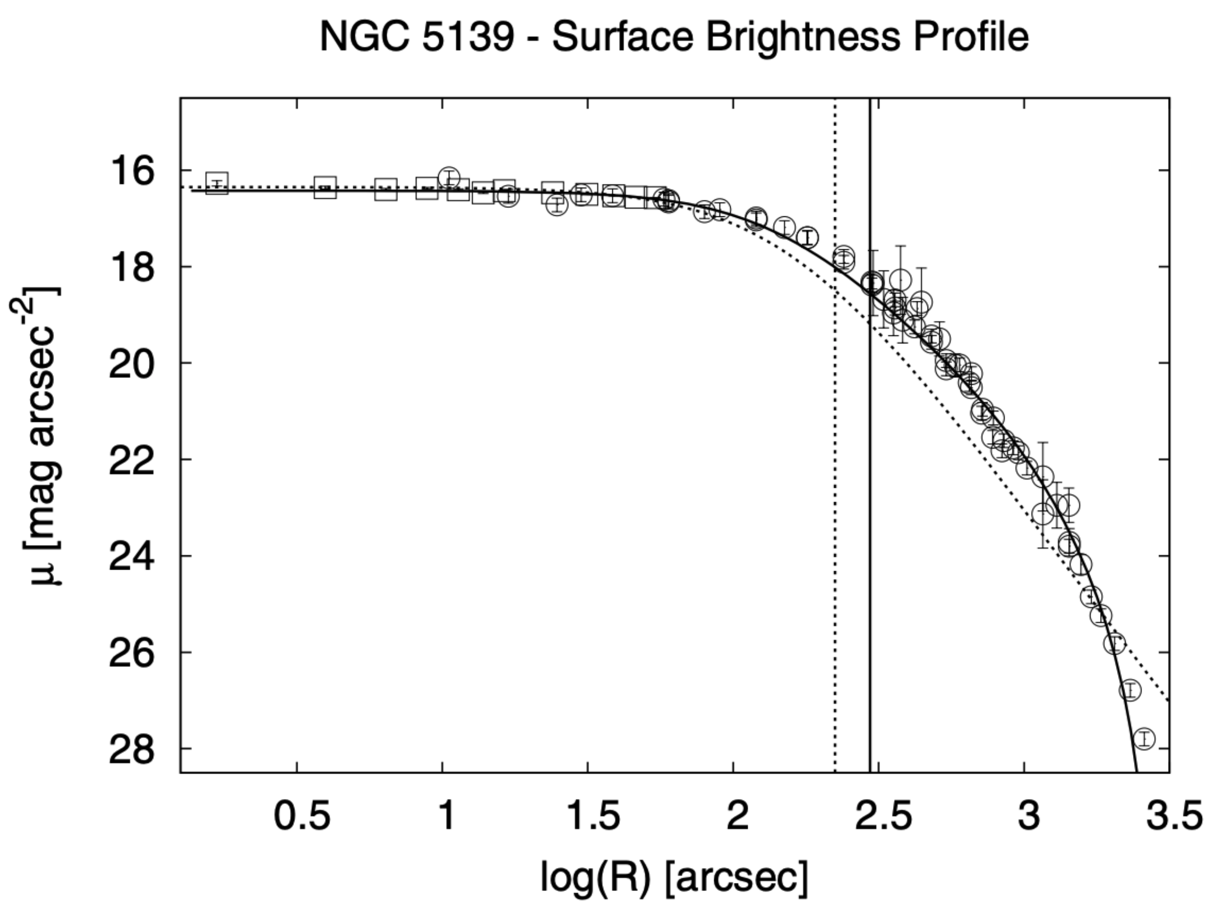
Size of field of view.

Zocchi et al. 2019

To the Periphery



De Boer et al. 2019



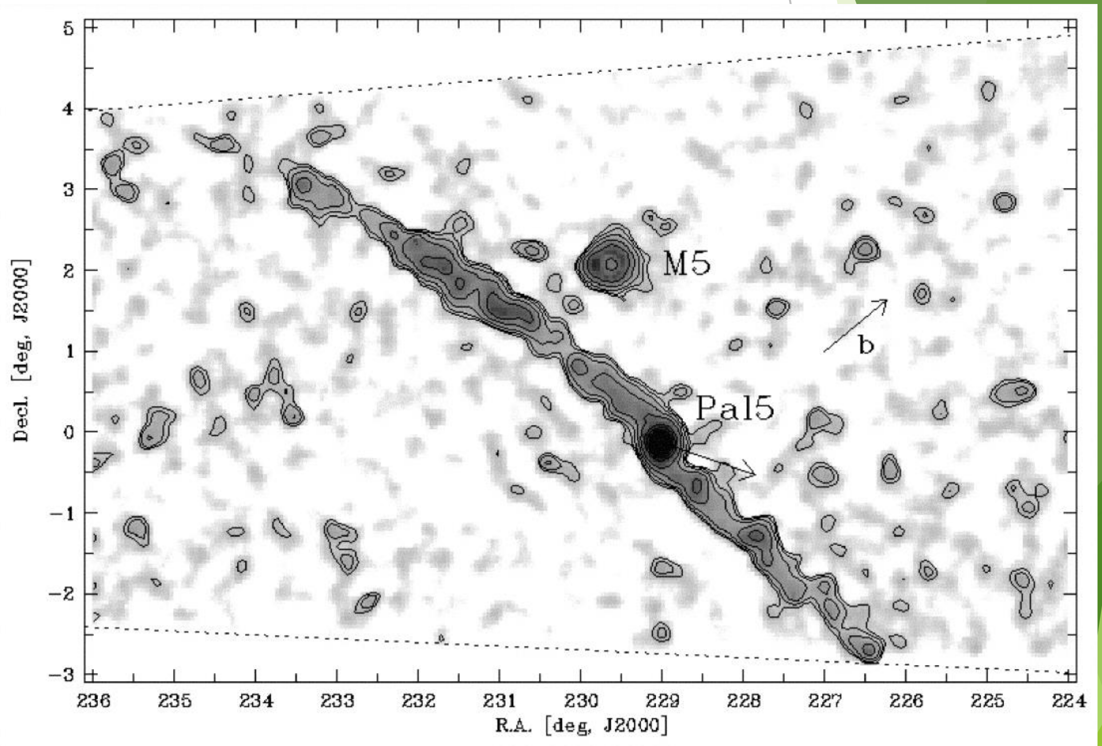
Zocchi et al. 2019

Extended Structure

Any kind of coherent, co-moving cluster-like stars in the periphery of GC, typically beyond the Jacobi radius.

Extended Structure – Tidal Tails

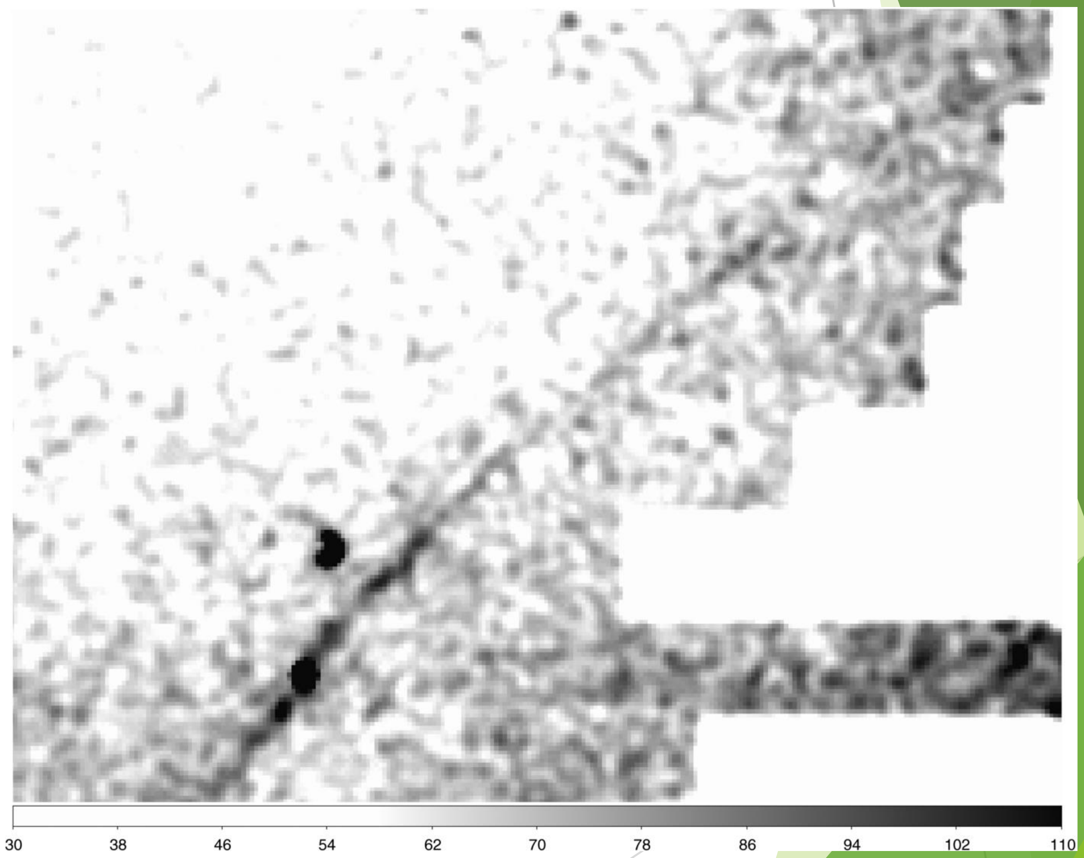
- The poster-child for extended structure is Palomar 5 (Odenkirchen et al. 2001,2003).
- Only a small group of known tidal existed pre-gaia.



Pal 5 (Odenkirchen et al. 2001)

Extended Structure – Tidal Tails

- Formation of Tidal tails (e.g., Kupper et al. 2011):
  - Excitement of stars through interactions with Galactic Potential (e.g., Disk shocks).
  - Excited stars pass through the Lagrange points of the GC, creating axisymmetric streams.
  - Tails typically follow the progenitor's orbit.
- Useful to understand many facets of the MW halo:
  - Tail substructure.
  - Shape of the Galactic halo at the stream.

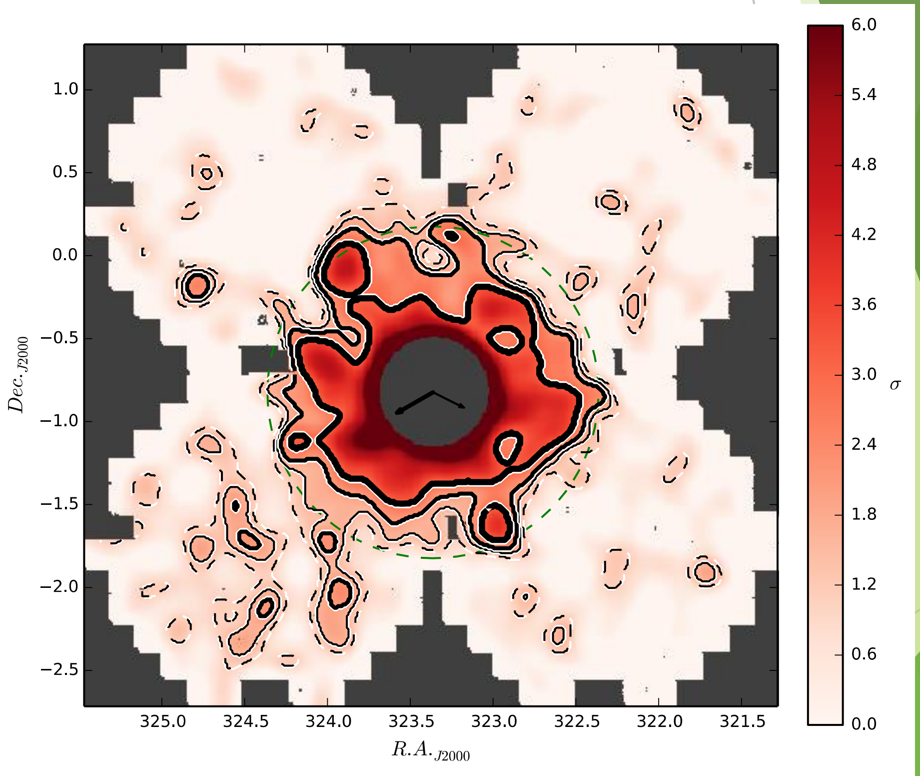


Gaps in the Pal 5 Stream (Carlberg et al. 2012)

Extended Structure - Spherical Envelopes

- Large Spherical diffuse envelopes of stars embed GCs.

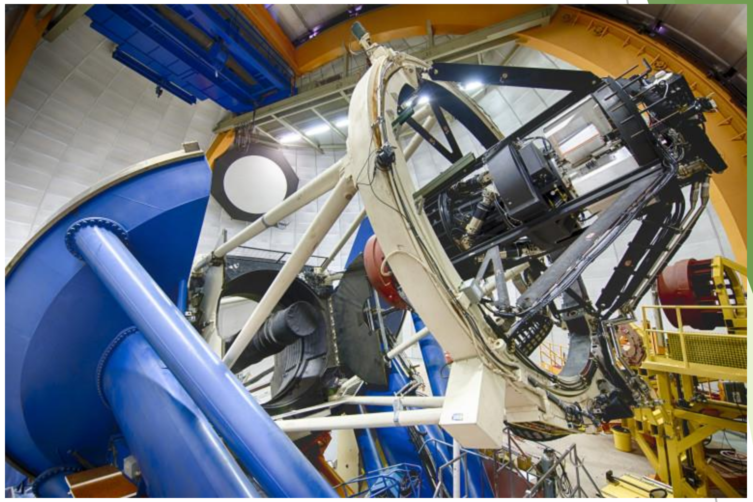
- Formation less unclear:
  - Embedded in a dark matter sub halo? (Penarrubia et al. 2018)
  - Indicative of a GC in the midst of disrupting? (e.g., Kupper et al. 2011)
  - Nucleated dwarf galaxy core? (e.g., Pfeffer et a.l 2014)



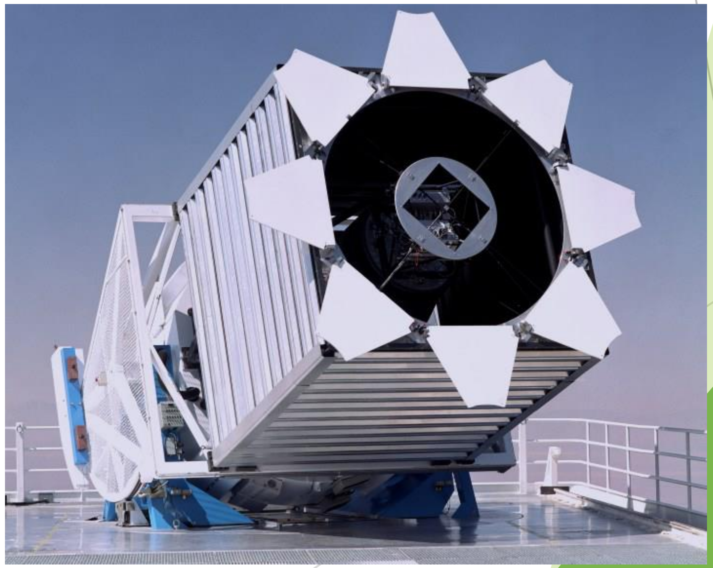
Kuzma et al. 2016

Pre-Gaia

- Pre-Gaia, to detect such features:
  - Deep photometry
  - Large regions of sky
- To achieve both, it is expensive and impractical.
- Other issues include:
  - Effective contamination from the MW field.
  - Lack of overall chemistry/kinematics.

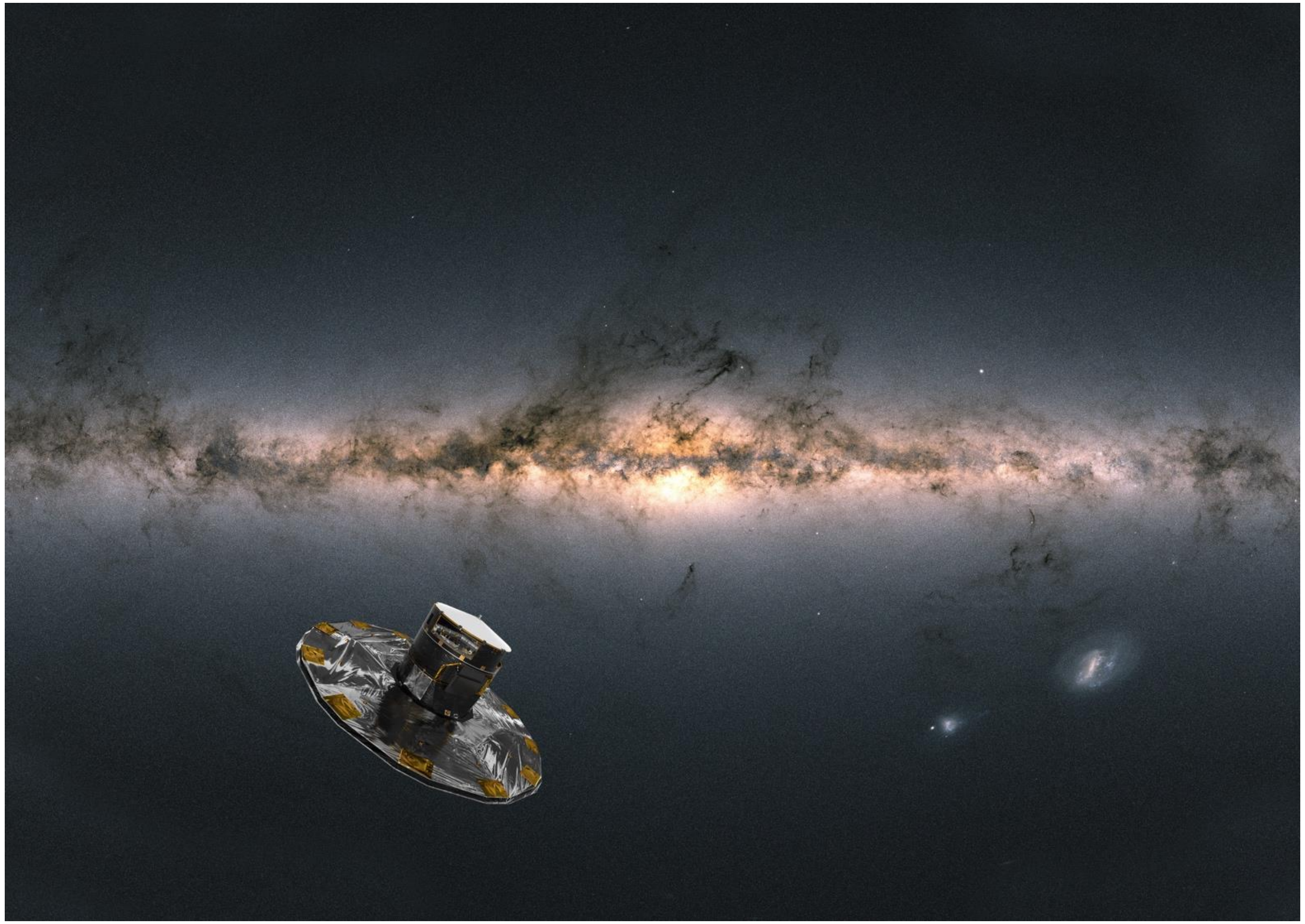


DECam



SDSS

The Gaia Revolution

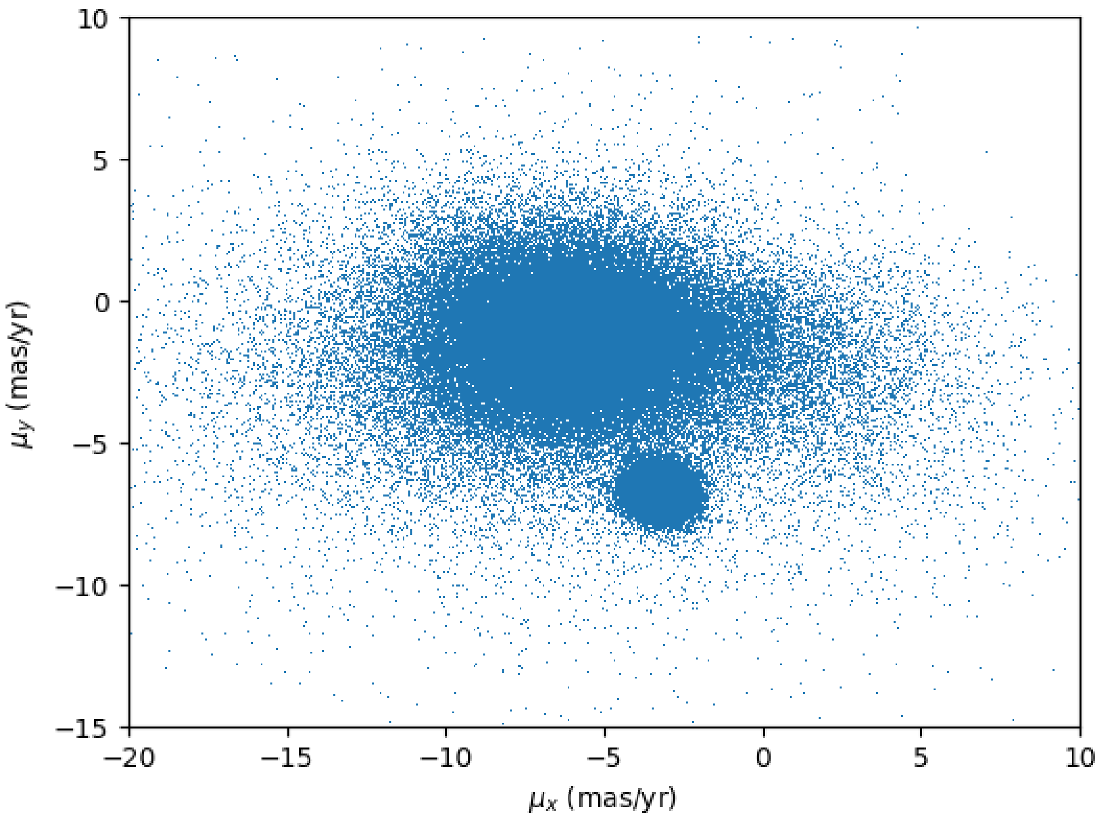


ESO

The Gaia Revolution

- The Gaia Space Mission provides:
  - Precision astrometry
  - Photometry
  - Parallaxes

With respect to GCs, it provides the large coverage, good photometric depth and crucially, superior field contamination detection.

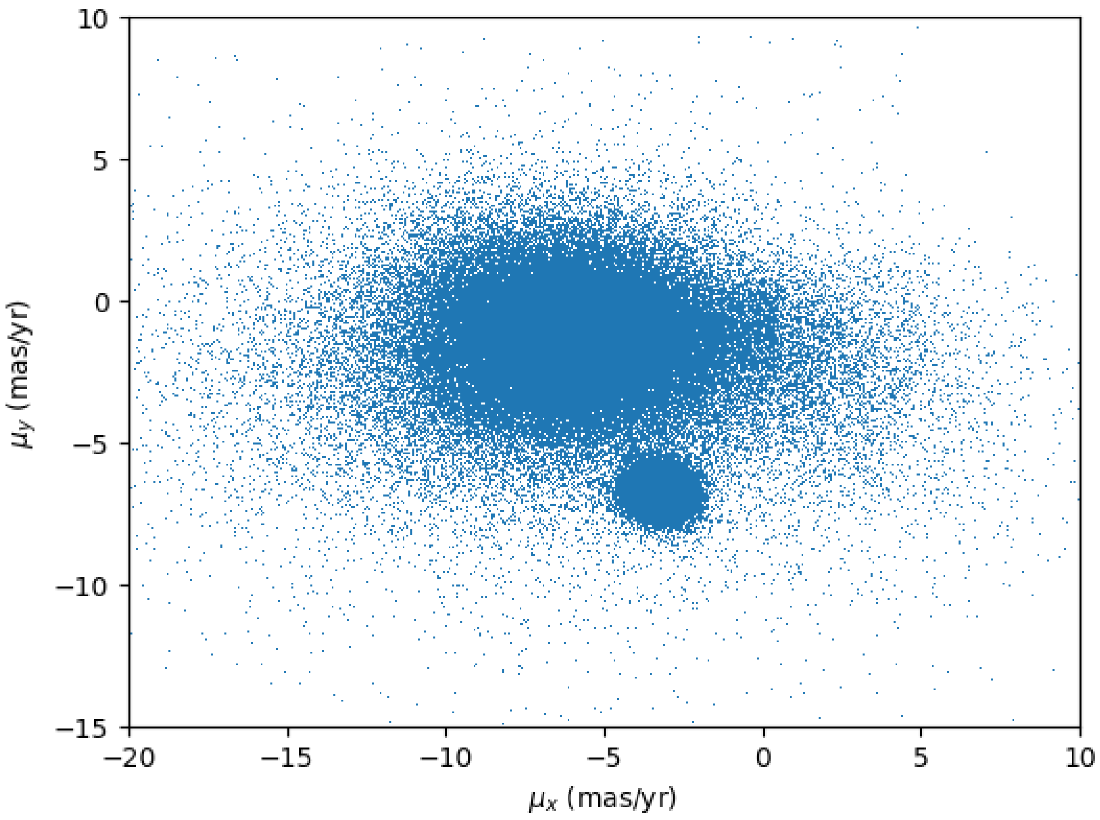


NGC5139 proper motion space

Bayesian Analysis of Gaia

- Bayesian Analysis of Gaia includes a mixture model across two parameters spaces:
  - Proper motion space
  - Spatial distribution

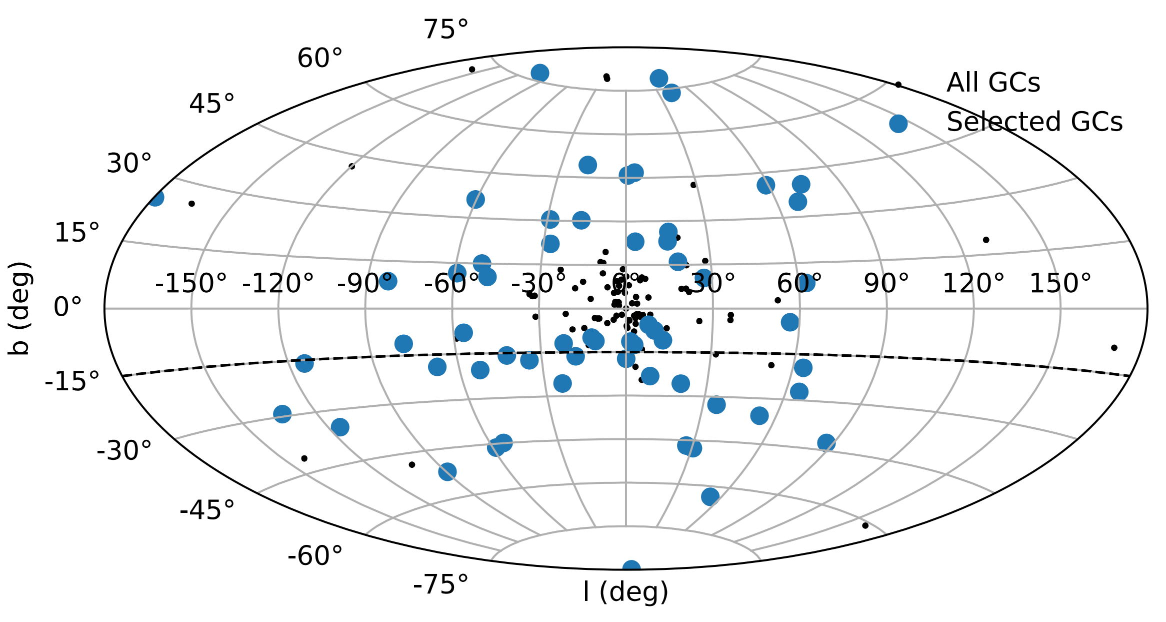
- Proper motion for discerning co-moving stars from the field.
- Spatial distribution for underlying substructure.



NGC5139 proper motion space

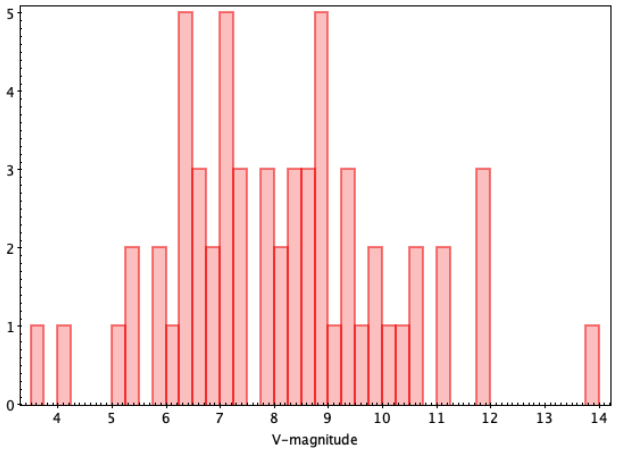
The Ground Work

- We retrieve a 5 deg radius around approx. 60 GCs from Gaia DR3.
- GCs typically adhering to the following criteria:
  - Within 25 kpc
  - V-band magnitudes <= 5 mag
  - |b| > 10 deg



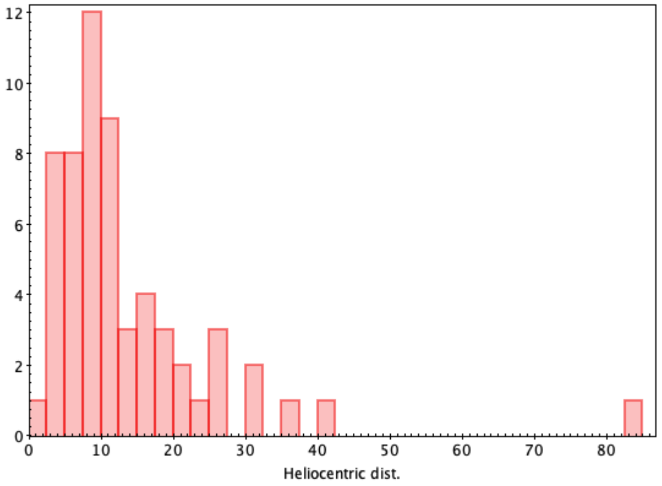
Kuzma et al. 2024 in prep

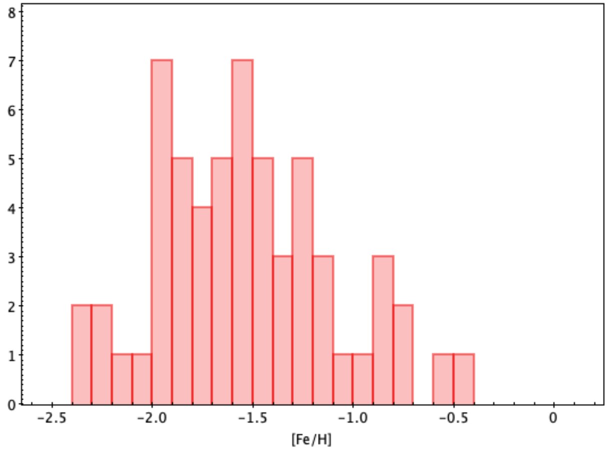
The Ground Work



← V-band Magnitude

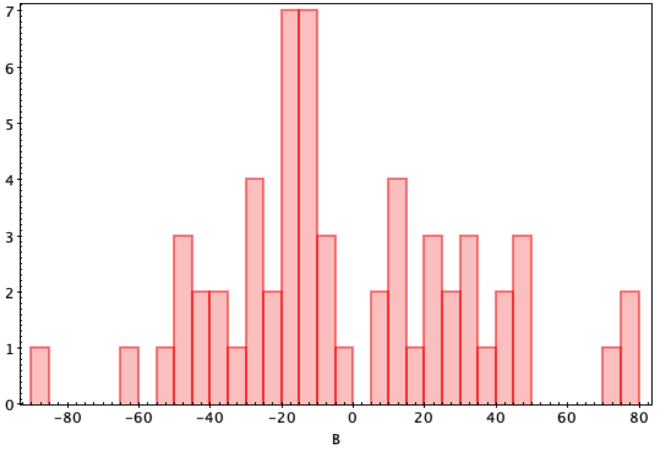
Heliocentric distance →





← Metallicity

Galactic Latitude →



The Ground Work

- Some data filtering:
  - Have colour index >1.6 mag (removing field dwarfs).
  - Stars within 3 kpc with resolved parallaxes.
  - Poor or no astrometric solution (e.g., re-normalised unit weight error).
  - Isochrone fitting and sigma clipping on photometry.

- Co-ordinate transformations and corrections for solar reflex motion.
- Reddening effects considered per cluster/

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The Technique: Likelihood

- The likelihood function takes the form of a mixture model, and it contains three components:
  - Globular Cluster (cl)
  - Extended structure (ex)
  - Milky Way Foreground (MW)

$$\mathcal{L}_{tot} = f_{cl+ex}\left(f_{cl}\mathcal{L}_{cl} + (1 - f_{cl})\mathcal{L}_{ex}\right) + (1 - f_{cl+ex})\,\mathcal{L}_{MW}$$

- We calculate membership probability as:

$$P_{mem} = \frac{f_{cl+ex}\left(f_{cl}\mathcal{L}_{cl} + (1 - f_{cl})\mathcal{L}_{ex}\right)}{\mathcal{L}_{tot}}$$

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The Technique: Proper Motion

- Proper motions are modelled as bivariate Gaussian distributions.
  - Cluster + extended components have the same proper motion.
  - No proper motion dispersion assumed in the extended structure component.
  - MW field is assumed to follow a bivariate Gaussian as well.

Kuzma et al. 2024 in prep

The Technique: Spatial Distributions

- Spatial distributions are different for each component:
  - King (1962) model for the cluster.

- Adopted despite limitations.
- Tidal radius adopted as a “transition radius”.
- Core radius fit where possible.

Kuzma et al. 2024 in prep

The Technique: Spatial Distributions

- Spatial distributions are different for each component:
  - Linear gradient model for the foreground;

- Linear model as a reasonable assumption across the field-of-view.

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The Technique: Spatial Distributions

- Spatial distributions are different for each component:
  - Quadrupole model for the extended component:

$$\Sigma(r,\theta) = (1+r)^{-\gamma}(1+\kappa_{ex}\ \cos^2(\theta-\theta_{ex}))$$

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The Technique: Spatial Distributions

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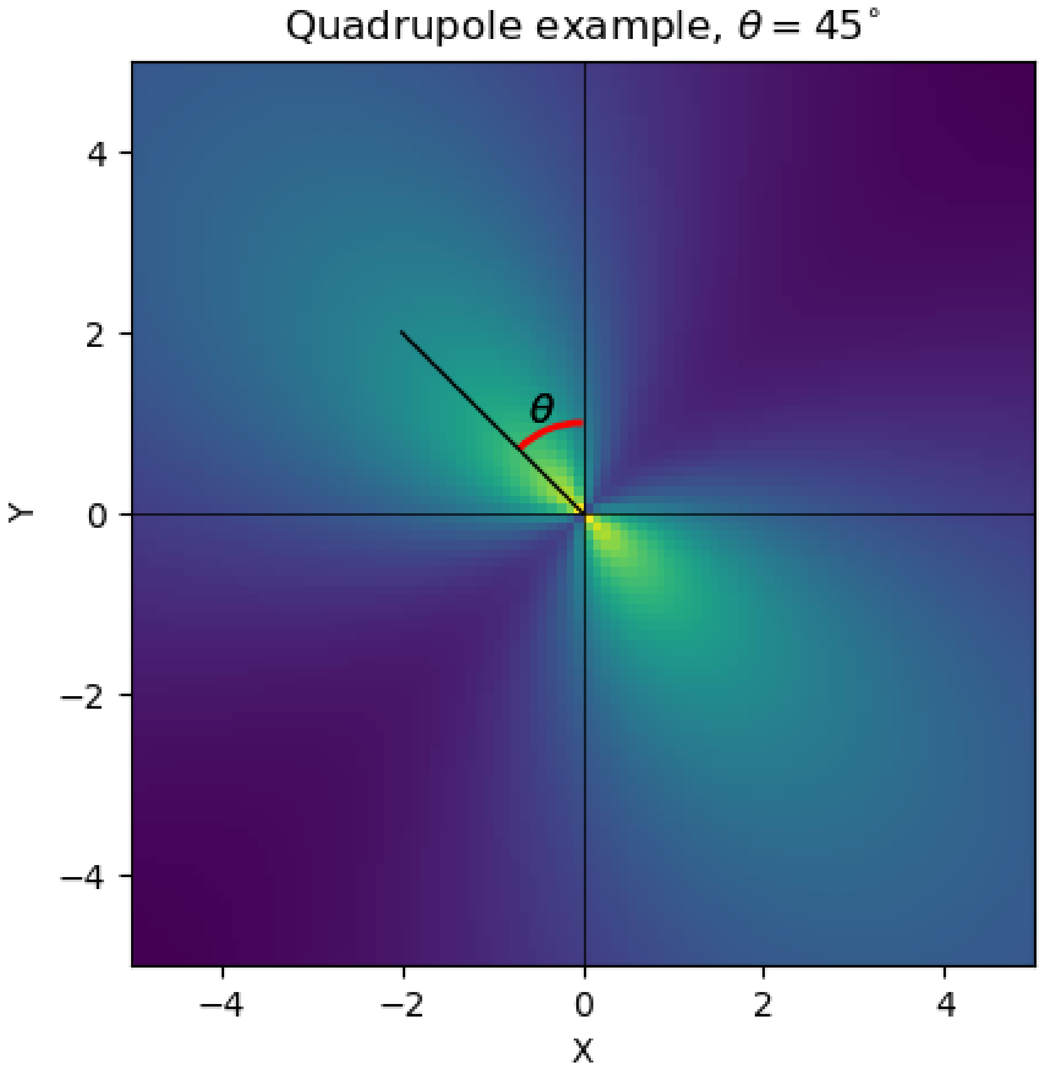

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Validation: Sample Design

- Need to comprehend how the Technique works before application.

- We simulated a series of GCs with different parameters and debris to explore how the technique behaves:
  - 10^5 particles with 0.1% – 1% mass in the debris, or no debris;
  - Proper motions both inside and outside the field motions;
  - GCs at 5 and 15 kpc;
  - Varying Galactic latitudes and concentrations.

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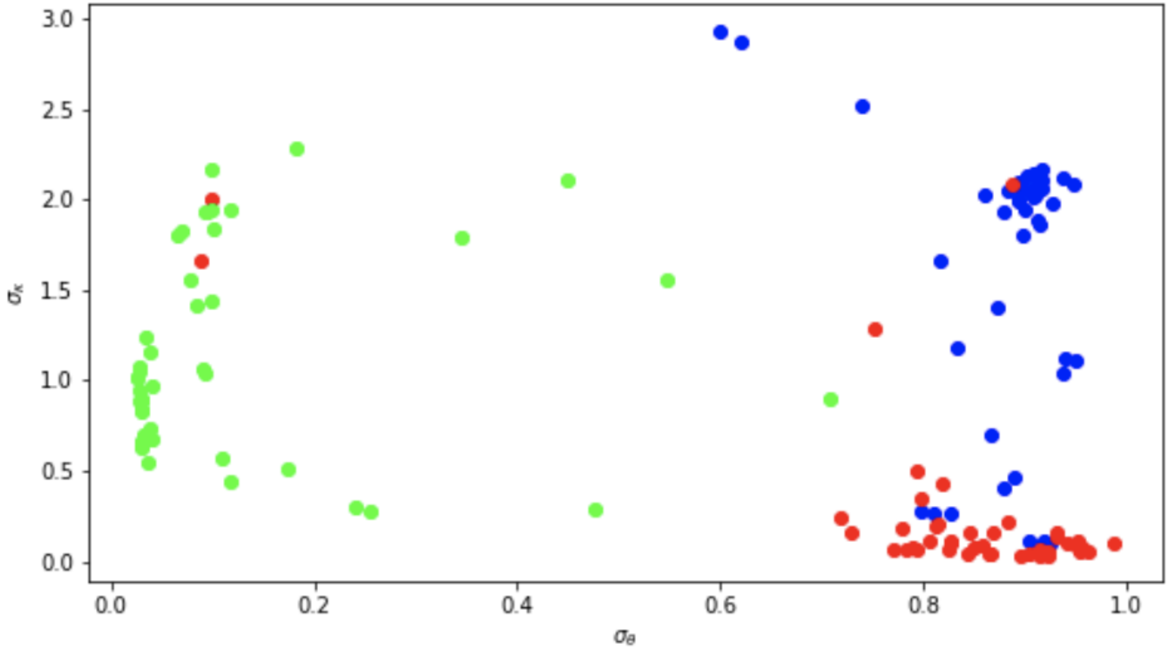
Validation: Optimal Classification

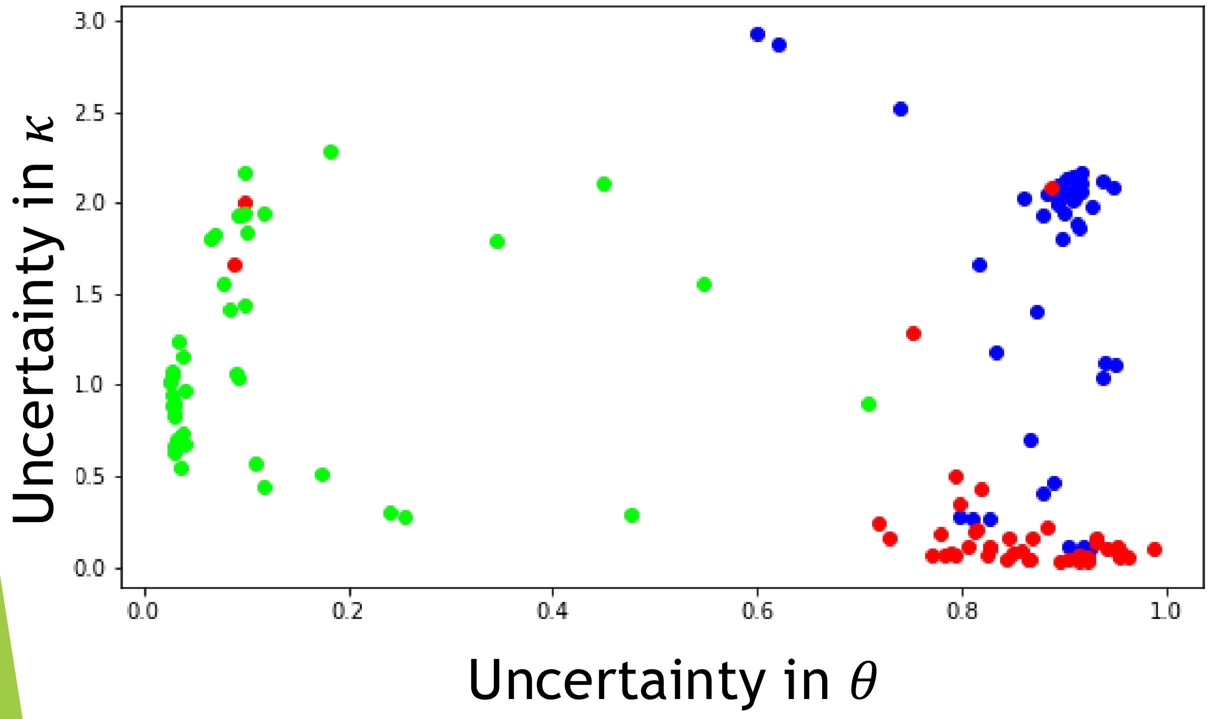


Green = TT, Red = Envelope, Blue = None

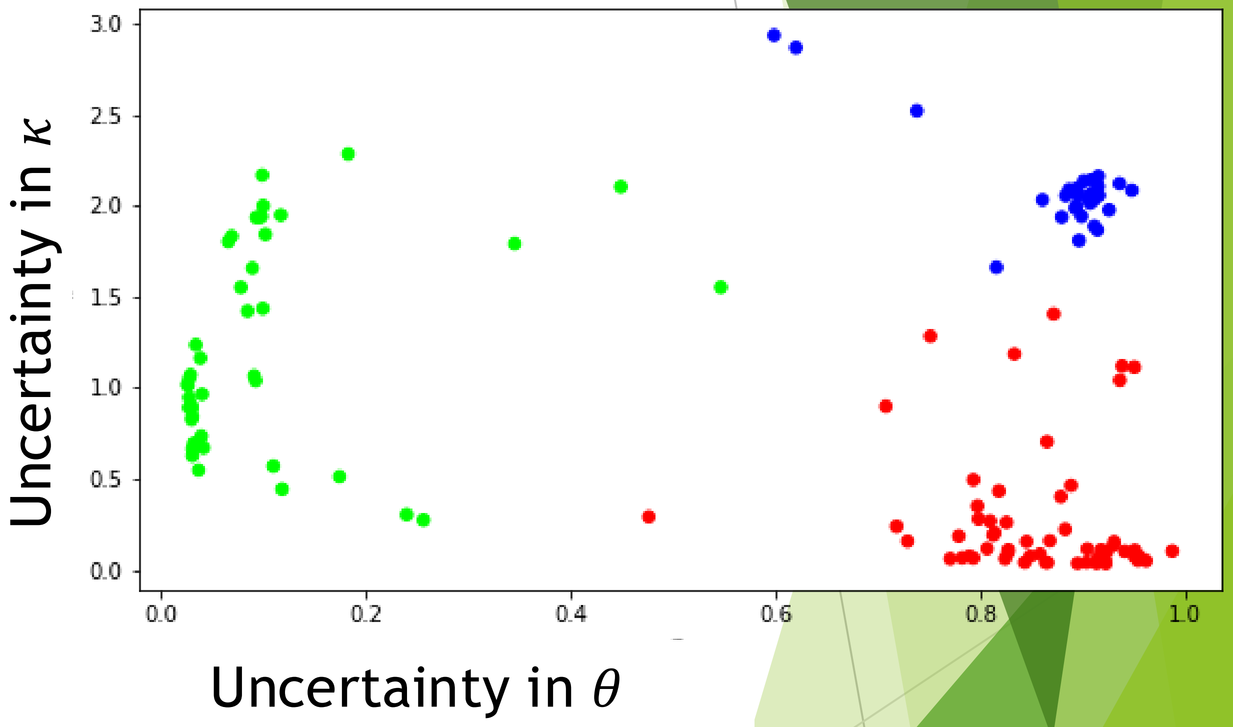
- Exploring the measurement uncertainty in θ, κ and γ, we can group the known debris using k-mean clustering.

Kuzma et al 2024A, in prep

Validation: Clustering Comparsion



“True” classification

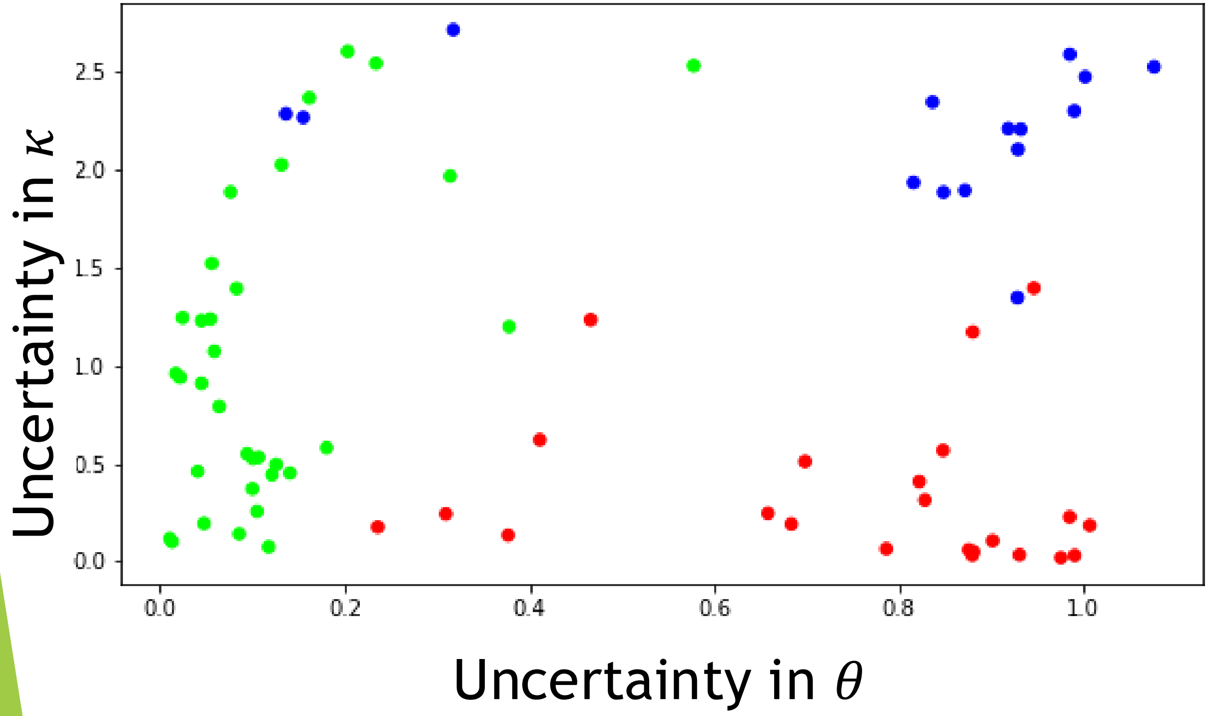


“Agnostic” *k*-means clustering

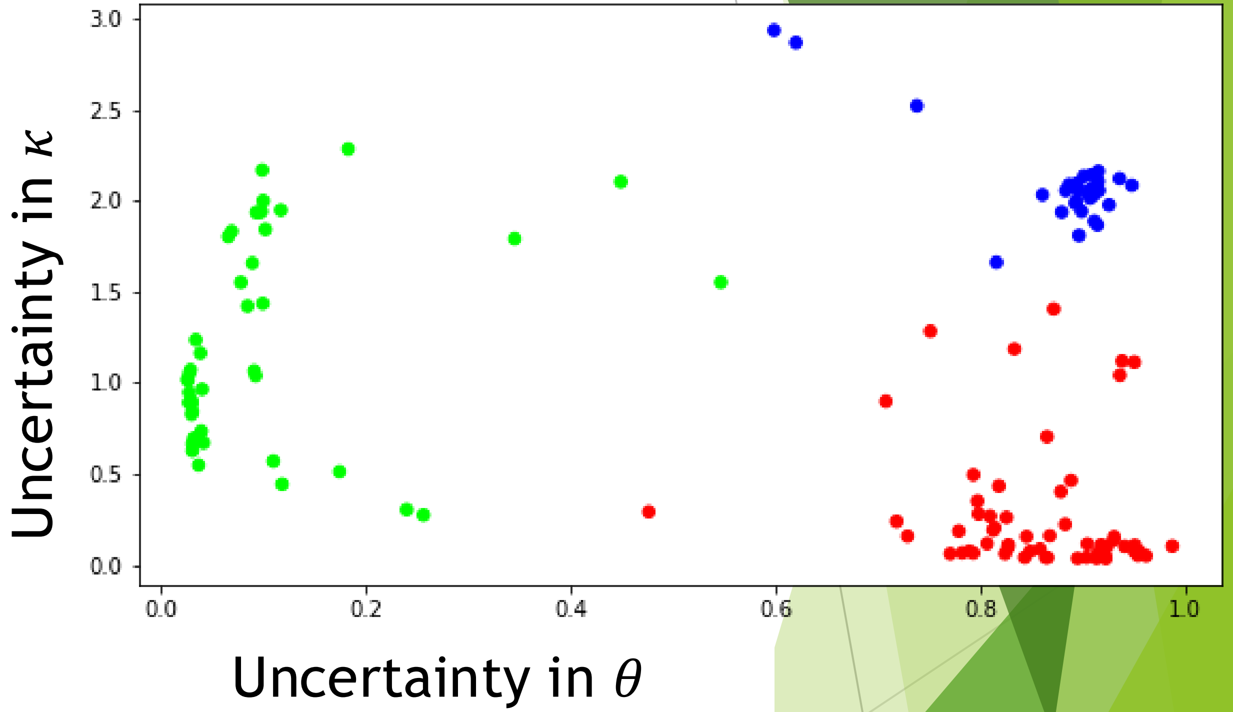
Kuzma et al 2024A, in prep

Green = TT, Red = Envelope, Blue = None

Validation: Getting real…



MW GC data clustering



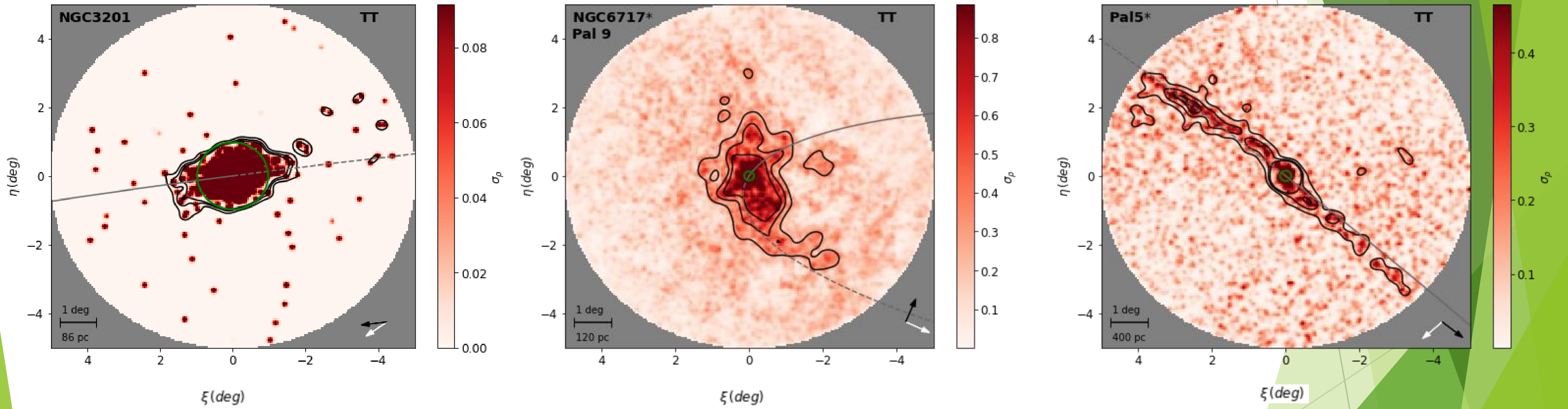
k-means

Green = TT, Red = Envelope, Blue = None

Kuzma et al 2024A, in prep

Results!

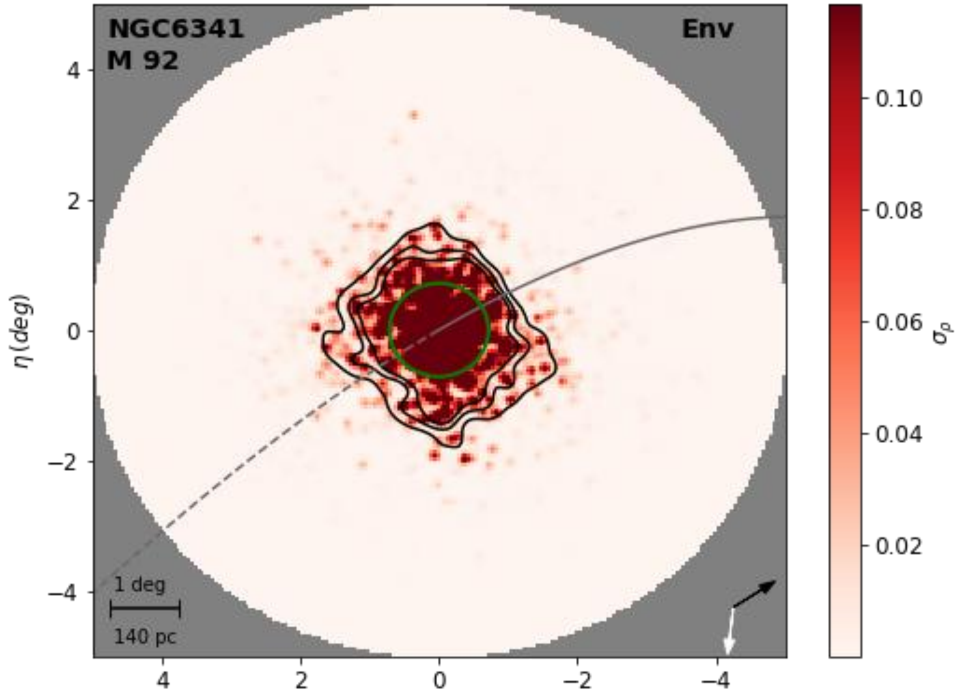
Tidal Tails…

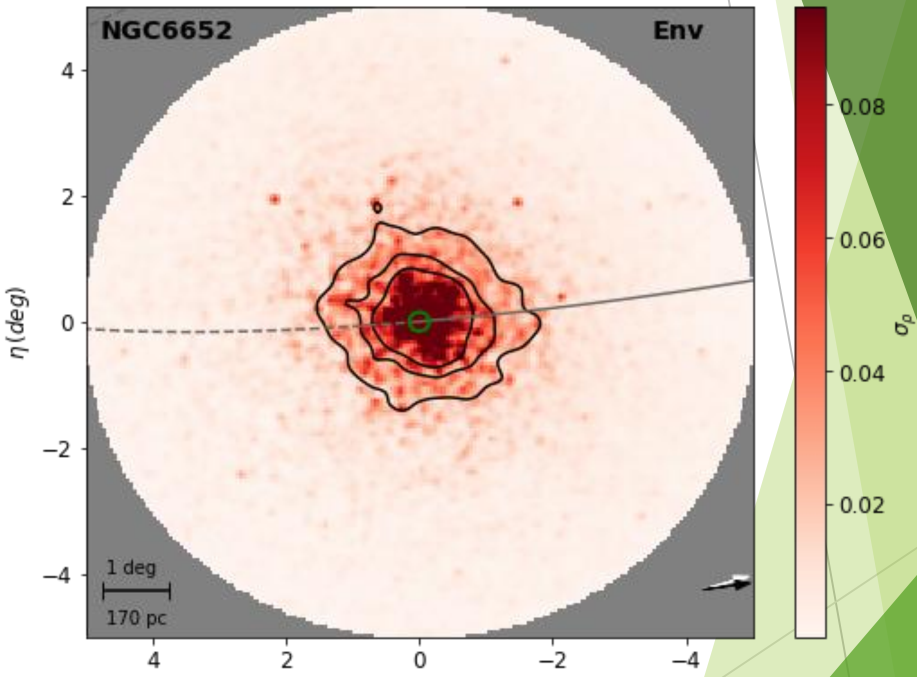


Familiar and new detections!

Results!

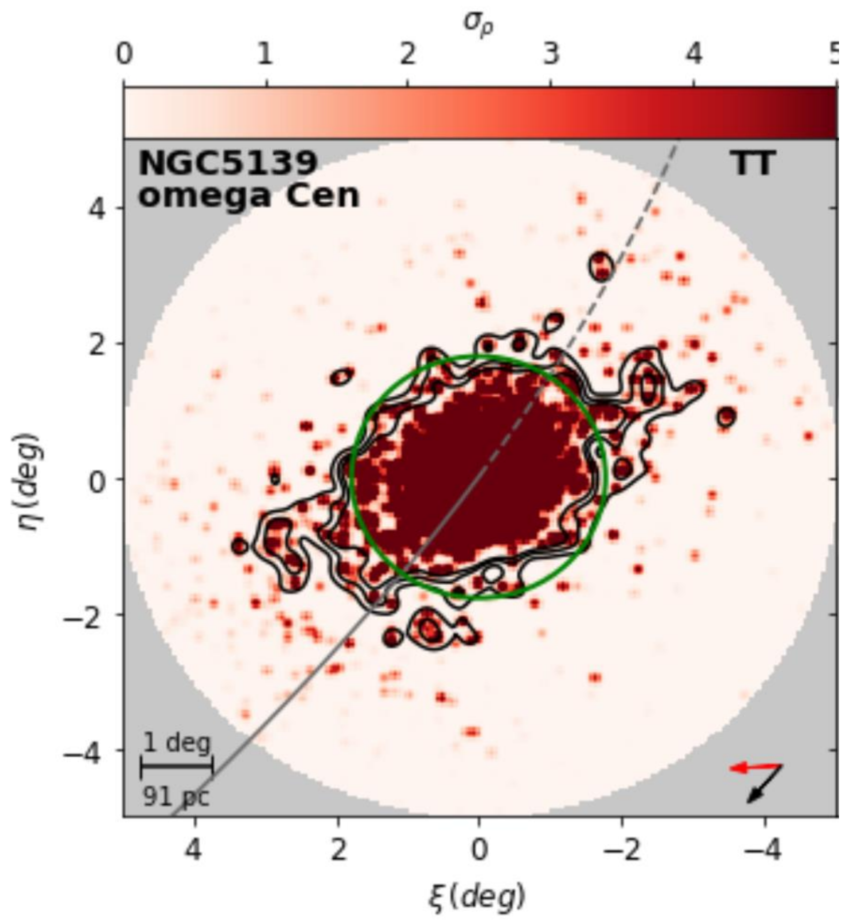
…and Envelopes!





First application to Omega Cen: Kuzma et al 2021.
Stay tuned for the full sample soon!

The Numbers



- What are the numbers?
- Out of the ~60 GCs:
  - 40% have tidal tails

    (7 new detections)
  - 36%GC possess envelopes

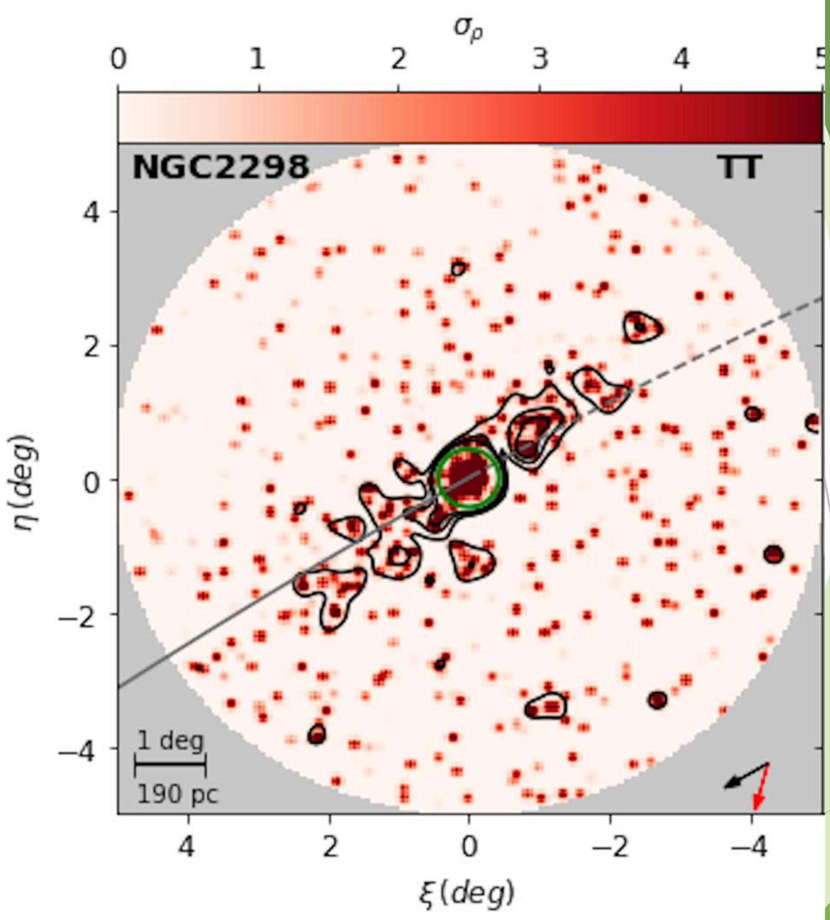
    (6 new detections)
  - 24% () classified as none/undetermined.

Kuzma et al 2024A in prep

The Numbers

Key take aways:

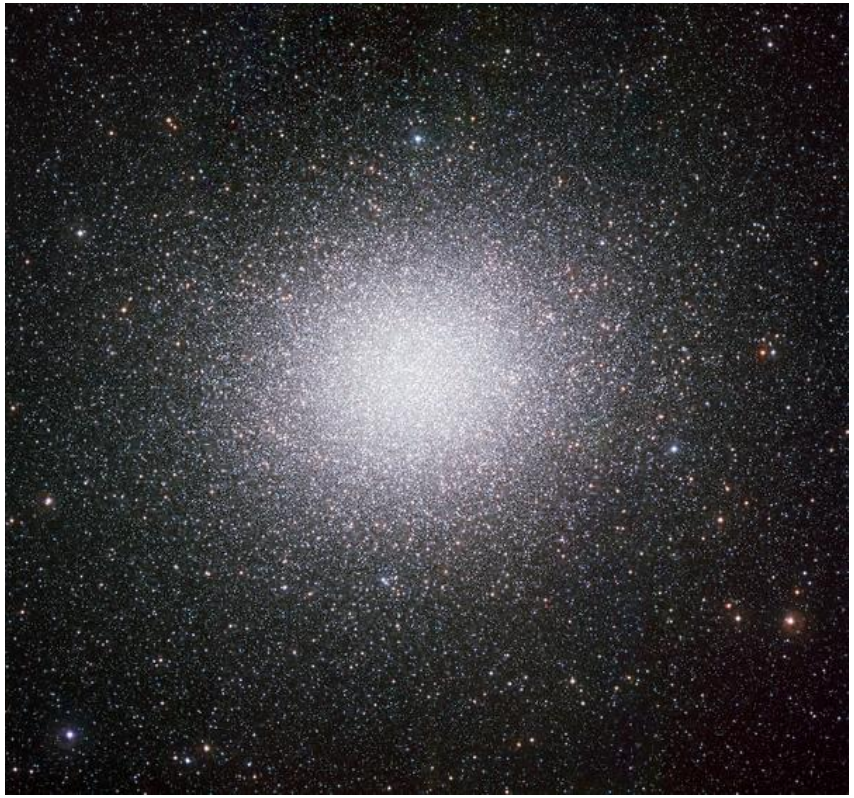
- No clear GC parameter that links a GC to no or some extended structure
- GCs with larger mass + larger appear more likely to have spherical structure
- No tidal tails found in GCs beyond galactocentric distances of 20 kpc.



Kuzma et al 2024A in prep

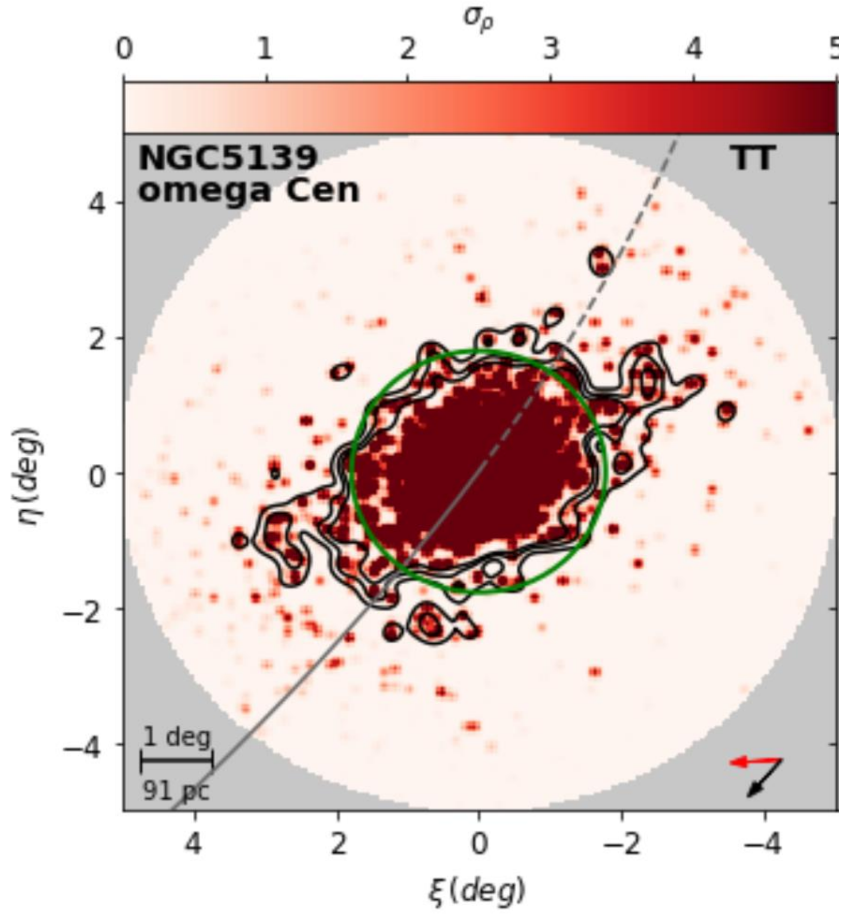
What now?

- Chemistry and Kinematics remain to try to connect extended structures to their host GCs or any known stream of accretion event.

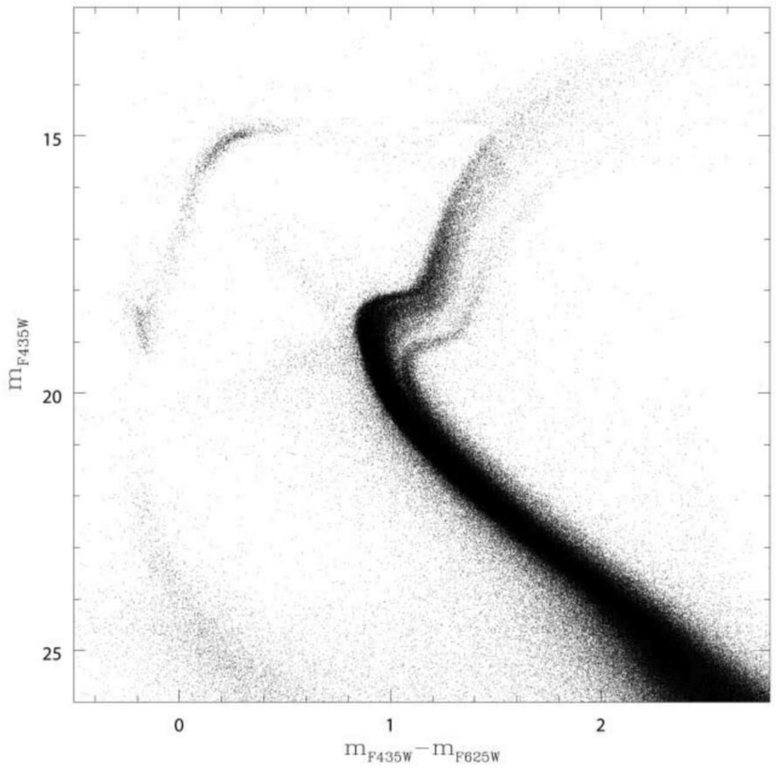


NGC 5139 (Omega Centauri)

Omega Centauri



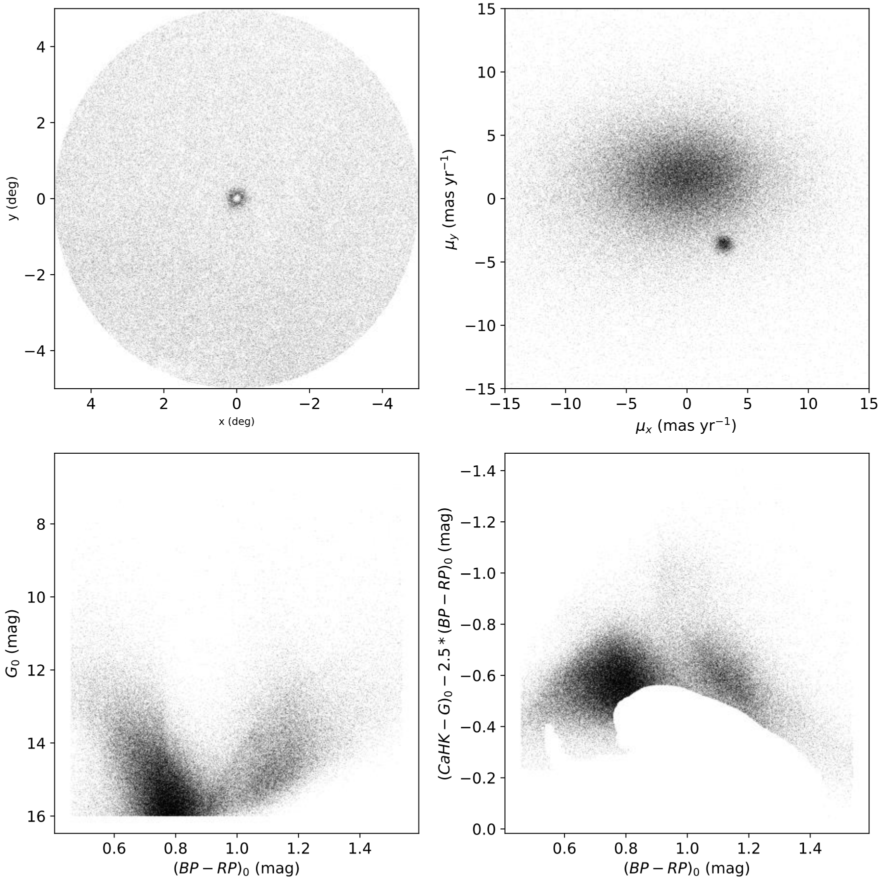
Kuzma et al 2024A in prep



Omega Centauri, Villanova et al. 2007

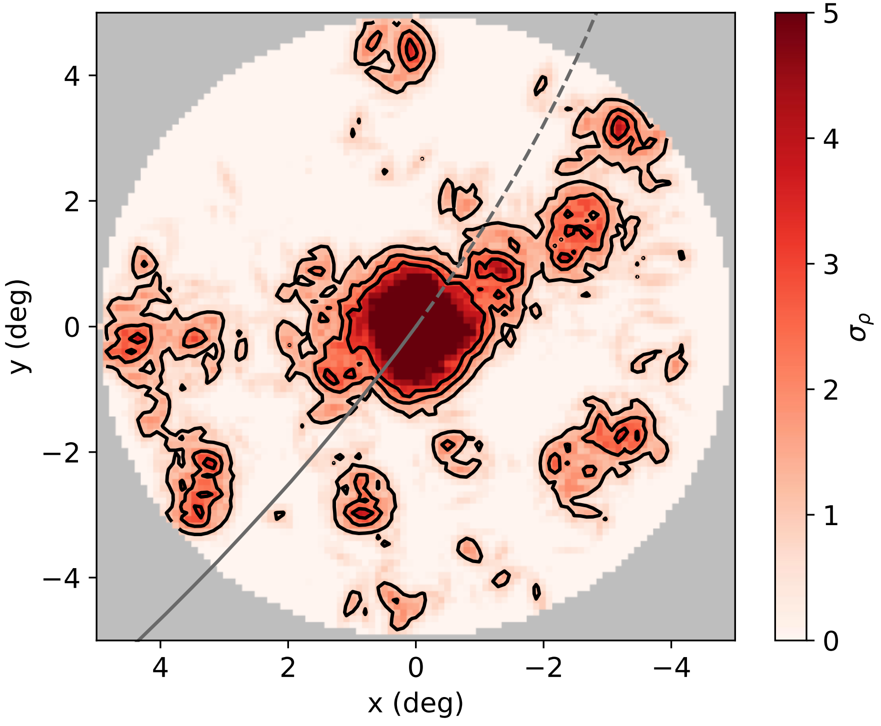
Omega Centauri - Pristine

- Pristine Survey provides all-sky synthetic photometric metallicities (through CaHK filter) to approx. 17 mag (Martin et al. 2023).
- Omega Centauri perfect for assessing metallicity outside the Jacobi radius



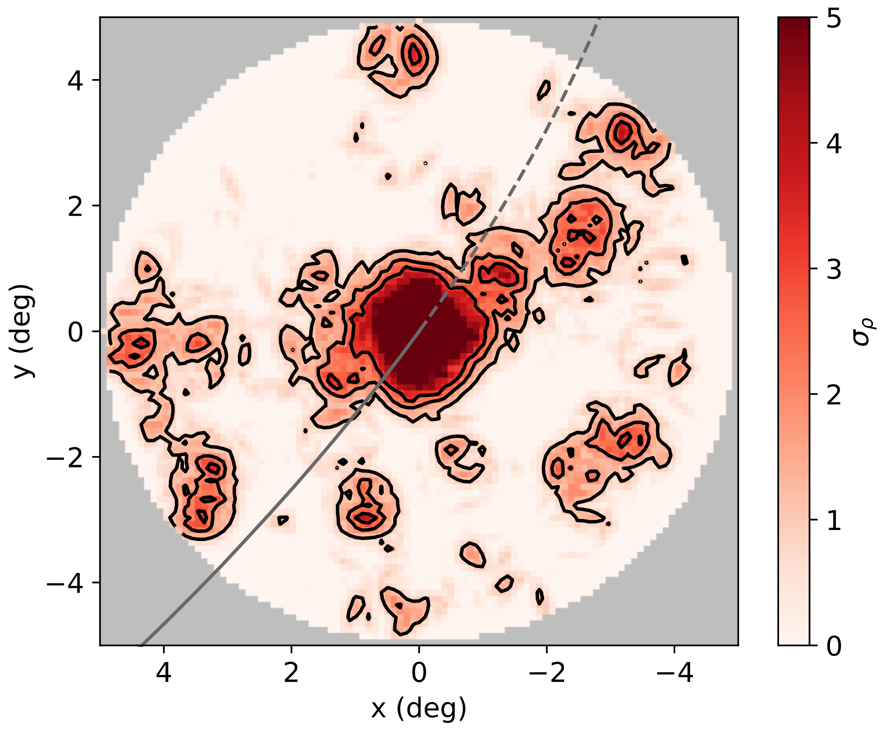
Kuzma & Ishigaki 2024, in prep

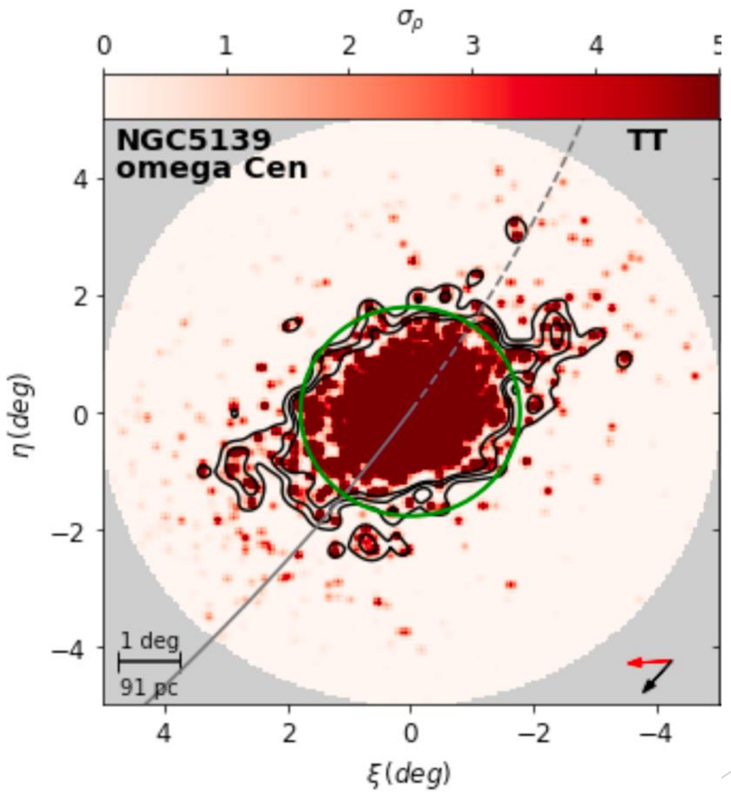
Omega Centauri - Pristine



Kuzma & Ishigaki 2024, in prep

Omega Centauri - Pristine

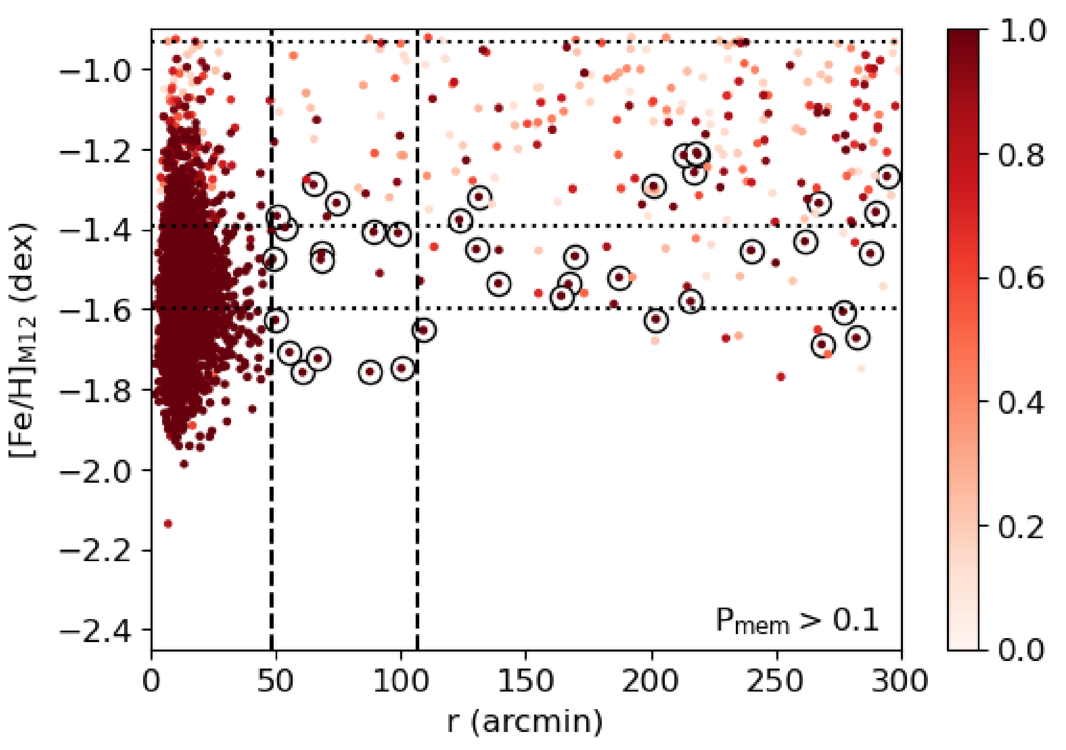




Kuzma & Ishigaki 2024, in prep

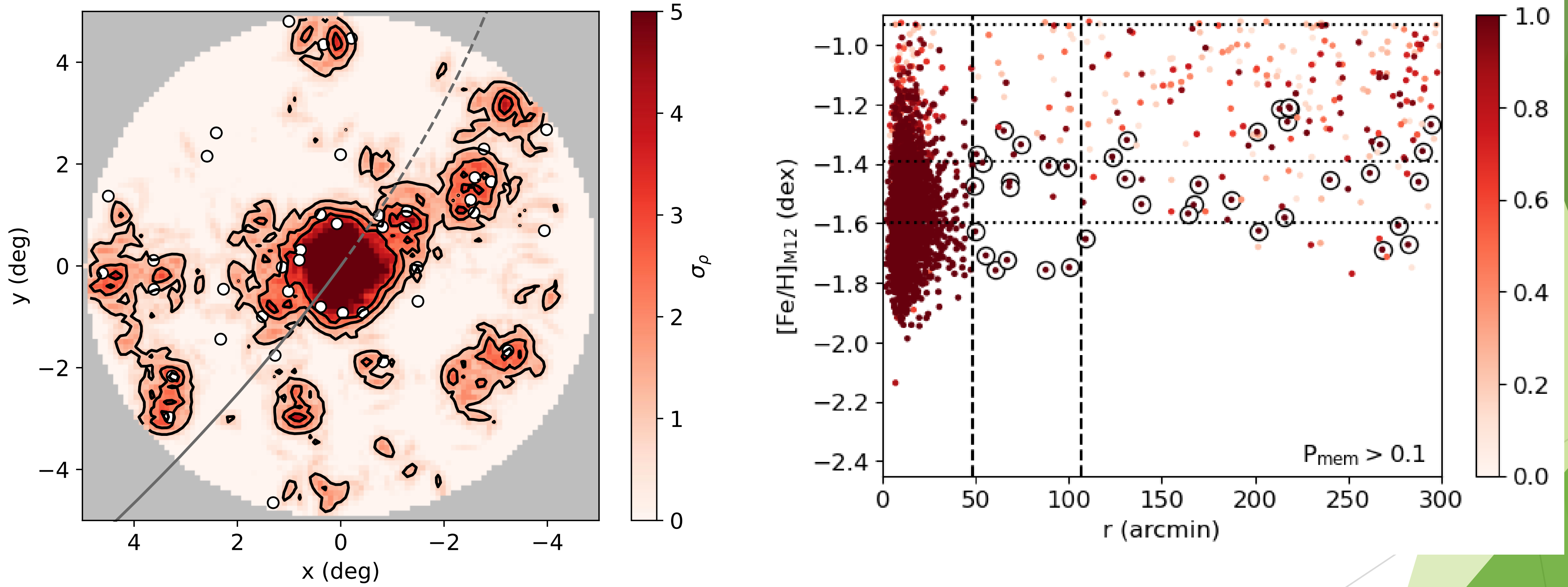
Omega Centauri - Pristine

- Metallicity function as a function radius
  - Between tidal and Jacobi radius, two distinct populations (first detection of multiple stellar populations in the outer regions of a GC!)
  - Highest probable stars closely follow the [Fe/H] distribution of Omega Cen.



Kuzma & Ishigaki 2024, in prep

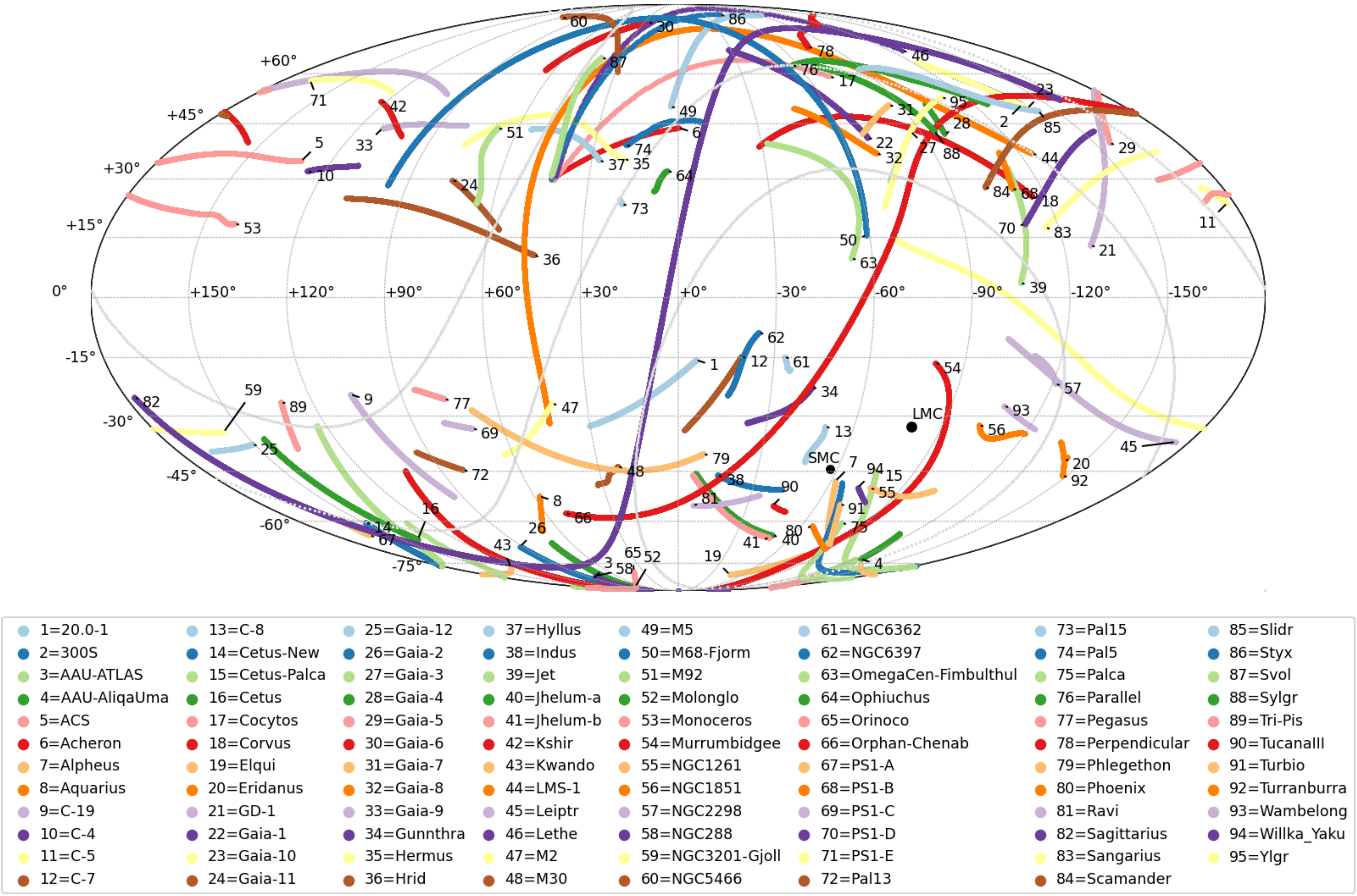
Omega Centauri - Pristine



Highest probable stars are distributed along the orbit/direction of the stream!

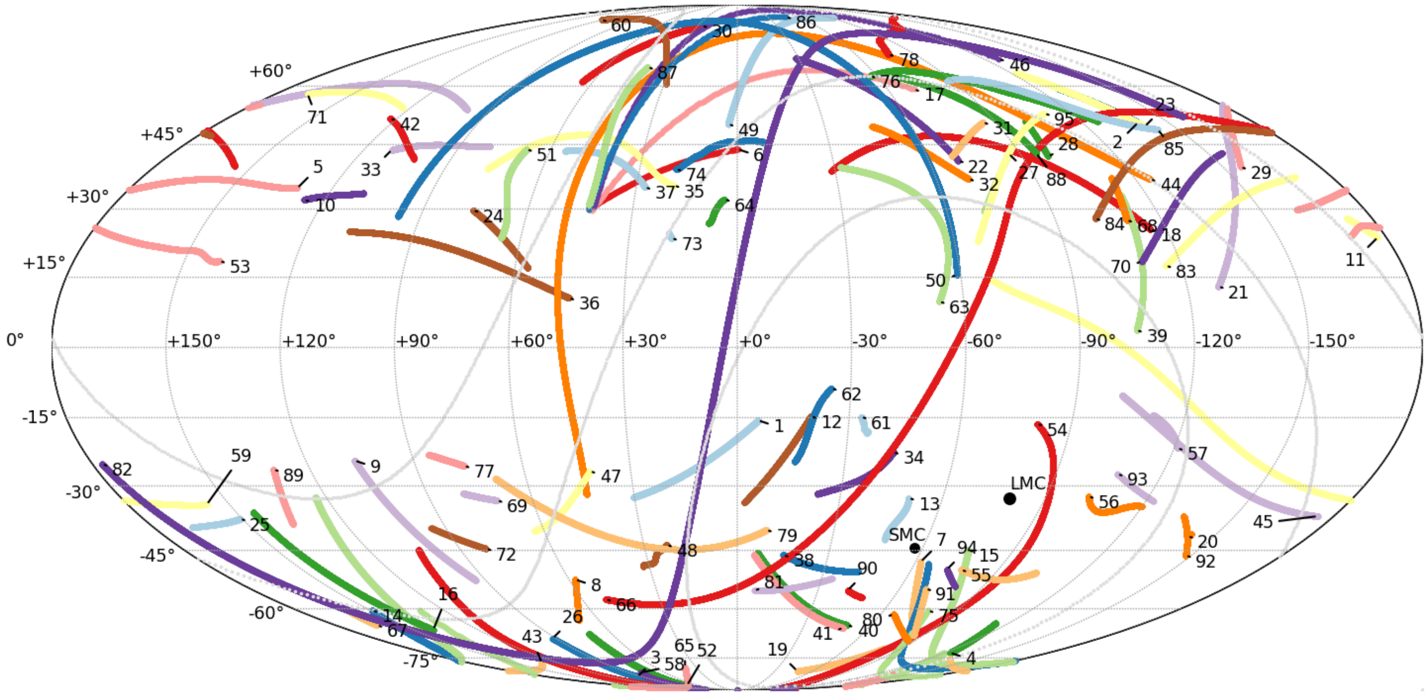
Kuzma & Ishigaki 2024, in prep

GCs and streams - Pristine



Galstreams, Mateu et al. 2023

GCs and streams - Pristine

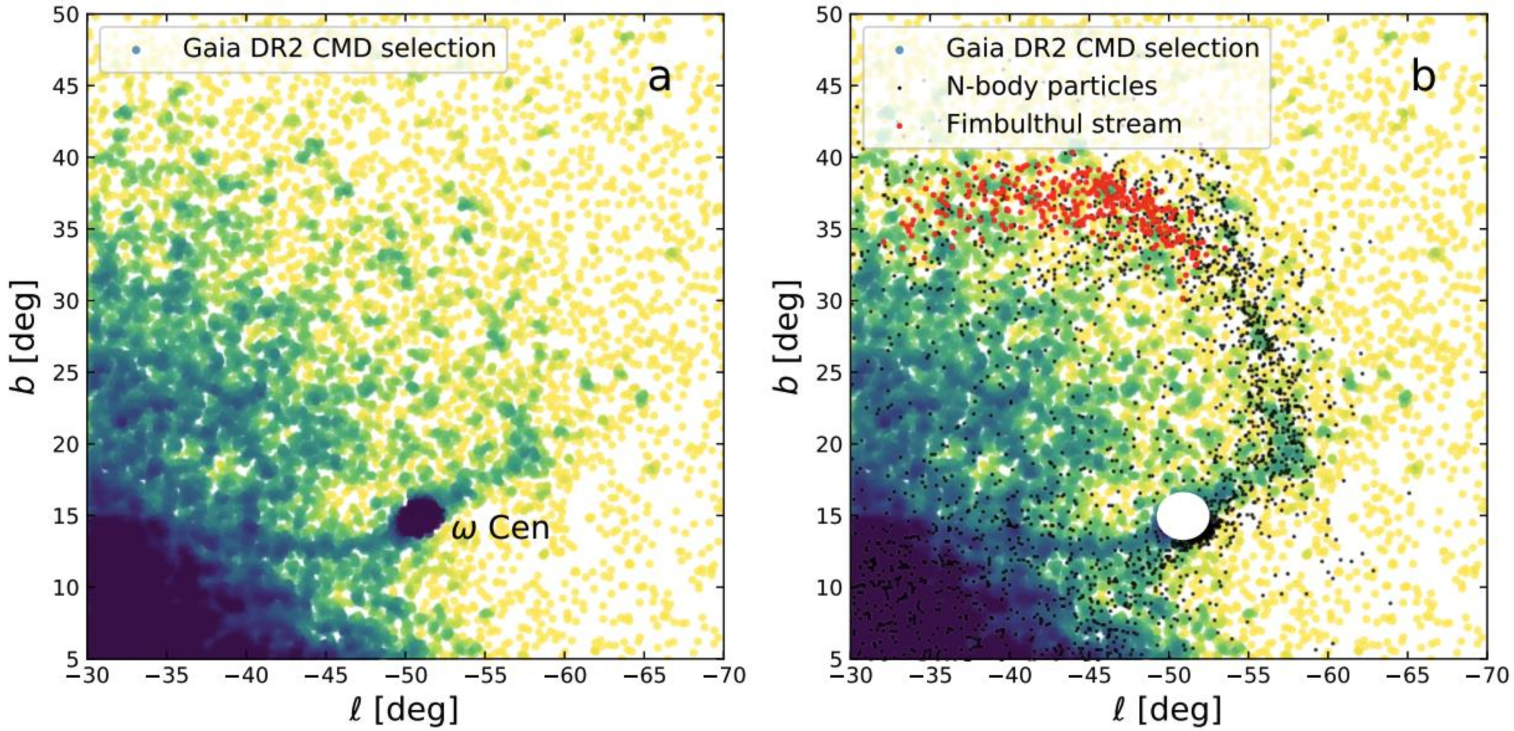


- Tracing lost stars to known GCs
- Linking GCs and extended structure to known stellar streams
- Need kinematics…

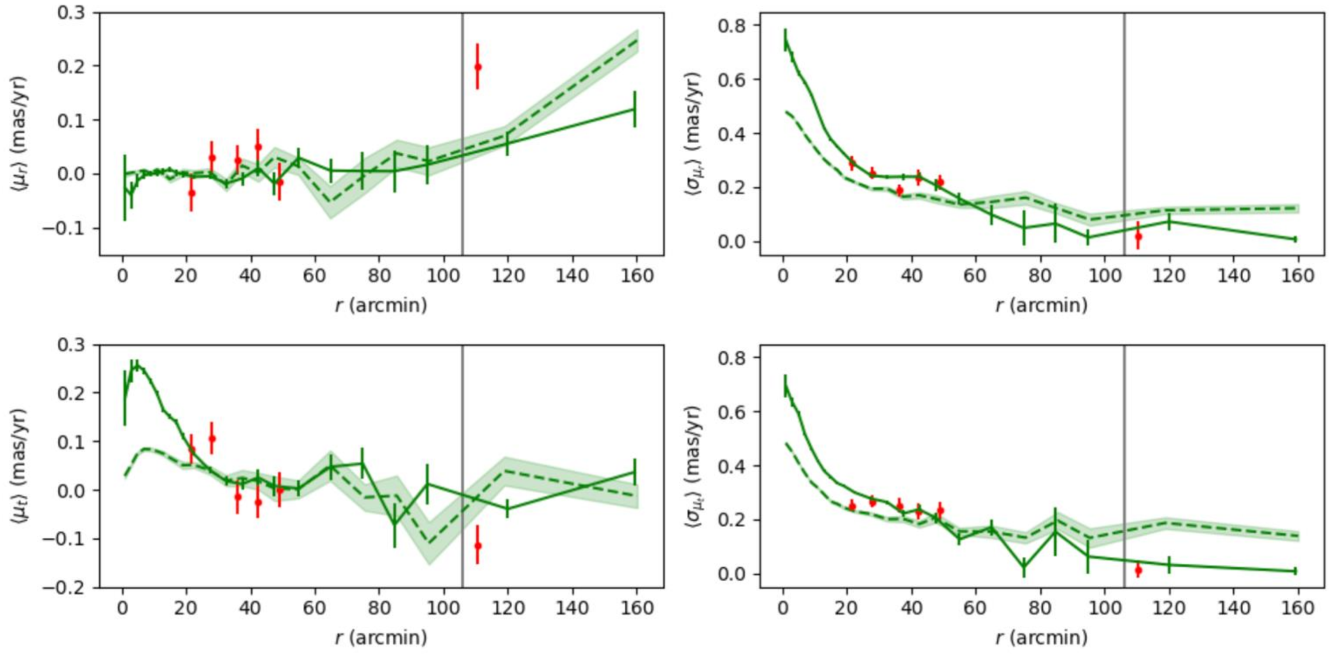
Galstreams, Mateu et al. 2023

Kinematics – Omega Centauri

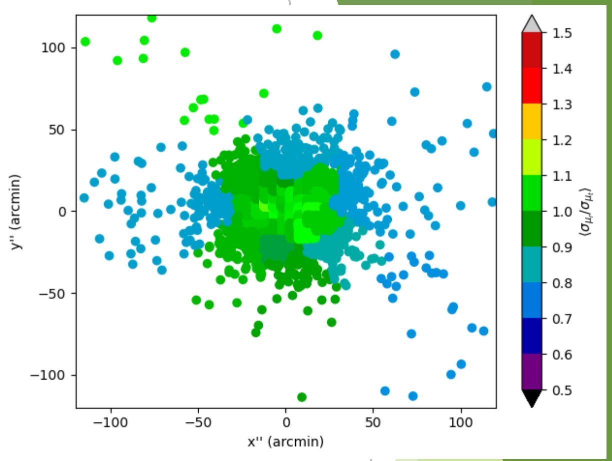
- The tidal tails of Omega Centauri may be connected to the stellar stream Fimbulthul (Ibata et al. 2019)

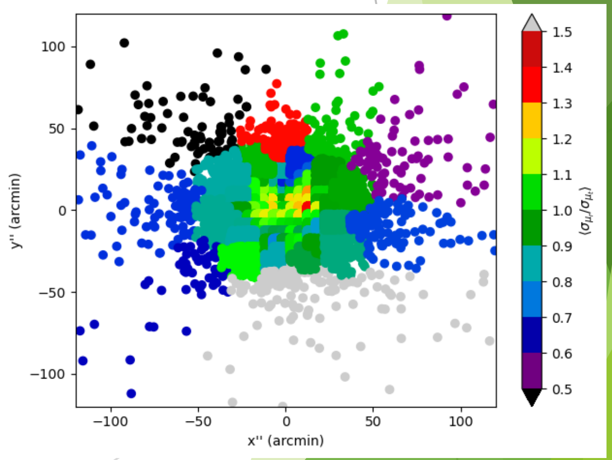


Kinematics – Omega Centauri



↑ Radial velocities to fill in the gap between the King tidal radius and the Jacobi radius. Be careful with projection effects!



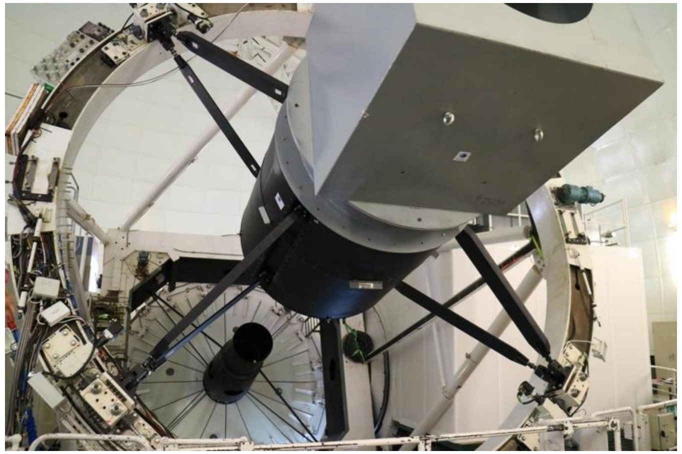


2D Anistropy maps for Omega Centauri. →

Kuzma et al. in prep 2024

Upcoming Surveys – WEAVE

- WHT Enchanced Area Velocity Explorer – WEAVE. MOS and IFU on board. Currently operational.
- Multi-object Spectrograph – 1000 fibres across ~2 square degrees, which coverage over 3600-6060 Ang, 5790 – 9590 Ang in LR.
- Science Verification project targeting M2 or M5.
- Metallicities and radial velocities to confirm tidal structure, comment on the nature of the feature



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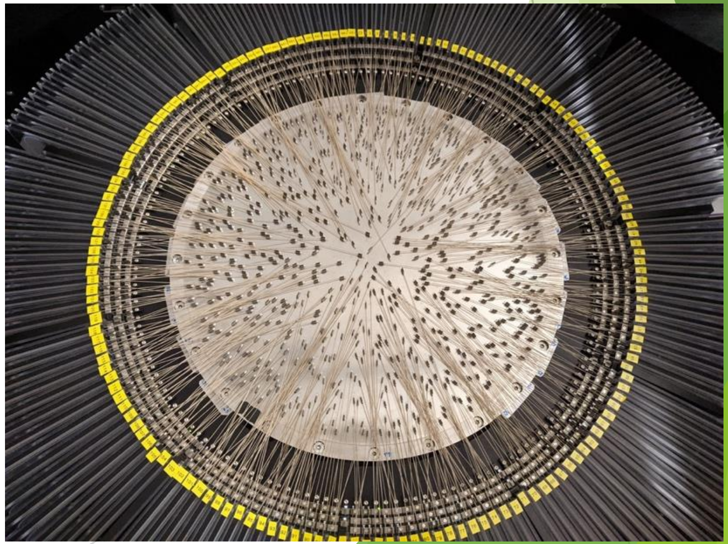
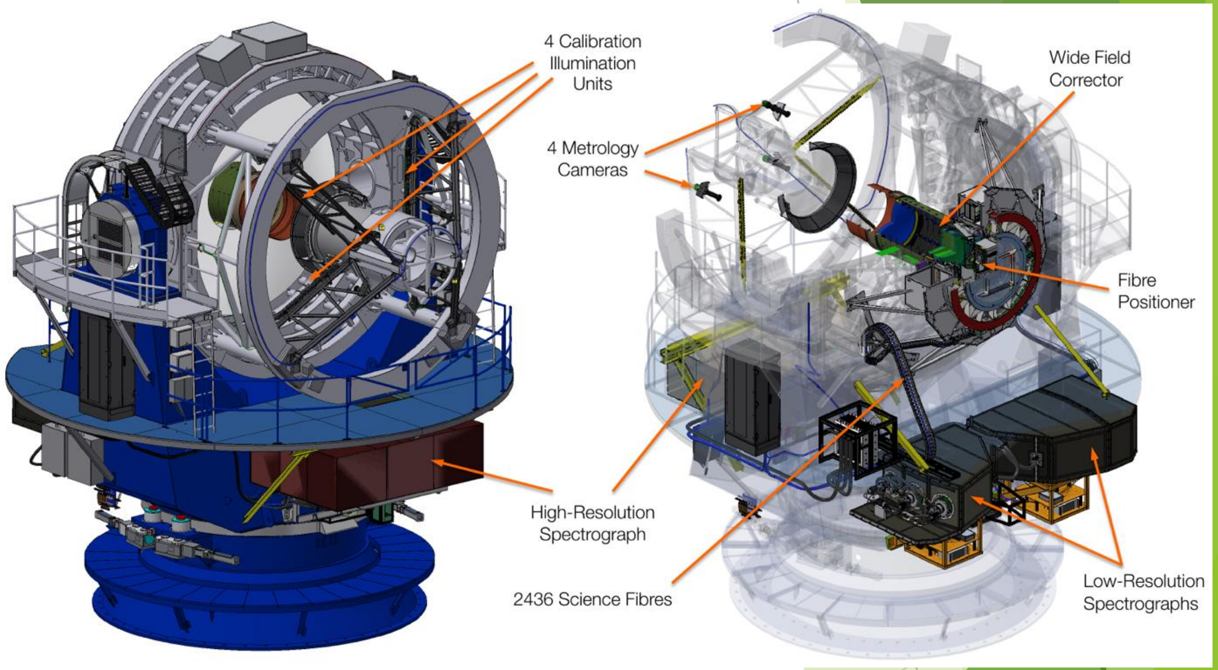


Upcoming Surveys – 4MOST

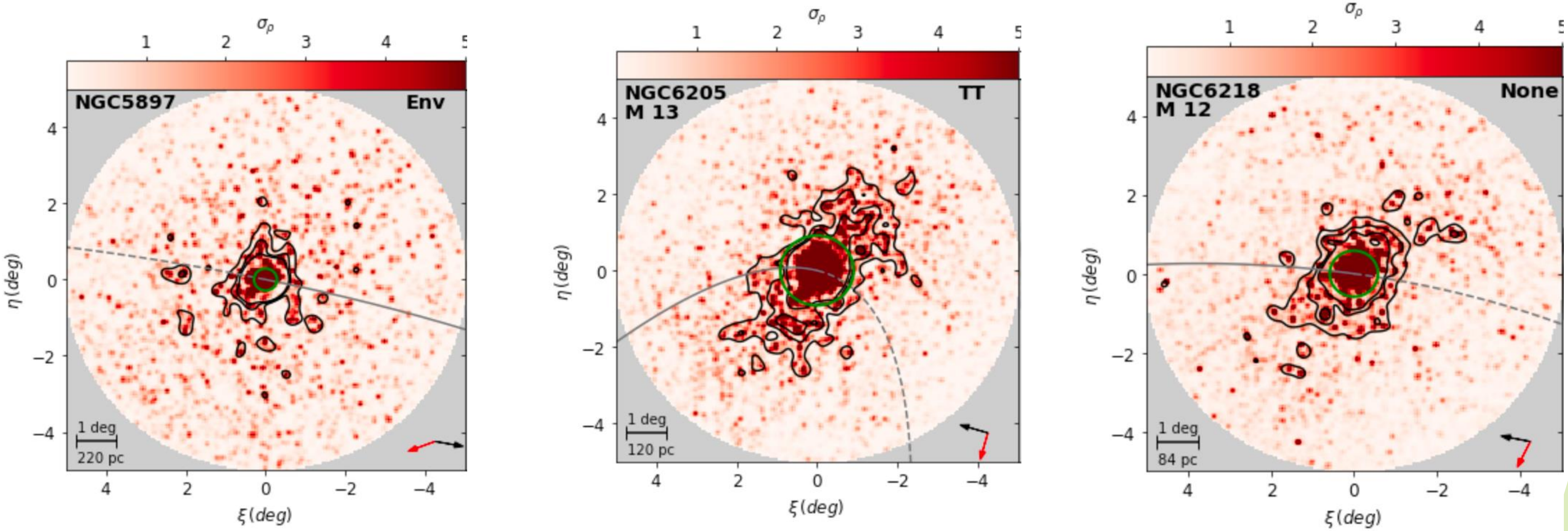
- 4MOST – 4 metre Multi-Object Spectrograph
- 2400 fibres in a ~4 square degree field of view.
- Wavelength coverage: 3700-9500 Ang

- S13: Stellar Clusters in 4MOST – target all star clusters possible (GC, Open Clusters and Young Massive Star Clusters)



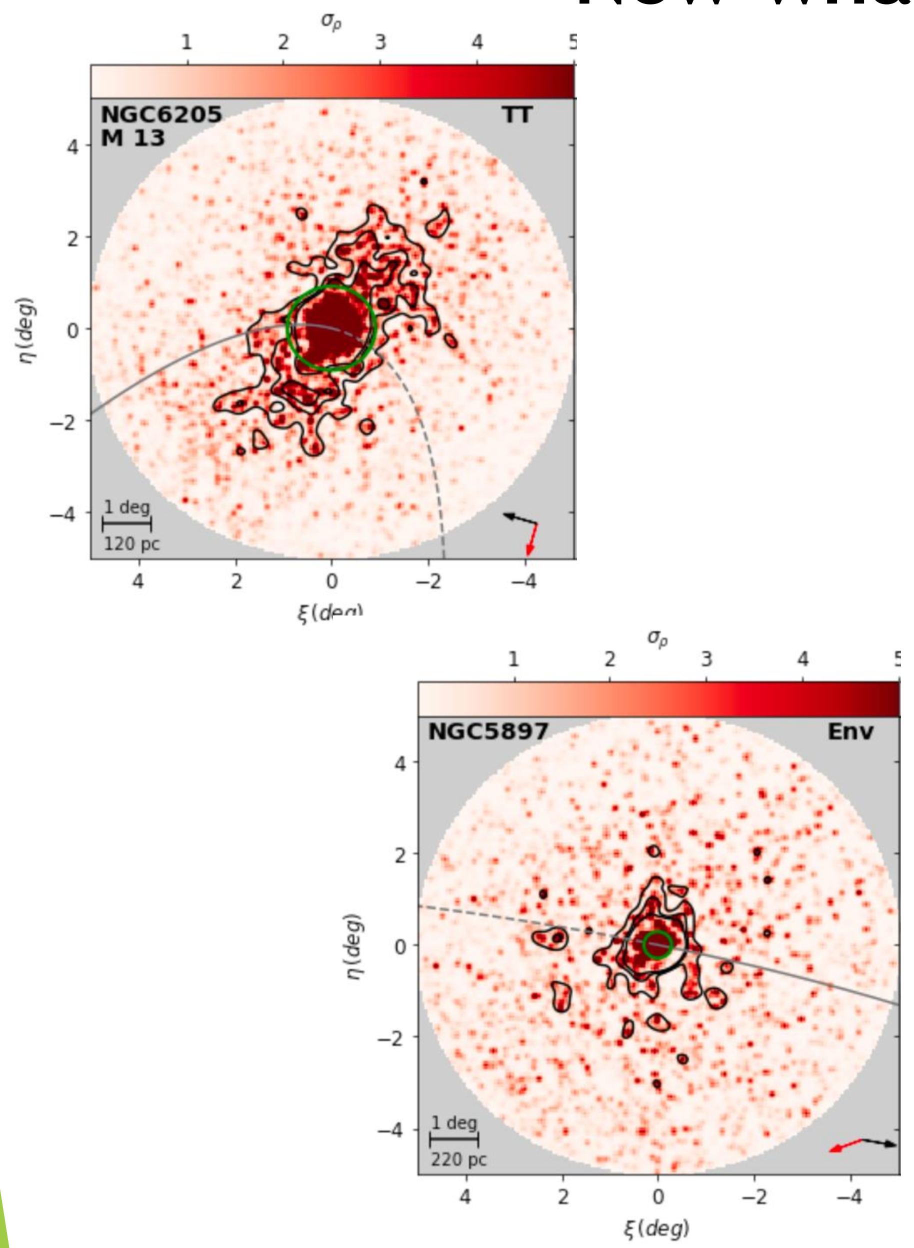
Schematic of 4MOST

PFS is perfect for exploring GC peripheries!



GC revolution is about to begin!

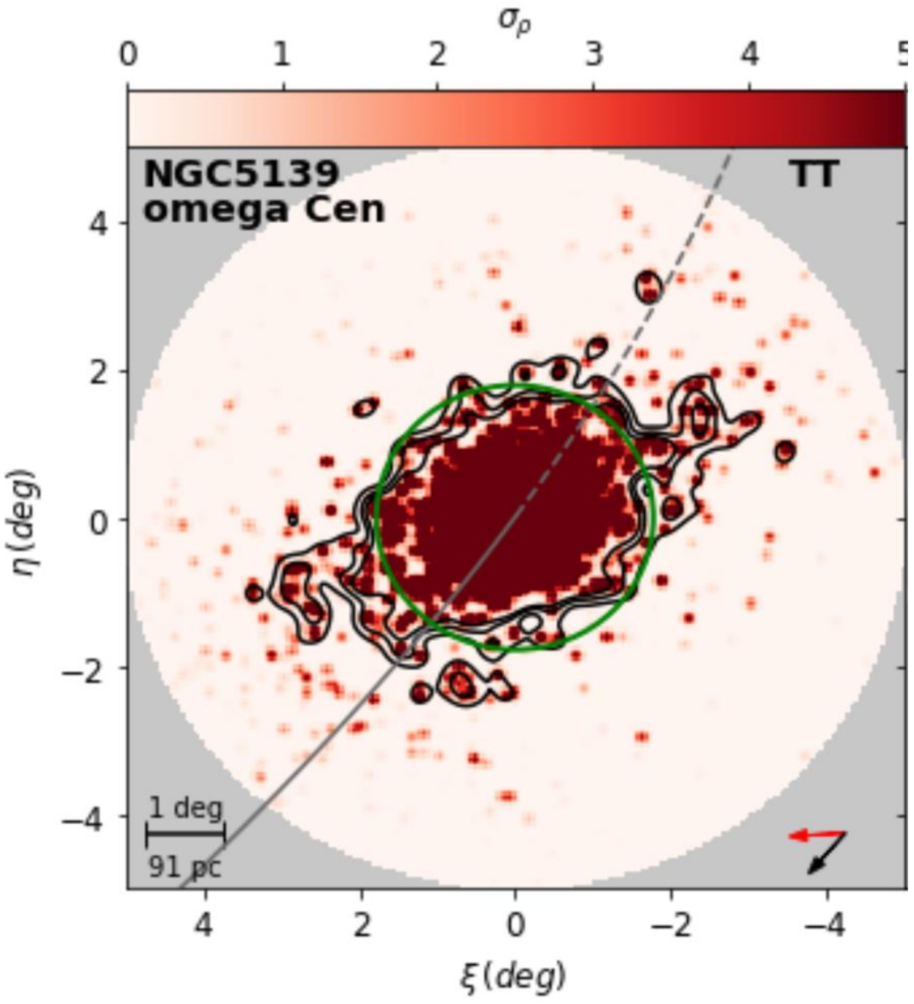
Now what? GC Extended Structure



Inferring GC/Galactic properties from extended structure:

- GC evolution/disruption (e.g., Bianchini et al. 2021);
- Stellar Populations within/without the GC (e.g, Pristine)
- Diffuse stellar envelopes as evidence for GCs embedded in dark matter subhaloes (e.g., Penarrubia et al. 2017)
- Attempt to model the Galactic halo shape (e.g., Palau et al. 2023);
- And more…

The future of GC Extended Structures



Radial velocities and chemistry are the missing pieces of the puzzle.

Our technique will allow us to identify stars in the peripheries of GCs with radial velocities, perform chemical tagging, and establish 3D kinematics with:

- WEAVE (with M2/M5)
- 4MOST (all possible GCs)
- PFS (?)