

Unleashing the proper motions: revolution in the inner Galaxy

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This presentation is available at:

fegranc.github.io/files/FGran_PhD_Defense.pdf

The thesis is available at:

fegranc.github.io/files/FGran_PhD_Thesis.pdf



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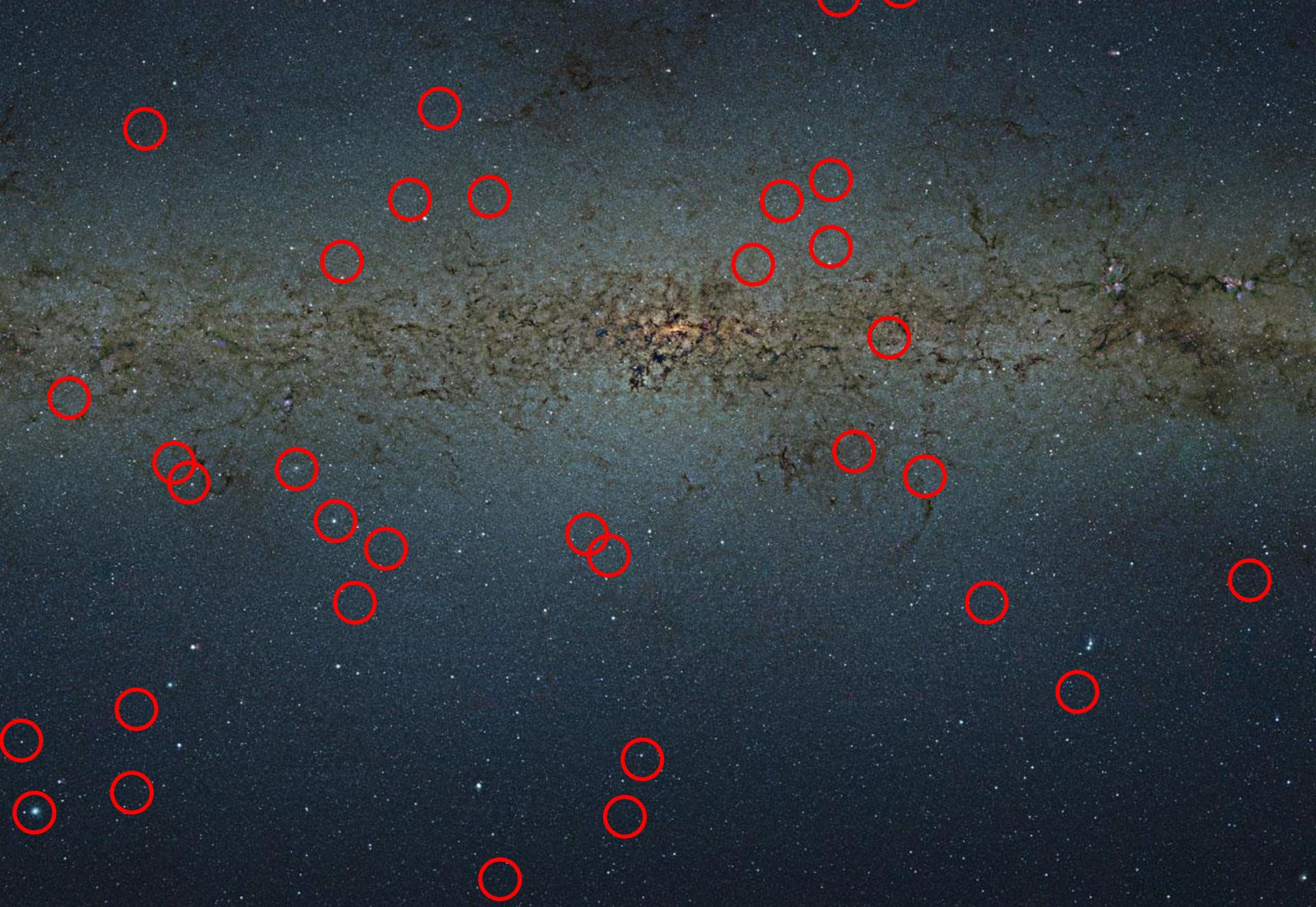
Unleashing the proper motions: revolution in the inner Galaxy



F. Gran, M. Zoccali, I. Saviane, E. Valenti,
R. Contreras Ramos, A. Rojas-Arriagada, et al.



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A total of 43+ globular clusters are known in the bulge area

Unleashing the proper motions: revolution in the inner Galaxy

- ★ Introduction
- ★ The chaotic phases of a PhD thesis:
 - ★ APOGEE observations: the stellar content of the inner Galaxy
 - ★ NGC 6544 as the learning case
- ★ The *intermezzo*: GCs and PMs
 - ★ Analysis of the inner Galaxy
- ★ Hidden in the haystack:
 - ★ 5 bonafide GCs towards the Galactic bulge
- ★ Future work and summary

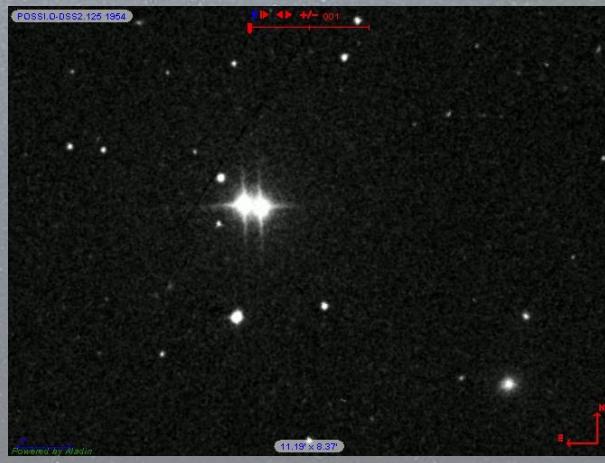
Key concept #1: stellar proper motions



POSS1, POSS2, DSS



Steve Quirk, Wikipedia Commons



DSS/STScI

Key concept #1: stellar proper motions

- ★ Brief (and biased) history of proper motion measurements:
- ★ Halley 1717: ~few stars

I. *Considerations on the Change of the Latitudes of some of the principal fixt Stars.* By Edmund Halley, R. S. Sec.

Having of late had occasion to examine the quantity of the Precession of the Equinoctial Points, I took the pains to compare the Declinations of the fixt Stars delivered by *Ptolemy*, in the 3d Chapter of the 7th Book of his *Almag.* as observed by *Timocharis* and *Aristyllus* near 300 Years before *Christ*, and by *Hipparchus* about 170 Years after them, that is about 130 Years before *Christ*, with what we now find: and by the result of very many Calculations, I concluded that the fixt Stars in 1800 Years were advanced somewhat more than 25 degrees in Longitude, or that the Precession is somewhat more than 50" per ann. But that with so much

Halley 1717



Steve Quirk, Wikipedia Commons

Key concept #1: stellar proper motions

- ★ Brief (and biased) history of proper motion measurements:
 - ★ Halley 1717: ~**few** stars
 - ★ Ground-based observations until 1995: ~**8000** stars



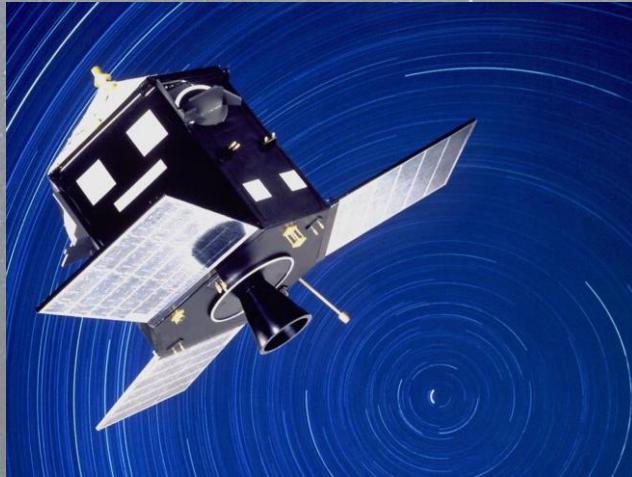
POSS1, POSS2, DSS



Steve Quirk, Wikipedia Commons

Key concept #1: stellar proper motions

- ★ Brief (and biased) history of proper motion measurements:
 - ★ Halley 1717: ~**few** stars
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 - ★ ESA Hipparcos space mission (early 90s): ~**115,000** stars



ESA, Hipparcos



POSS1, POSS2, DSS

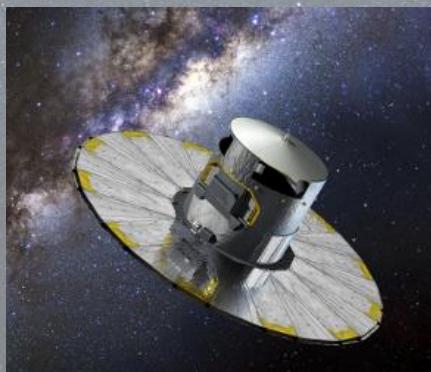


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Key concept #1: stellar proper motions

★ Brief (and biased) history of proper motion measurements:

- ★ Halley 1717: ~**few** stars
- ★ Ground-based observations until 1995: ~**8000** stars
- ★ ESA Hipparcos space mission (early 90s): ~**115,000** stars
- ★ ESA Gaia space mission (active):
~**1.46 billion** stars
~**1.460.000.000** stars



ESA, Gaia



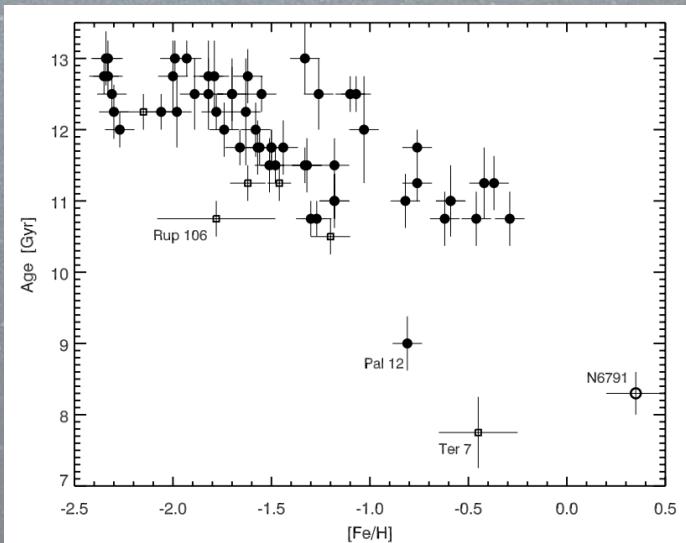
POSS1, POSS2, DSS



Steve Quirk, Wikipedia Commons

Key concept #2: the Galaxy evolution told by its globular clusters

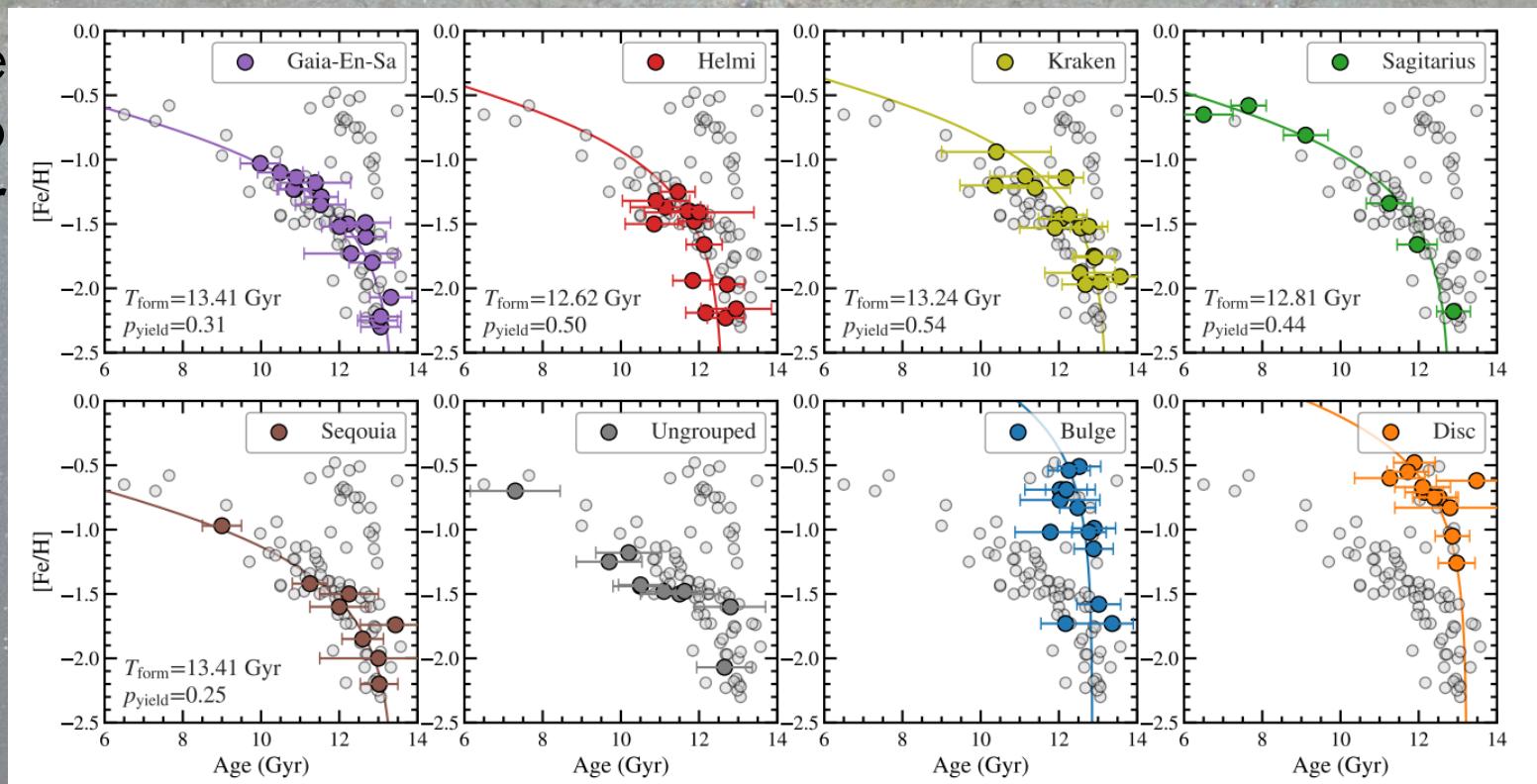
- ★ **Globular clusters** are one of the most valuable **tracers** when trying to understand **galaxy evolution**.
- ★ We can constrain **ages**, **masses**, and **distances**: the primary laboratory of stellar evolution including **chemical** and **enrichment processes**.



Key concept #2: the Galaxy evolution told by its globular clusters

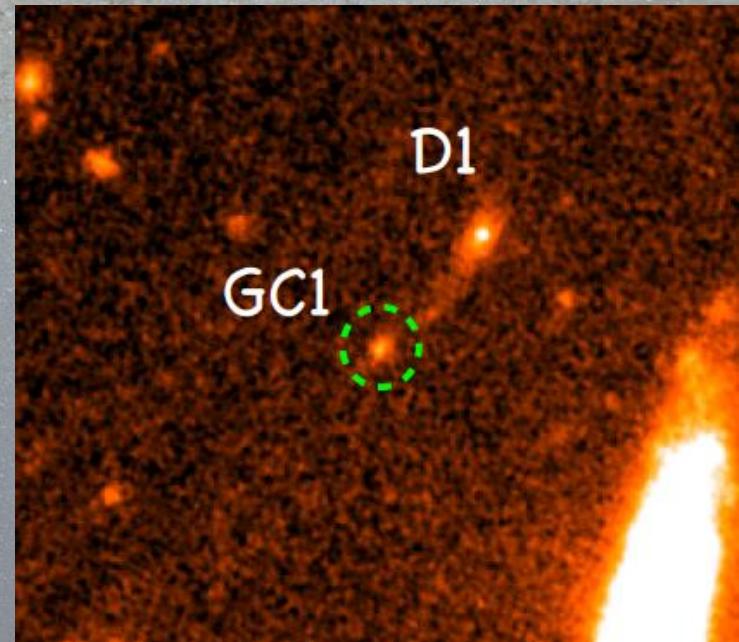
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★ We lab enr



Key concept #2: the Galaxy evolution told by its globular clusters

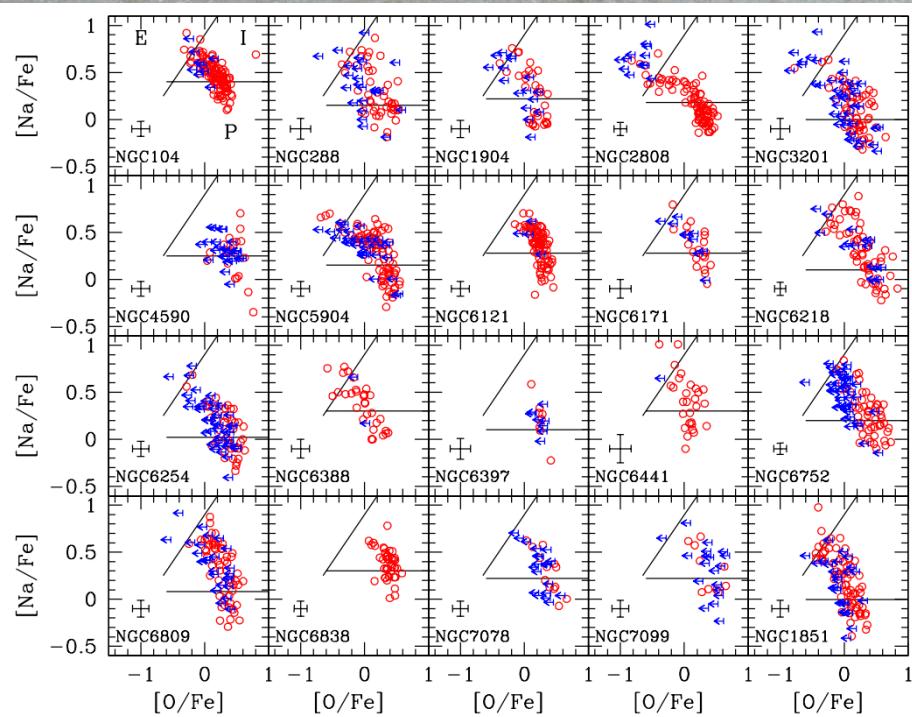
- ★ **Globular clusters** are one of the most valuable **tracers** when trying to understand **galaxy evolution**.
- ★ We can constrain **ages, masses,** and **distances**: the primary laboratory of stellar evolution including **chemical** and **enrichment processes**.
- ★ **Observations** and **simulations** can work together to account the different properties of **nowadays** clusters and the ones formed at **high redshift**.



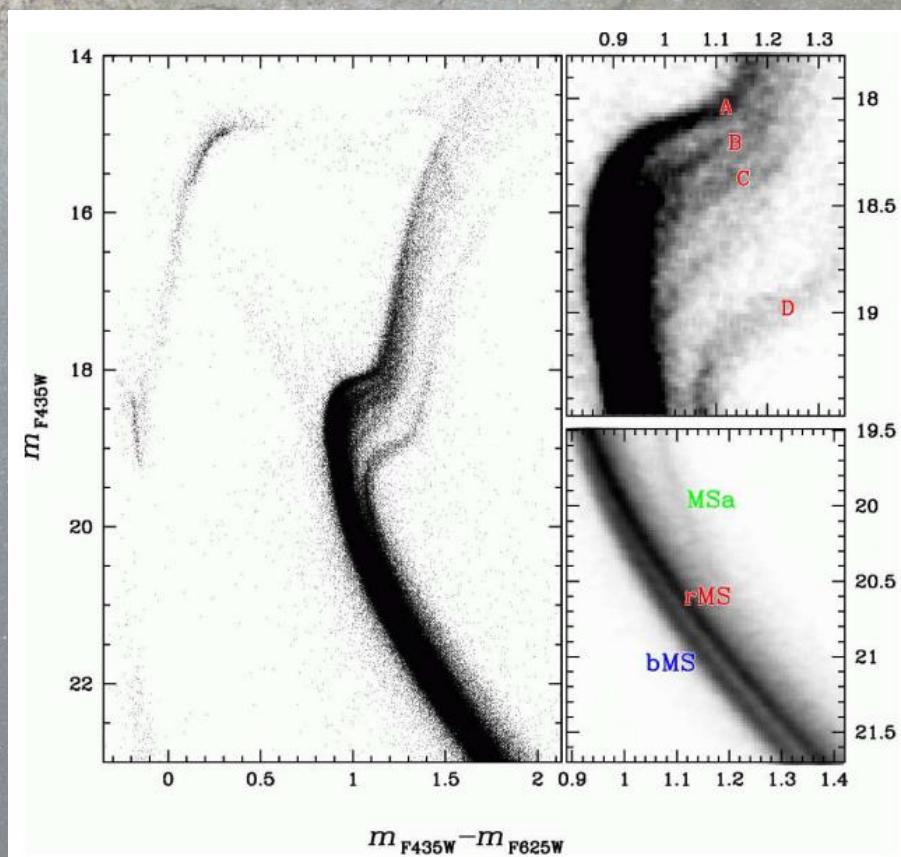
Vanzella et al. 2017

Key concept #3: multiple stellar populations within globular clusters

- ★ From “simple stellar population” to the Pandora’s box: photometrical and spectroscopical differences.



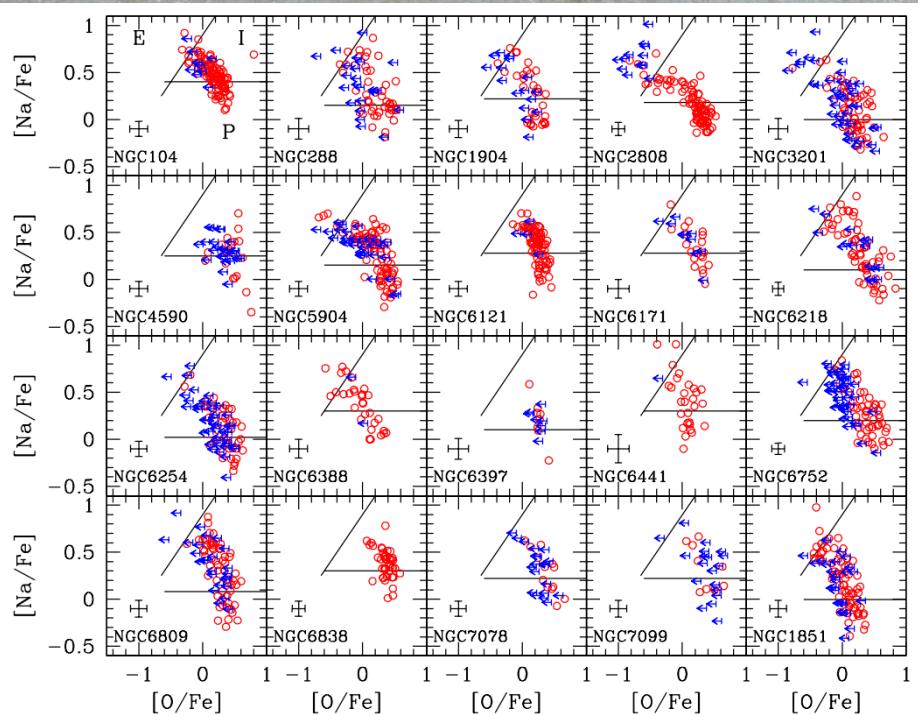
Carretta et al. 2009



Bellini et al. 2010, 2017

Key concept #3: multiple stellar populations within globular clusters

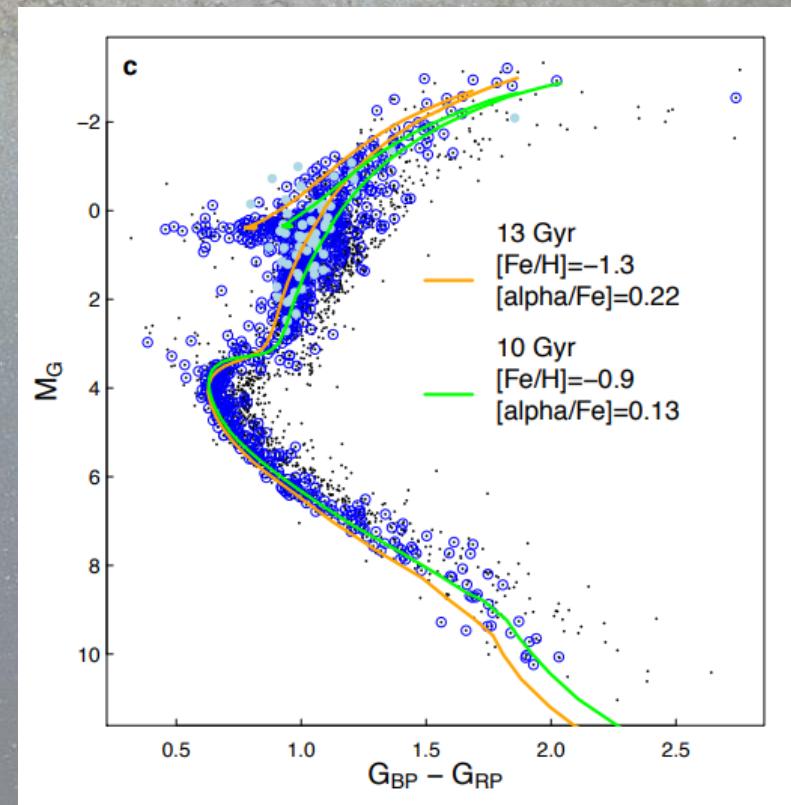
- ★ From “simple stellar population” to the Pandora’s box: photometrical and spectroscopical differences.



- ★ Fe enrichment in only a limited cases: massive clusters
- ★ Light-element (proton capture) variations!
 - ★ C, N, O, Na, Mg, Al, Si, ... among others!
- ★ AGB and massive fast rotators: most likely contributors

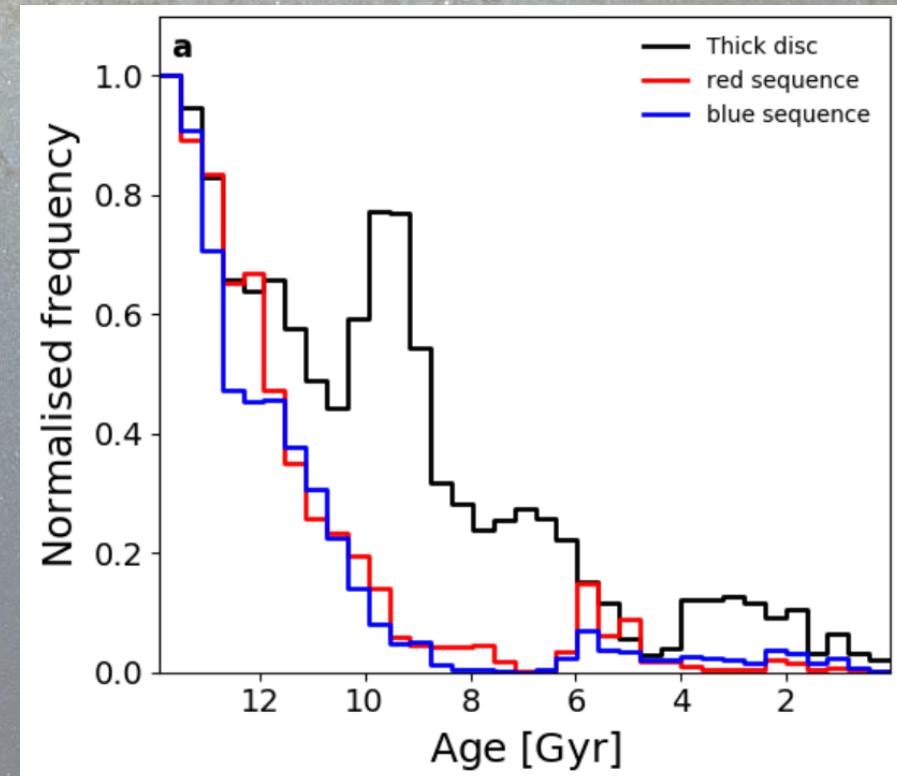
Key concept 1+2+3 = #6: proper motions to isolate different stellar populations

- ★ The Gaia satellite change our understanding of the Milky Way, giving us **dynamical information** of ~1.8 billion stars.
- ★ Discovery of a major Milky Way merger from orbital parameters
- ★ Star formation history of the Galaxy
- ★ Isolation of the Sagittarius dwarf galaxy across the entire sky



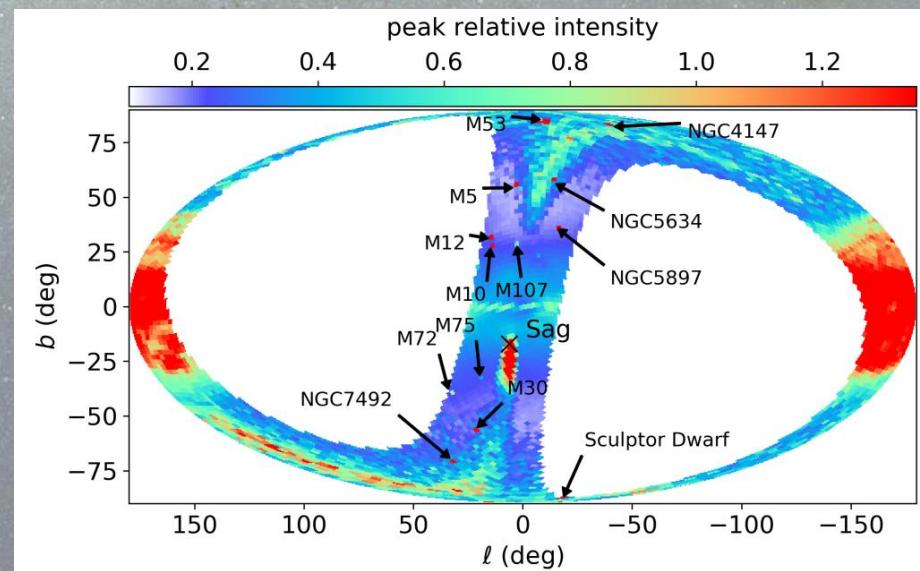
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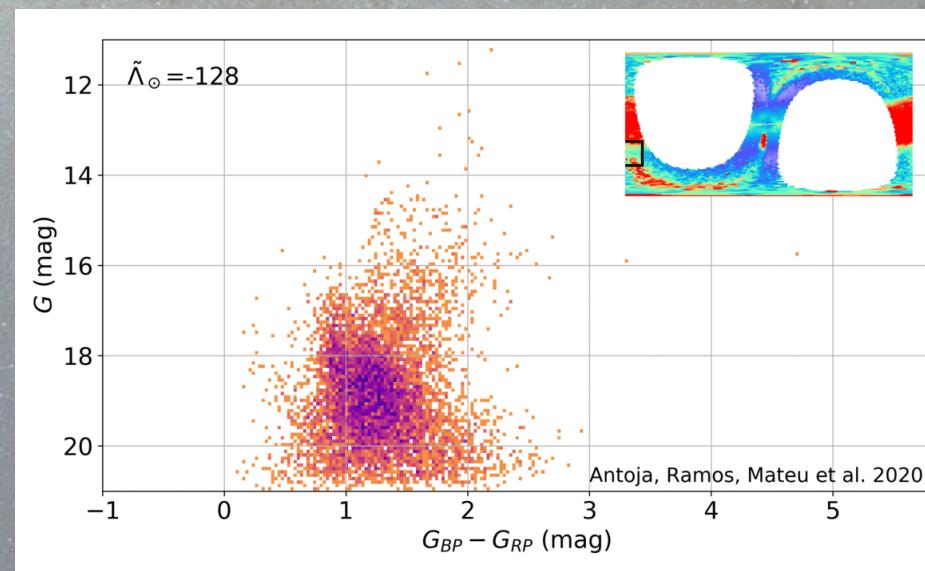
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Antoja et al. 2020;
Ramos et al. 2020

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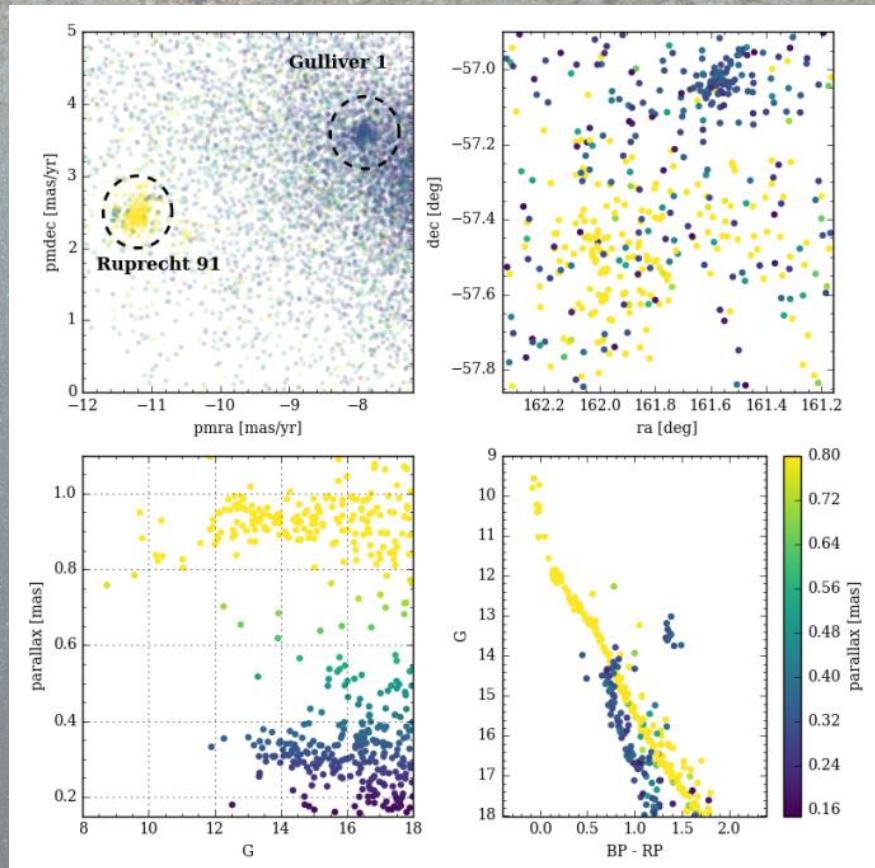


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★ CLUSTER SCIENCE!

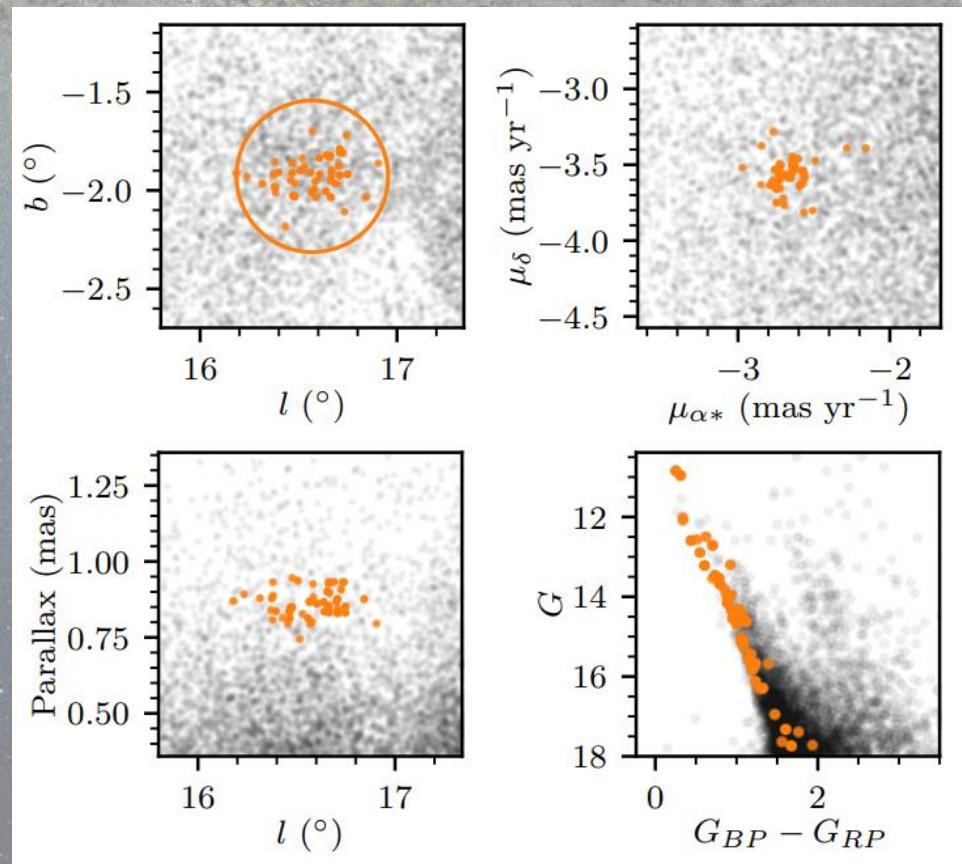


Cantat-Gaudin et al. 2018

Key concept 1+2+3 = #6: proper motions to isolate different stellar populations

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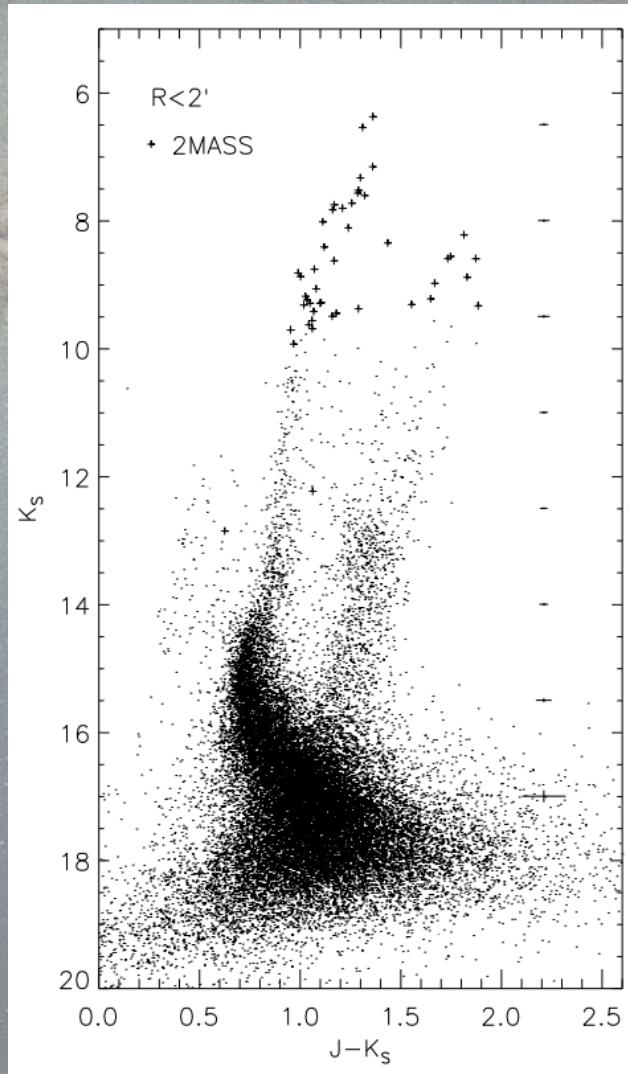
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APOGEE view of the
globular cluster NGC 6544



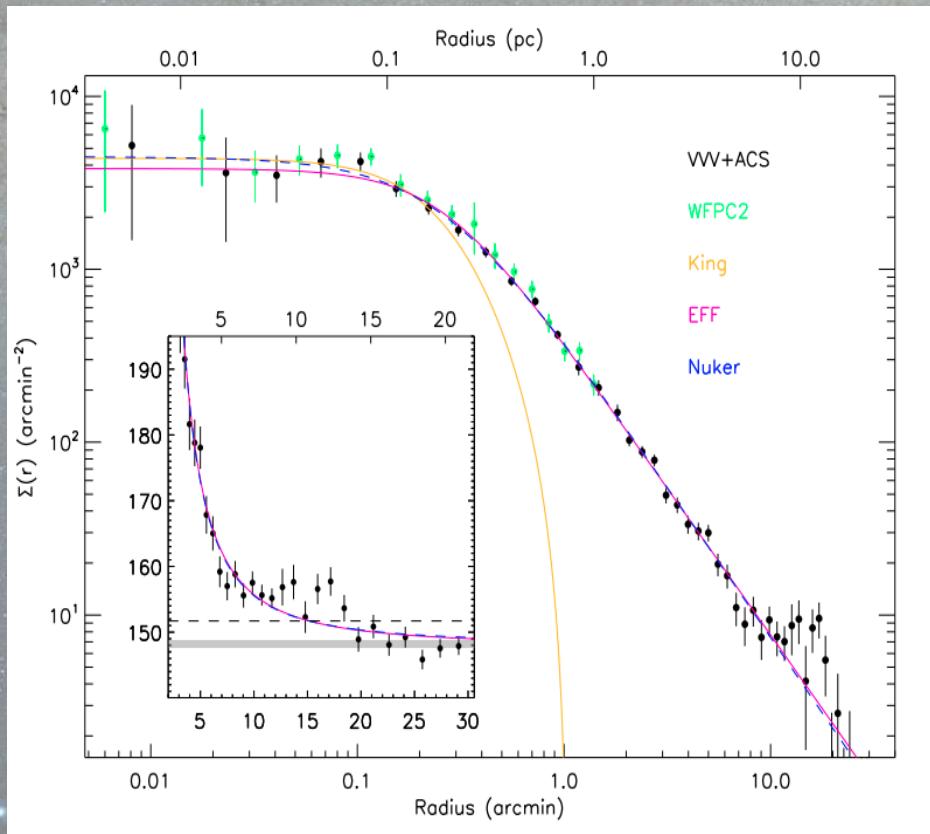
Context and history of NGC 6544

- ★ NGC 6544 ($\ell = 5.84^\circ, b = -2.2^\circ$) is located at **low Galactic latitudes**
- ★ Nearby globular cluster \sim 2.4 kpc
- ★ Poorly characterized due to highly variable **differential reddening**:
 $E(B-V) = 0.79$ mags



Cohen et al. 2014

Context and history of NGC 6544



Cohen et al. 2014

- ★ NGC 6544 ($\ell = 5.84^\circ, b = -2.2^\circ$) is located at **low Galactic latitudes**
- ★ Clear evidence of **tidal interaction** with the MW
- ★ Metallicity only constrained by **low-resolution spectra**

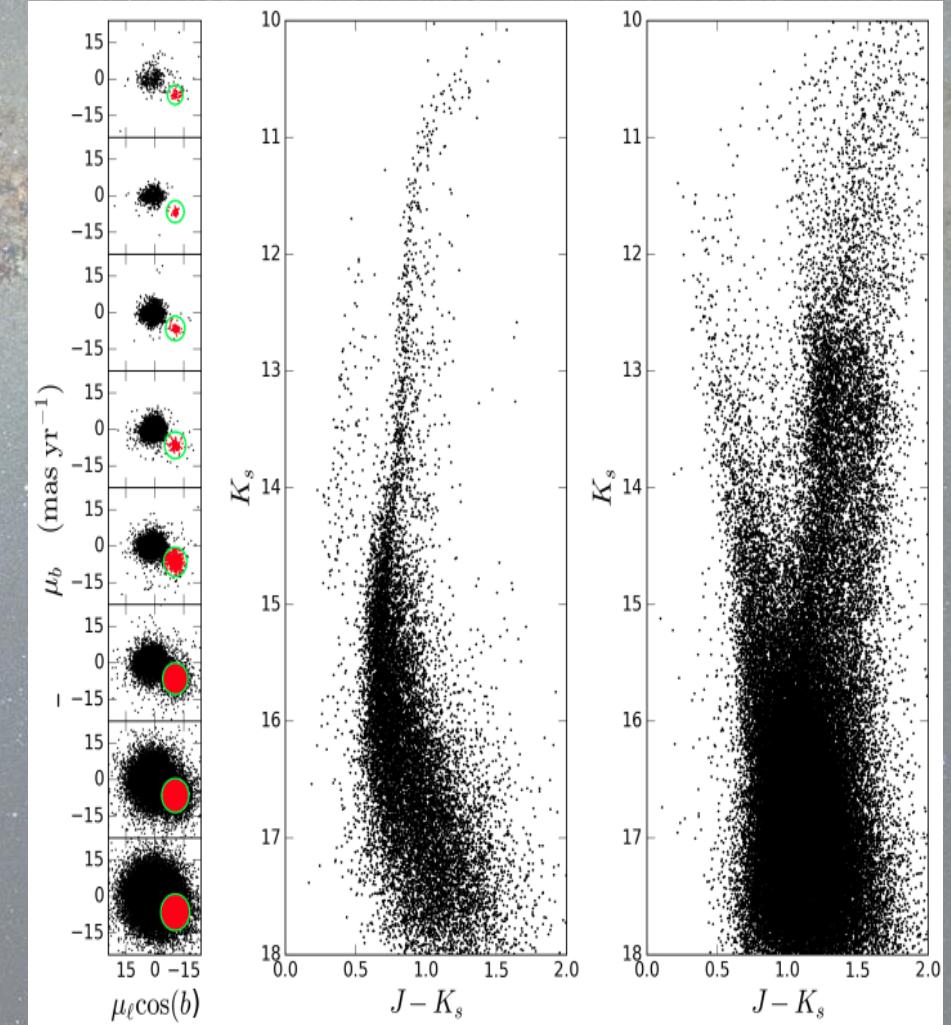
NGC 6544 in VVV/x survey



Near-IR survey
(ZYJHK_s)

~100+ K_s epochs

Relative proper
motions:
 $\mu_l \cos(b)$, μ_b



NGC 6544 in APOGEE survey



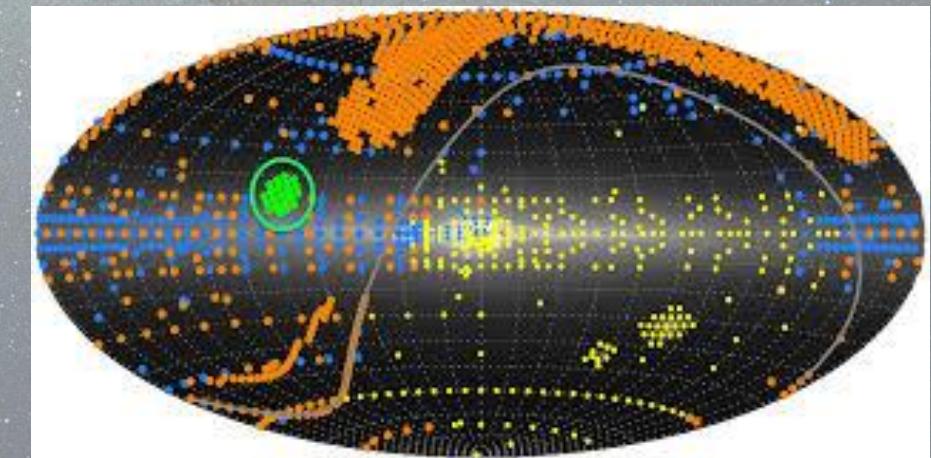
Near-IR (H-band),
high-resolution ($R \sim 20000$)

high-SNR (~ 100)
20+ abundances

~470000 spectra
~430000 stars

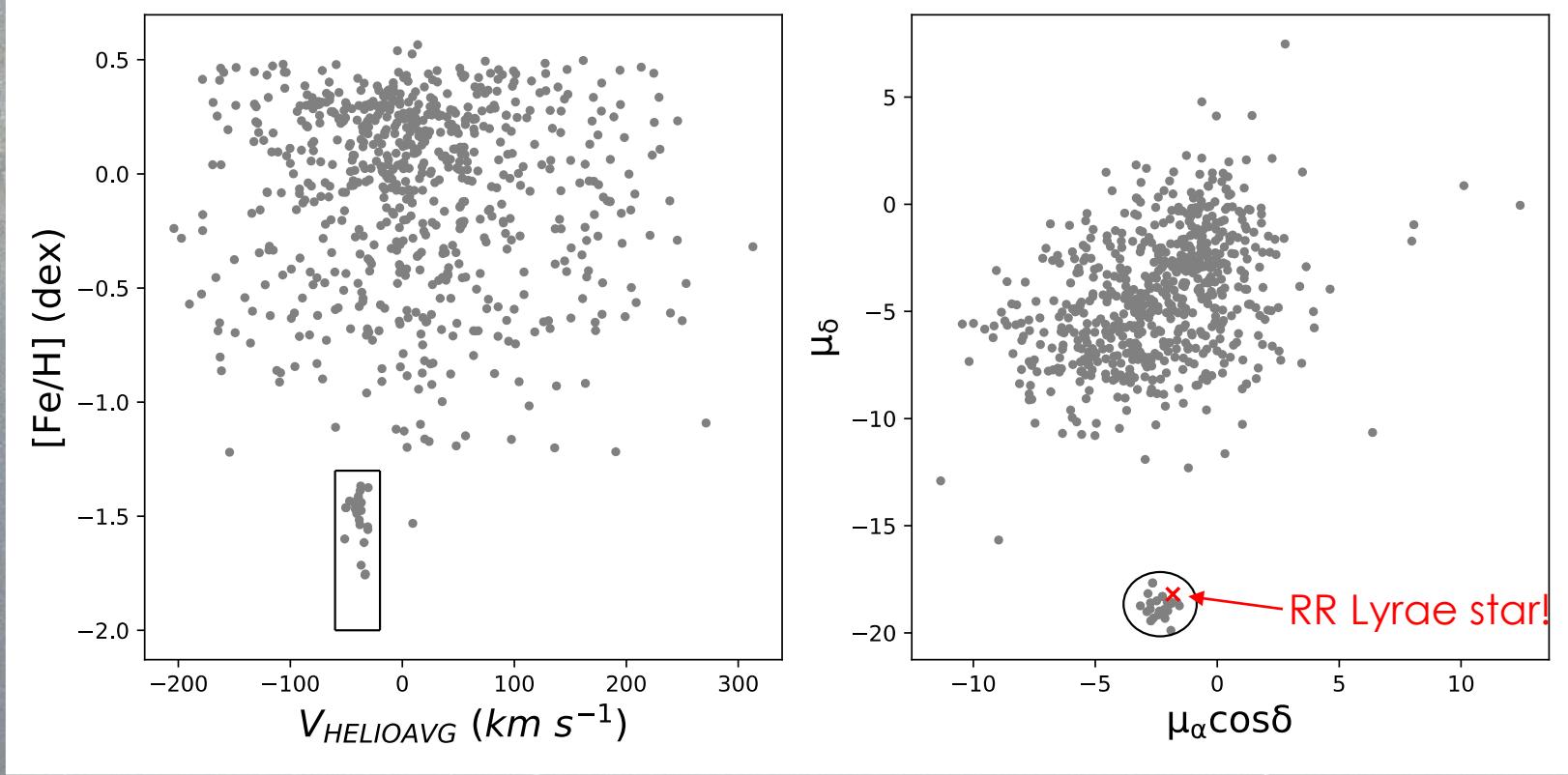
DR16 publicly available

- ★ Part of the SDSS collaboration (SDSS-III and SDSS-IV)
- ★ **Chilean Participation Group:** access to proprietary data



All-sky observations from APO and LCO.

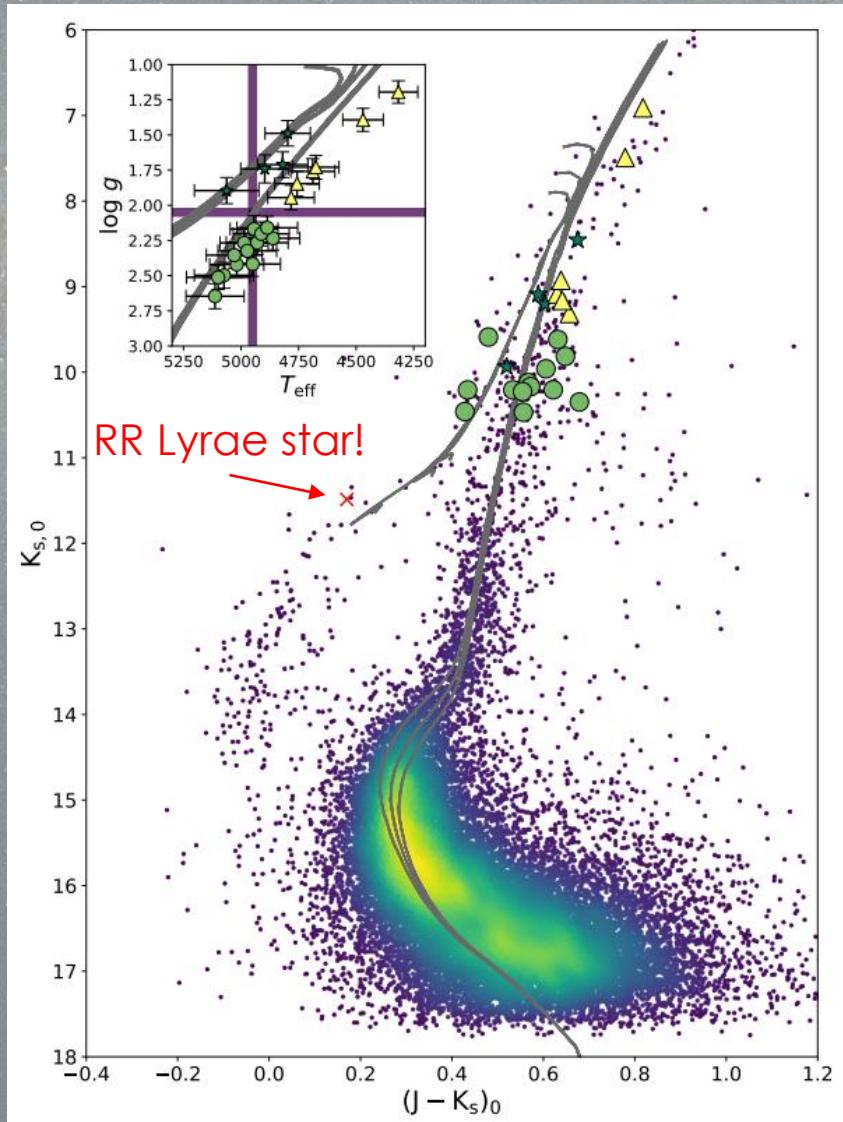
Selection of NGC 6544 members



(Left) APOGEE targets up to 45 arcmins from the cluster center.

(Right) Gaia DR2 VPD of the same stars around NGC 6544.

Fundamental properties of NGC6544



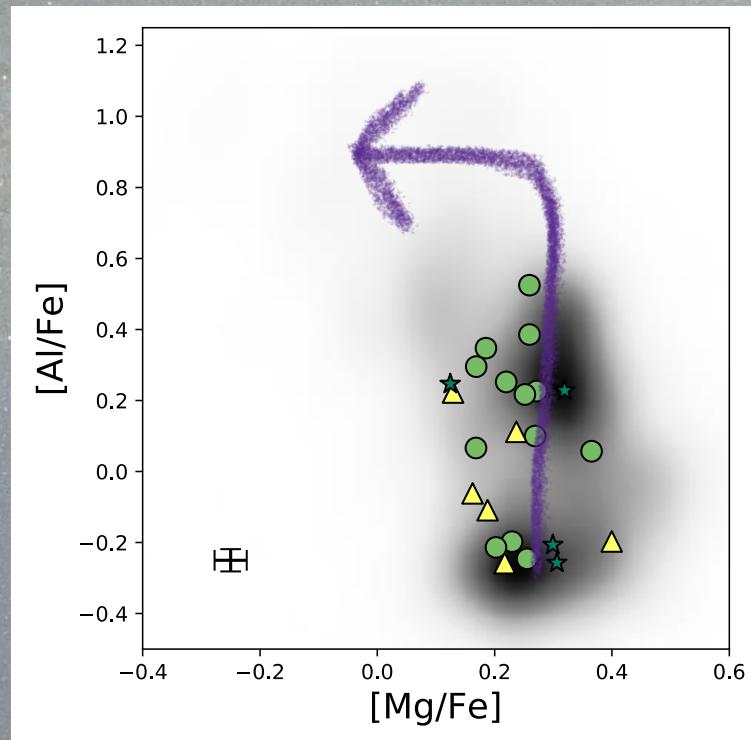
A total of 23 members were located:

- Lower RGB (below the bump)
- ⚠️ Upper RGB (above the bump)
- ★ AGB

$$\begin{aligned}V_{\text{HELIOAVG}} &= -38.2 \pm 3.7 \text{ km s}^{-1} \\ [\text{Fe}/\text{H}] &= -1.44 \pm 0.04 \text{ dex} \\ [\alpha/\text{Fe}] &= 0.20 \pm 0.04 \text{ dex}\end{aligned}$$

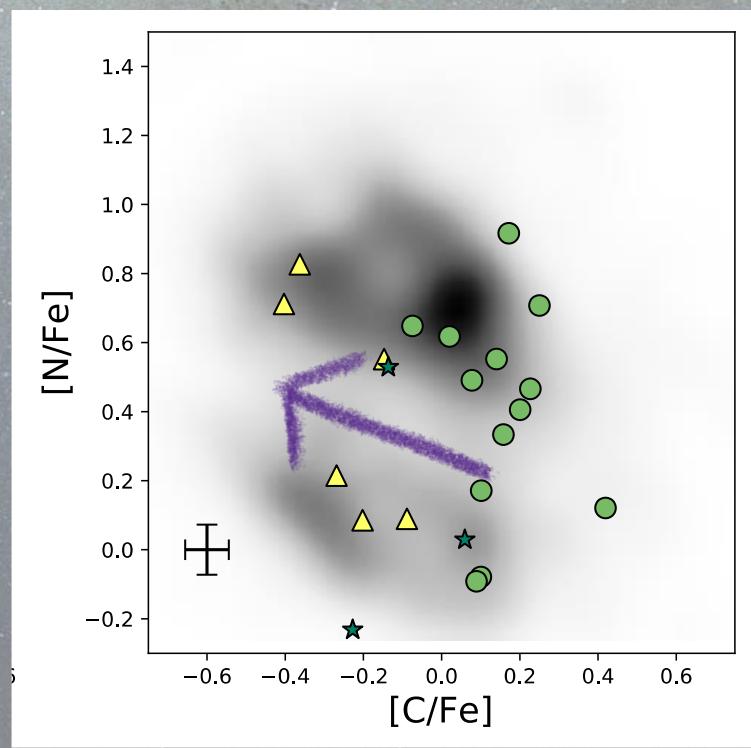
Dereddened VVV-2MASS
CMD of NGC 6544

Known anticorrelations in NGC 6544

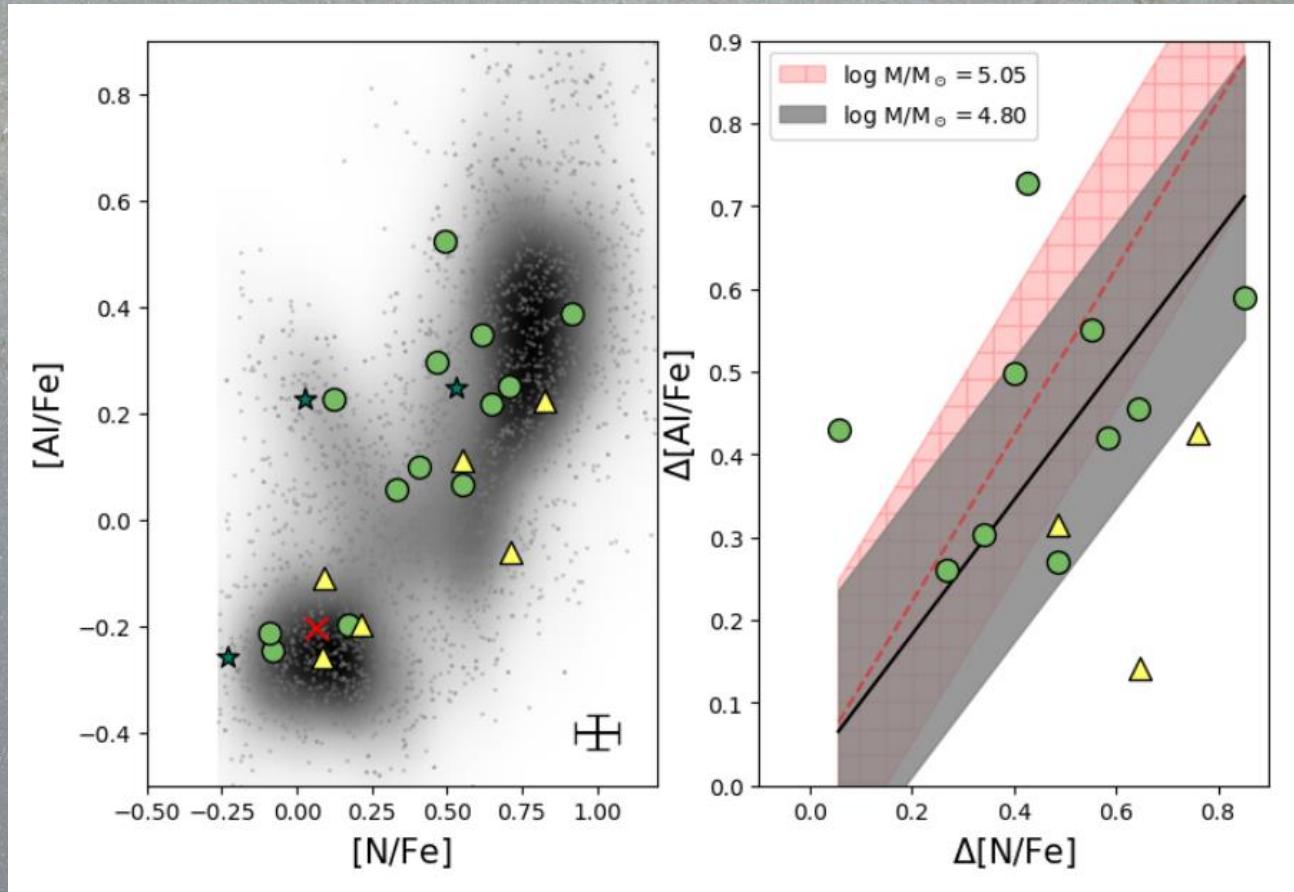


- Lower RGB (below the bump)
- ▲ Upper RGB (above the bump)
- ★ AGB

Background: APOGEE clusters



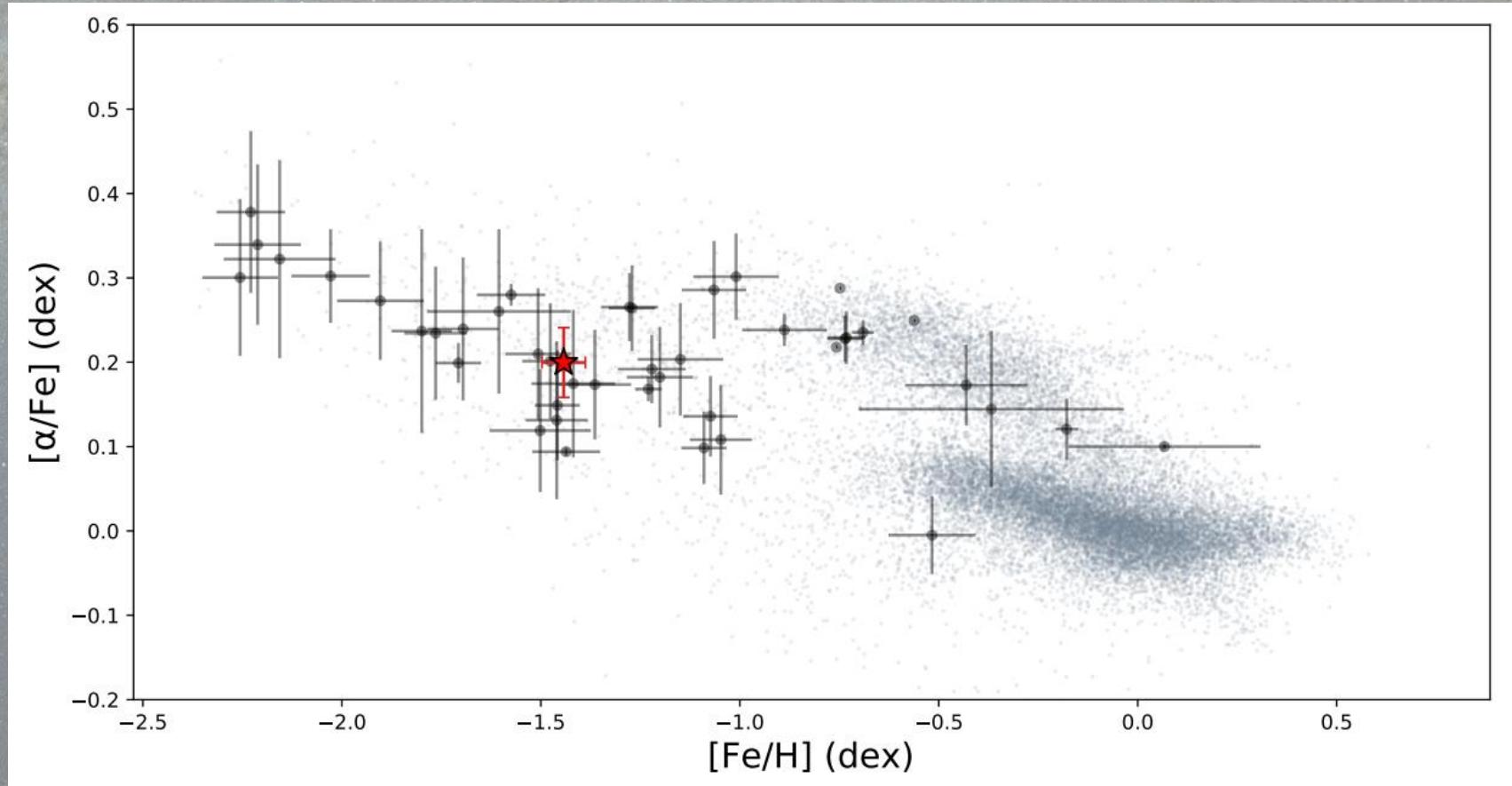
Abundance patterns and the mass of NGC 6544



Clusters from Masseron et al. 2019 and Schiavon et al. 2017 in the DR16

Galactic context: Tinsley diagram

Background sample: randomly selected 10% of all APOGEE DR16



Clusters from Masseron et al. 2019 and Schiavon et al. 2017 in the DR16

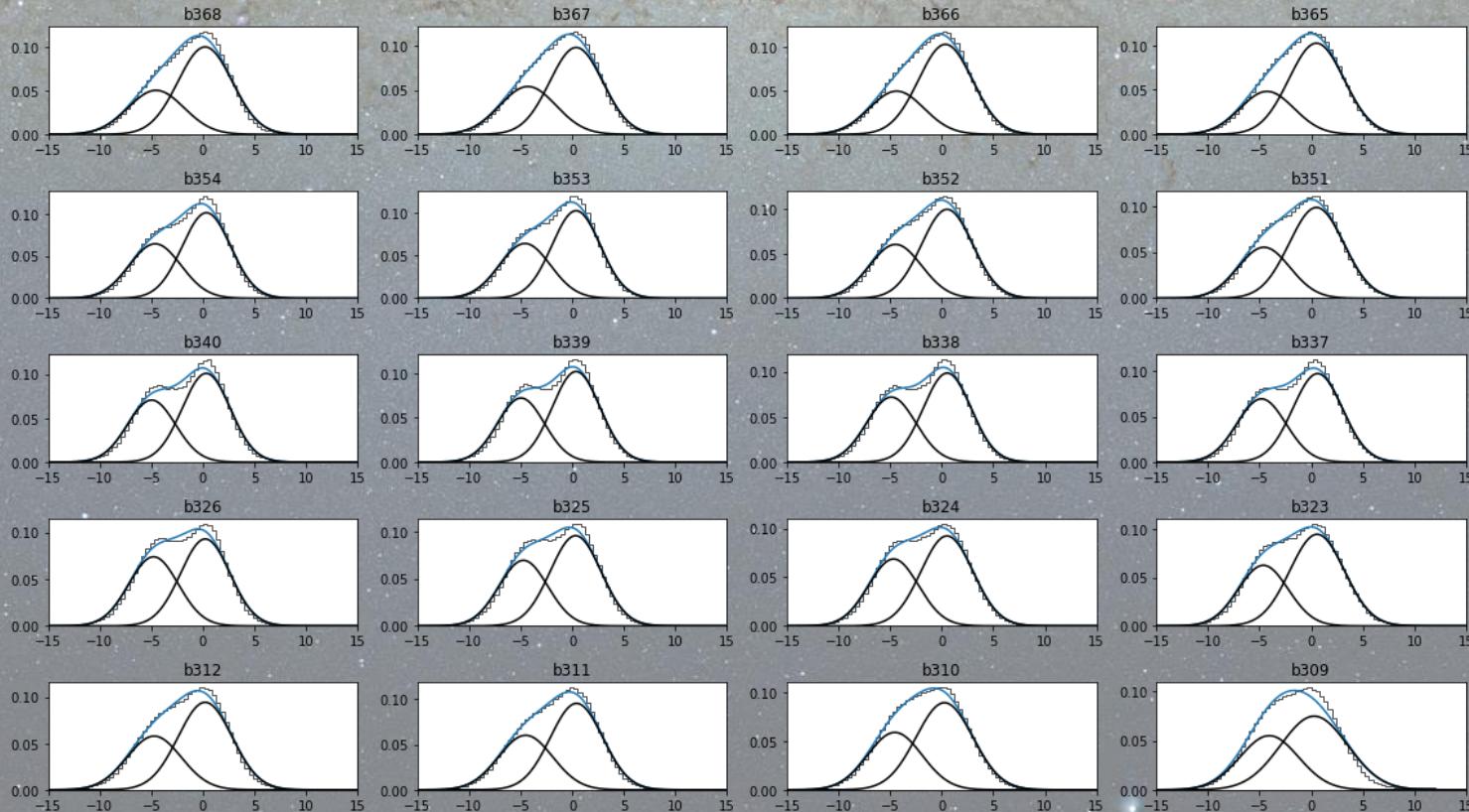
Summary #1

- ★ APOGEE observed **23 stars** from NGC 6544 (RGB+AGB)
- ★ Known anticorrelations were found (Mg-Al, C-N, Na-O)
- ★ with **distinct abundance patterns**:
 - ★ **9** first generation
 - ★ **14** second generation
- ★ Large [Al/Fe] spread and negligible [Mg/Fe] enrichment
- ★ Independent **distance measurement** (RR Lyrae star)
- ★ Consistent with the **metal-poor tail** of the canonical thick-disk
- ★ Multi-survey **synergies** (APOGEE, VVV, Gaia, 2MASS)

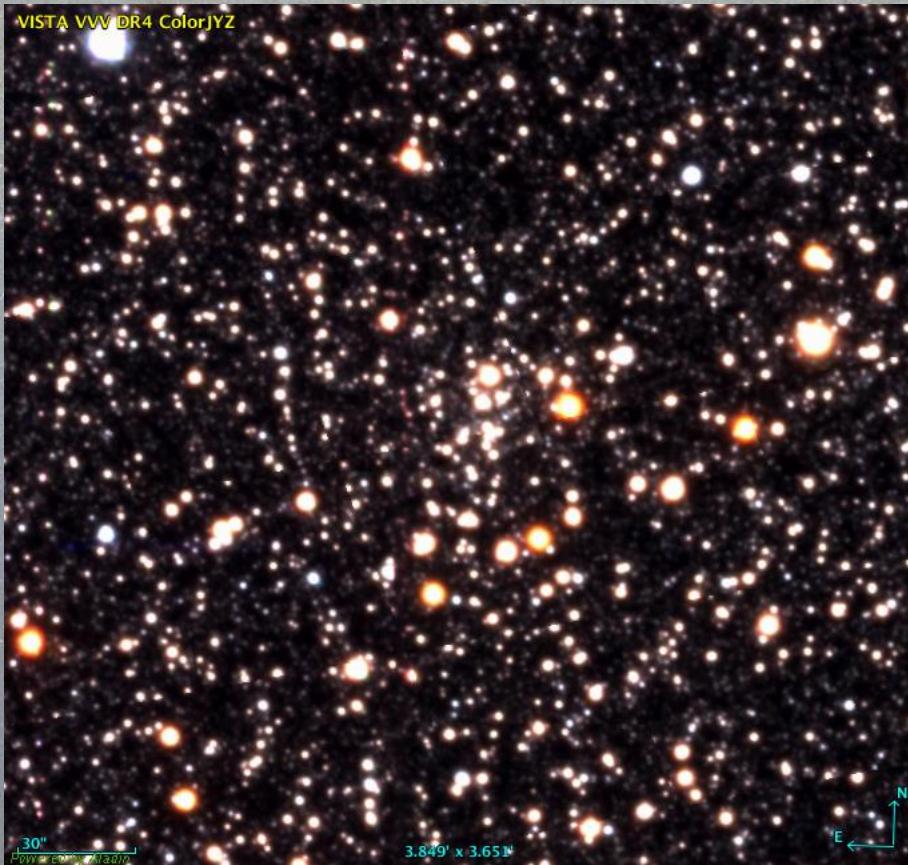


The *intermezzo*: GCs and PMs

- ★ Clouds impede us to observe the APOGEE plates:
 - ★ Explore other possibilities or small projects
- ★ There were several ideas and all of them include the VVV PMs



Hidden in the haystack: New globular clusters towards the Milky Way bulge



Gran et al. 2019

Hidden in the haystack:

New globular clusters towards the Milky Way bulge



Hidden in the haystack:

New globular clusters towards the Milky Way bulge



- ★ Valuable tracers of understanding the Milky Way evolution
- ★ Galactic bulge GCs compose a major part of the ***in situ*** component (Myeong et al. 2018)
- ★ The total number of GCs in the Milky Way is still **unknown**

Photometric searches of GCs

Several observational efforts have been done to characterize **new GCs** in the Galaxy.

Most of the recently discovered GCs belong to the **Milky Way halo**.

A NEW DISTANT MILKY WAY GLOBULAR CLUSTER IN THE PAN-STARRS1 3π SURVEY

BENJAMIN P. M. LAEVENS^{1,2}, NICOLAS F. MARTIN^{1,2}, BRANIMIR SESAR², EDOUARD J. BERNARD³, HANS-WALTER RIX², COLIN T. SLATER⁴, ERIC F. BELL⁴, ANNETTE M. N. FERGUSON³, EDWARD F. SCHLAFLY², WILLIAM S. BURGETT⁵, KENNETH C. CHAMBERS⁵, LARRY DENNEAU⁵, PETER W. DRAPER⁶, NICHOLAS KAISER⁵, ROLF-PETER KUDRITZKI⁵, EUGENE A. MAGNIER⁵, NIGEL METCALFE⁶, JEFFREY S. MORGAN⁵, PAUL A. PRICE⁷, WILLIAM E. SWEENEY⁵, JOHN L. TONRY⁵, RICHARD J. WAINSCOAT⁵, AND CHRISTOPHER WATERS⁵

¹ Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA

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A NEW DISTANT MILKY WAY GLOBULAR CLUSTER IN THE PAN-STARRS1 3π SURVEY

Segue 3: the youngest globular cluster in the outer halo[★]

S. Ortolani,^{1,2} E. Bica³ and B. Barbuy⁴†

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⁴Universidade de São Paulo, IAG, Rua do Matão 1226, Cidade Universitária, São Paulo 05508-900, Brazil

Photometric searches of GCs

KIM 3: AN ULTRA-FAINT STAR CLUSTER IN THE CONSTELLATION OF CENTAURUS

DONGWON KIM, HELMUT JERJEN, DOUGAL MACKEY, GARY S. DA COSTA, AND ANTONINO P. MILONE

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Received 2015 December 10; accepted 2016 February 12; published 2016 March 29

DISCOVERY OF A FAINT OUTER HALO MILKY WAY STAR CLUSTER IN THE SOUTHERN SKY

DONGWON KIM, HELMUT JERJEN, ANTONINO P. MILONE, DOUGAL MACKEY, AND GARY S. DA COSTA

Research School of Astronomy and Astrophysics, The Australian National University, Mount Stromlo Observatory, via Cotter Road, Weston, ACT 2611, Australia;

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Received 2015 January 1; accepted 2015 February 10; published 2015 April 16

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Gaia 1 and 2. A pair of new Galactic star clusters

S. Koposov,^{1,2} V. Belokurov¹ and G. Torrealba¹

¹ University of Cambridge, Cambridge CB3 0HA, UK

² Center for Cosmology, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

Accepted

DONGWON

Research School of Astro-

DISCOVERY OF TWO EXTREMELY LOW LUMINOSITY MILKY WAY GLOBULAR CLUSTERS IN THE SOUTHERN SKY

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DISCOVERY OF A FAINT

A NEW DISTANT MILKY WAY GLOBULAR CLUSTER

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Center for Cosmology, Carnegie Mellon University,

5213, USA

S. K. TWO STAR CLUSTER IN THE

EXTREMELY LOW BACK

Ket.

DONGWON

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P. MILONE

jangwon.kim@anu.edu.au

CAT'S EYE OF A FAINT ONE

CATS AND DOGS.

ND DOGS, HAIR AND A HERO: A QUINTET OF NEW MILKY WAY COMPANION V. BELOKUROV,² D. B. ZUCKER,² N. W. EVANS,² J. T. KLEYNA,³ S. KOPOSOV,⁴ S. T. HODGKIN,² M. I. WILKINSON,² M. FELLAUER,² D. M. BRAMICH,² P. C. HEWETT,² S. VIDRIH,² L. T. H.-W. RIX,⁴ E. F. BELL,⁴ R. F. G. WYSE,⁷ H. J. NEWBERG,⁸ P. A. O. Y. GNEDIN,¹² D. P. SCHNEIDER,¹³ T. C. BEERS,¹⁴ S. J. KLEYNA,¹⁵ M. HARVANEK,¹⁵ S. J. DA COSTA,¹⁶ AND GARY S. DA COSTA,¹⁶ 13 Santa Barbara Technology, Pasadena, CA 91109; published 2014 by the Royal Astronomical Society

THE DISC
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2 Departamen

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⁴ U. *idade de São Paulo, IAG, Rua do Matão 1226, Cidade Universitária, São Paulo 05508-900, Brazil.*

Photometric searches of GCs

Thanks to the recent **near-IR photometric surveys**, the number of star cluster candidates has risen exponentially in the last few years in the **bulge region**.



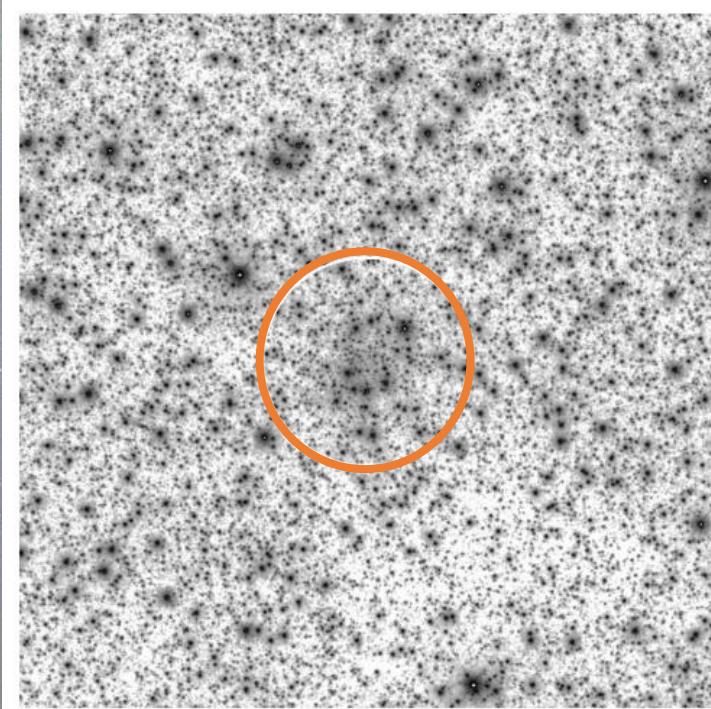
VVV CL 001

Minniti et al. 2011,
Gran et al. 2019

Photometric searches of GCs

Thanks to the recent **near-IR photometric surveys**, the number of star cluster candidates has risen exponentially in the last few years in the **bulge region**.

Moni-Bidin et al. 2011,
Gran et al. 2019



VVV CL 002

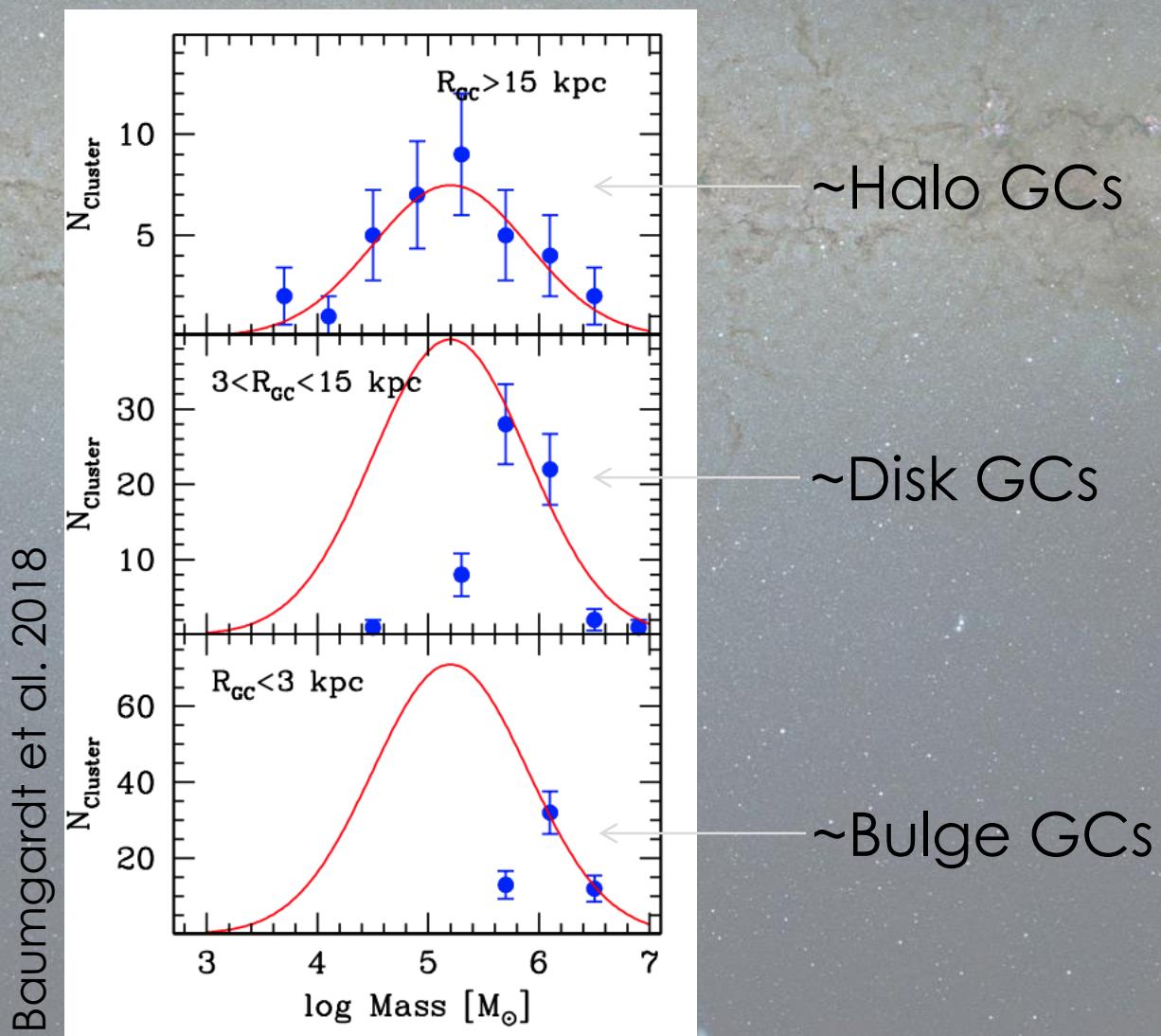
Photometric searches of GCs

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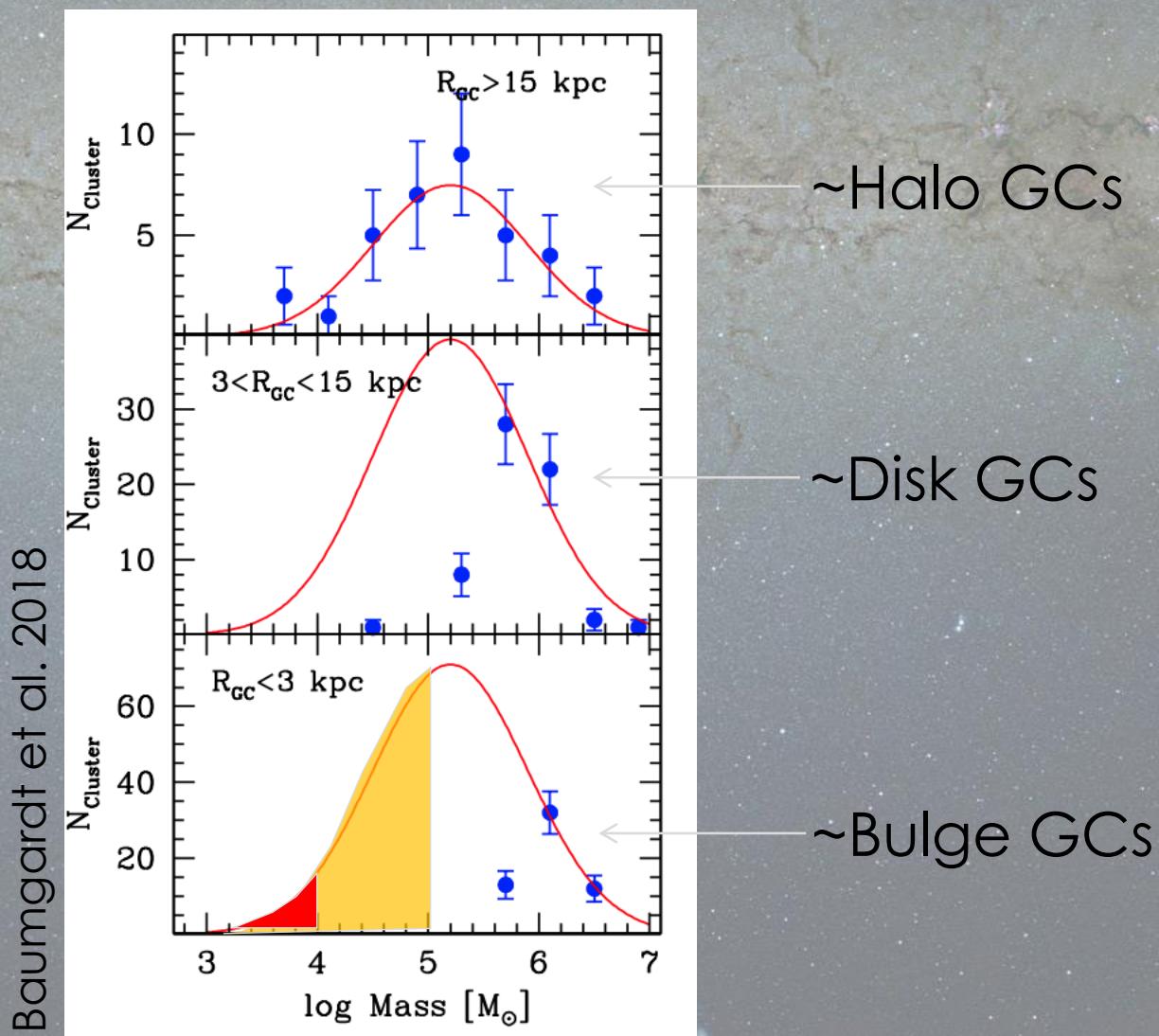
Unfortunately, most of them were recently **ruled out** using proper motions (**Gran et al. 2019**):

- ★ Spatial overdensities 
- ★ CMD different from field 
- ★ Coherent space motion 

Initial mass distribution of GCs in the MW



Initial mass distribution of GCs in the MW



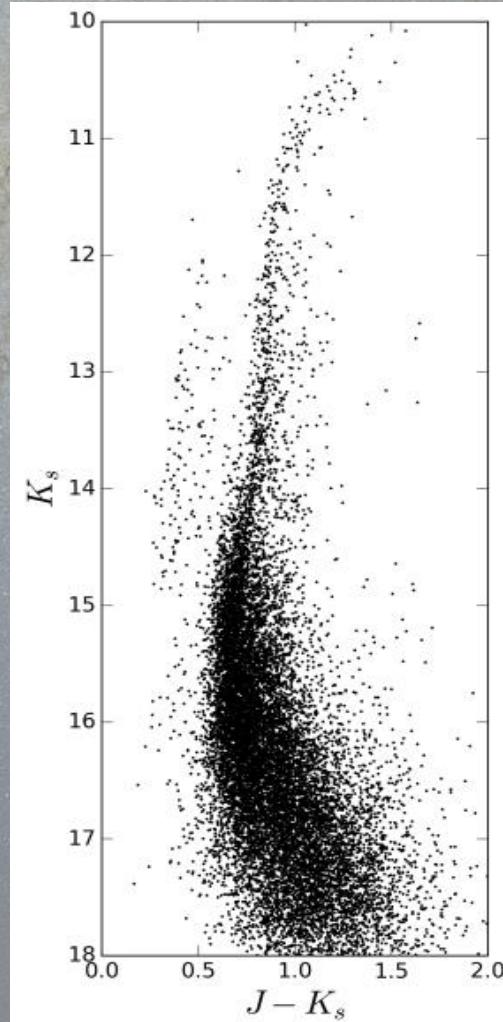
VVV proper motion catalog



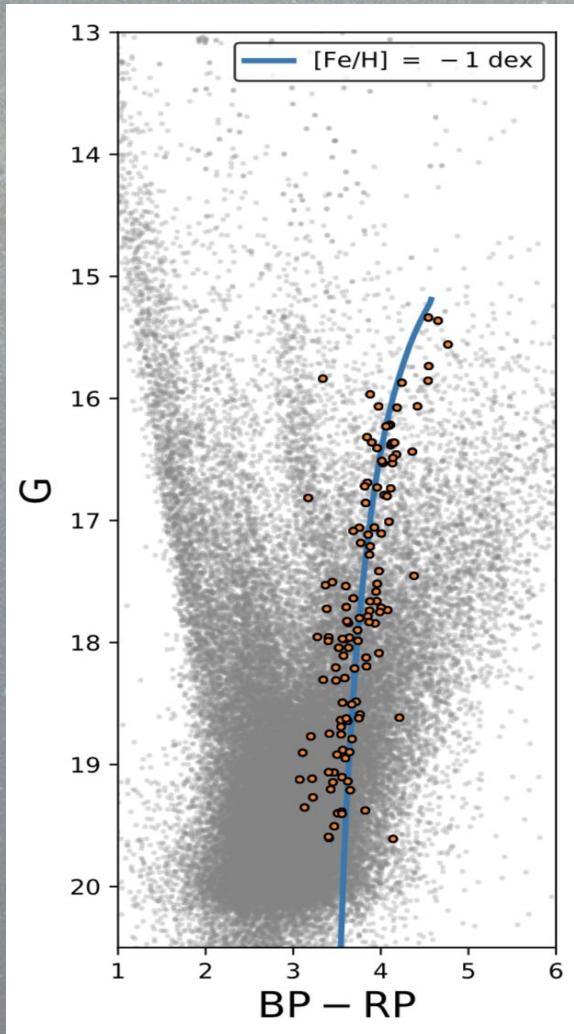
Near-IR survey
(ZYJHK_s)

~100+ K_s epochs

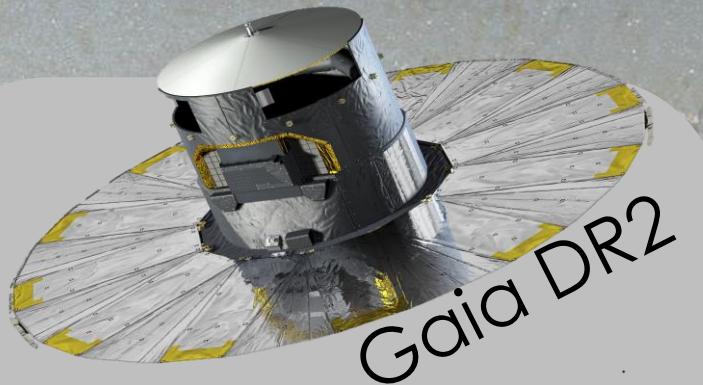
Relative proper
motions:
 $\mu_l \cos(b)$, μ_b



Gaia DR2 proper motion catalog



Gran et al. 2019



Optical survey
(G, G_{BP}, G_{RP})

Valid for $|b| \geq 2^\circ$

Absolute proper
motions:
 $\mu_a \cos(\delta), \mu_\delta$

Gaia Collaboration 2018

Clustering on a 5-D phase-space

$-10 \leq l \text{ (deg)} \leq 10$
 $-10 \leq b \text{ (deg)} \leq 10$



$l, b, \mu_l \cos(b), \mu_b, G_{BP} - G_{RP}$
 $l, b, \mu_l \cos(b), \mu_b, J - K_s$



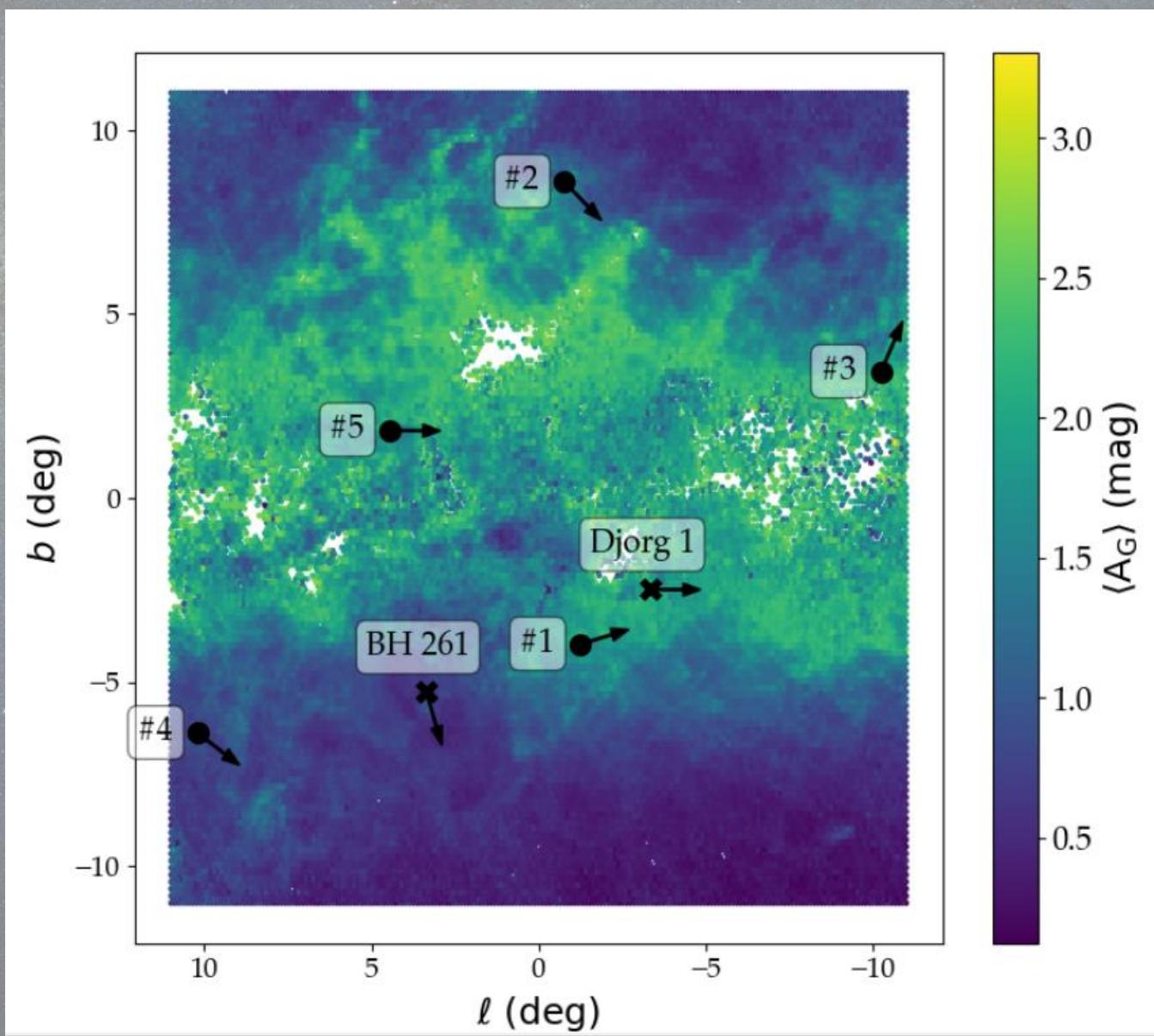
scikit learn: KDTree
and DBScan

Pedragosa et al 2011



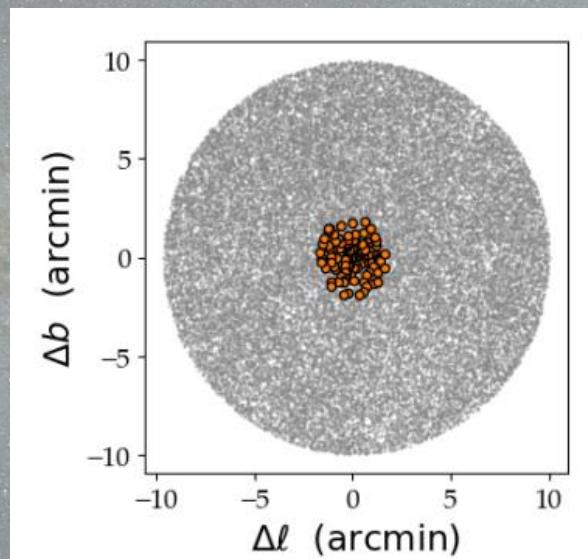
i
Candidate
clusters in the 5-D
phase space!
!

Map of the new GCs



Gran et al. 2021

New GCs: the case of Gran 3

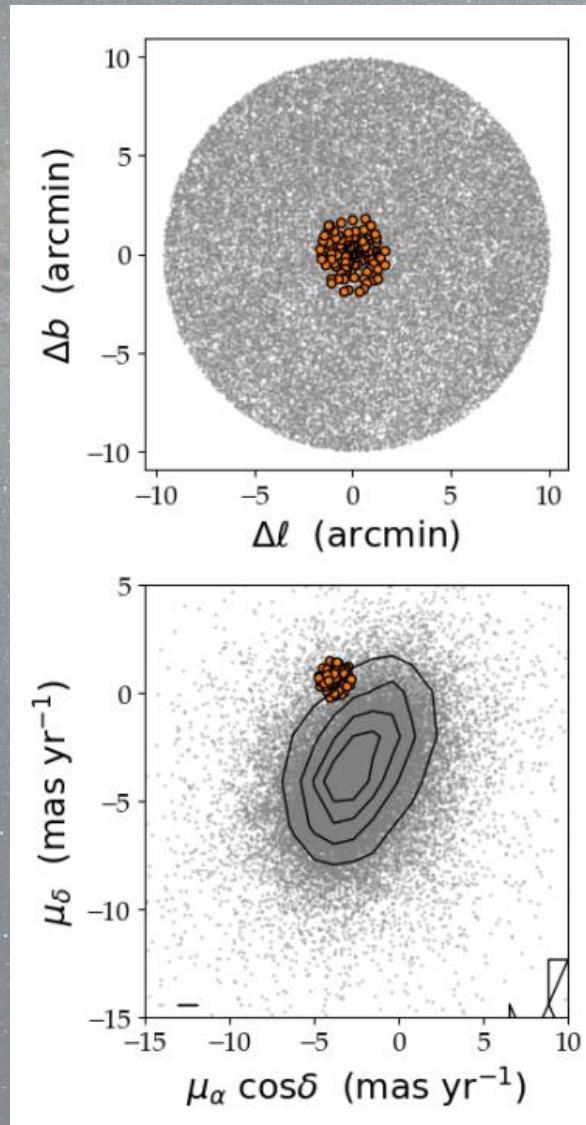


Clustering requirements:

- Grouped in space (ℓ, b)

Gran et al. 2021

New GCs: the case of Gran 3

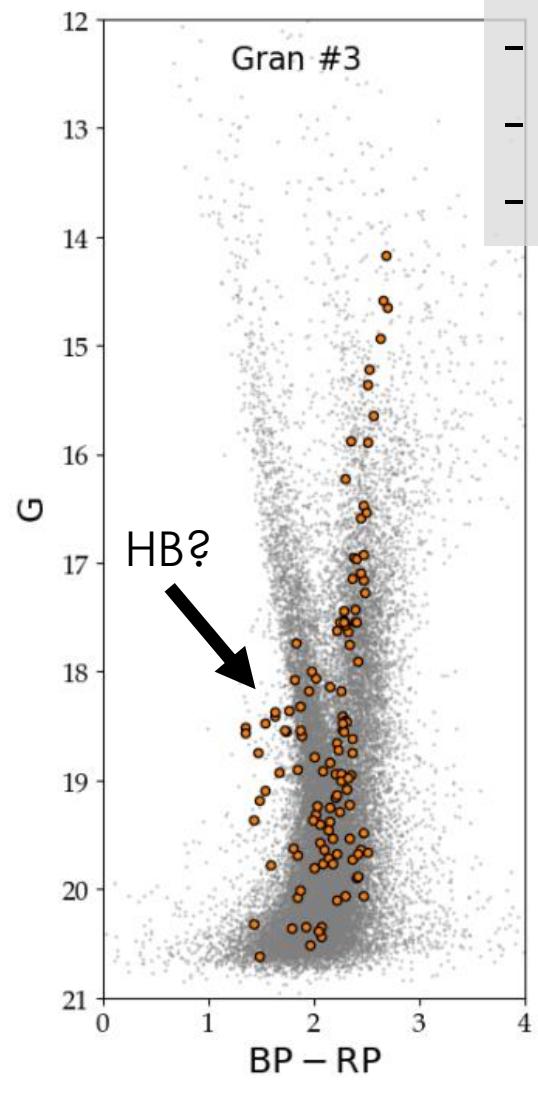
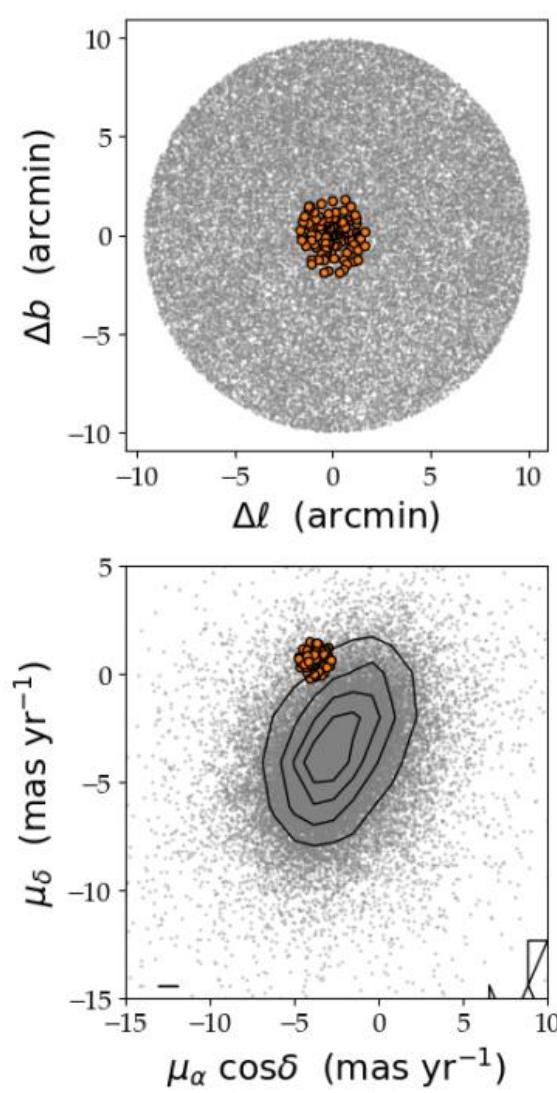


Clustering requirements:

- Grouped in space (ℓ, b)
- Coherent motion (PMs)

Gran et al. 2021

New GCs: the case of Gran 3

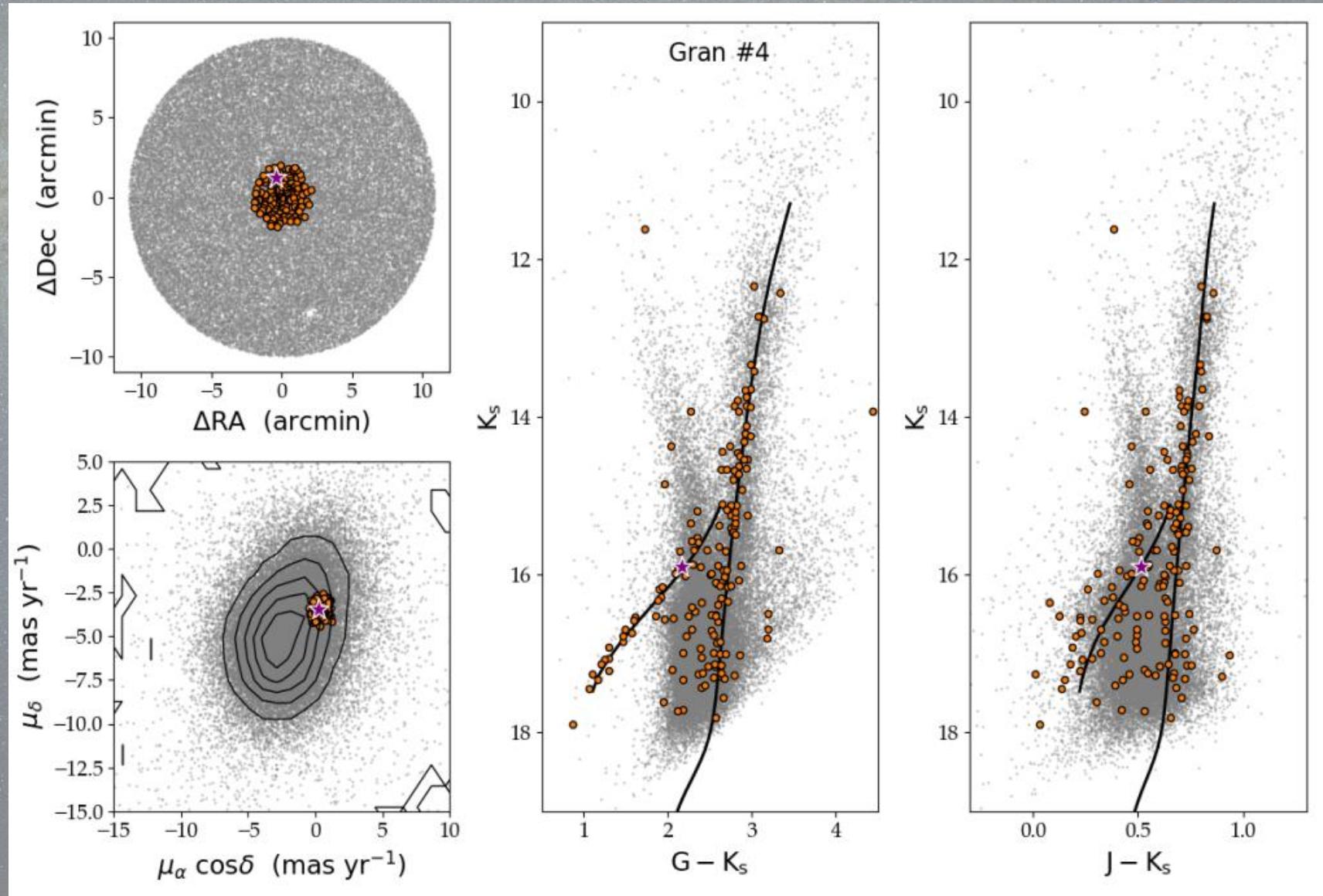


Clustering requirements:

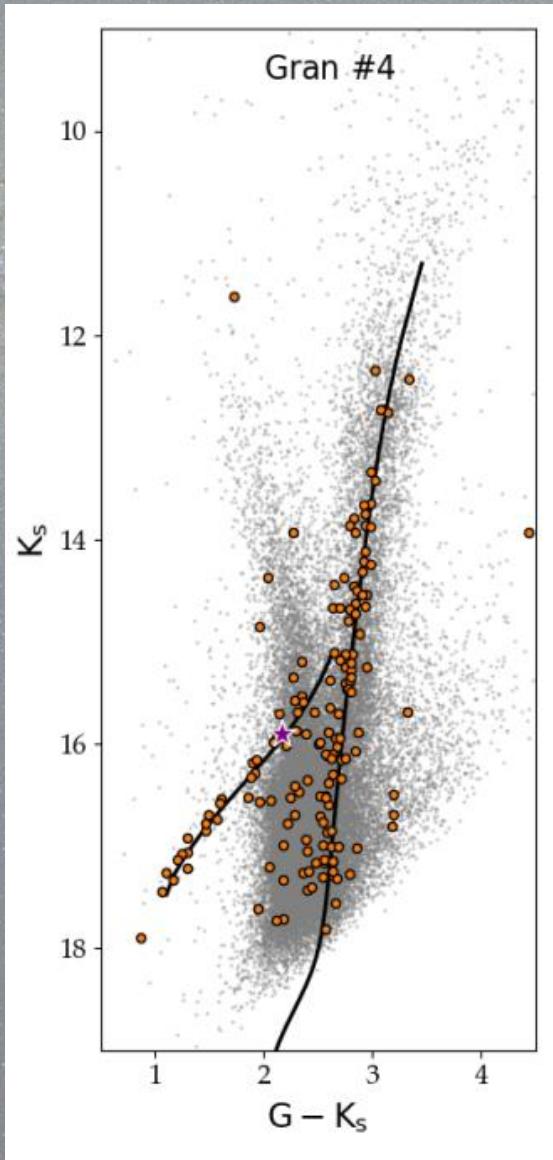
- Grouped in space (ℓ, b)
- Coherent motion (PMs)
- Old stellar sequences

Gran et al. 2021

New GCs: the case of Gran 4



New GCs: the case of Gran 4



Gran et al. 2021

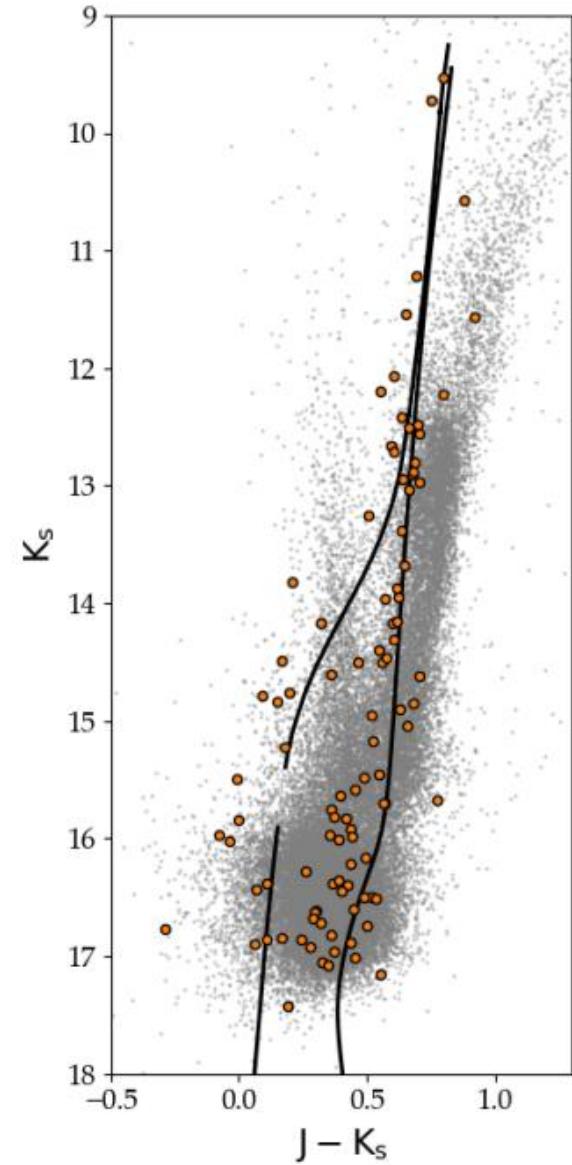
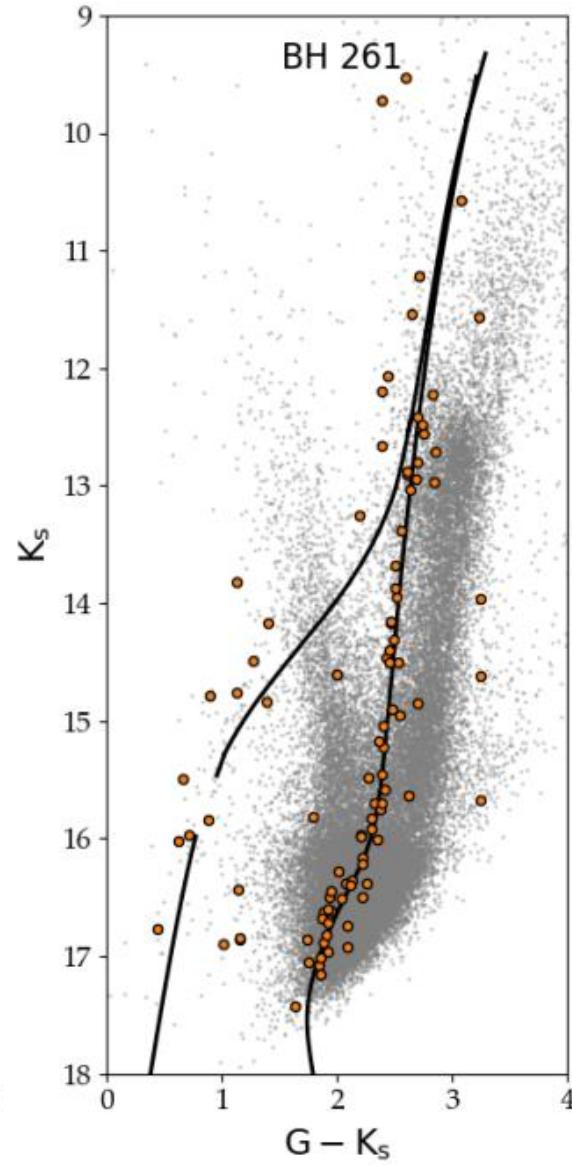
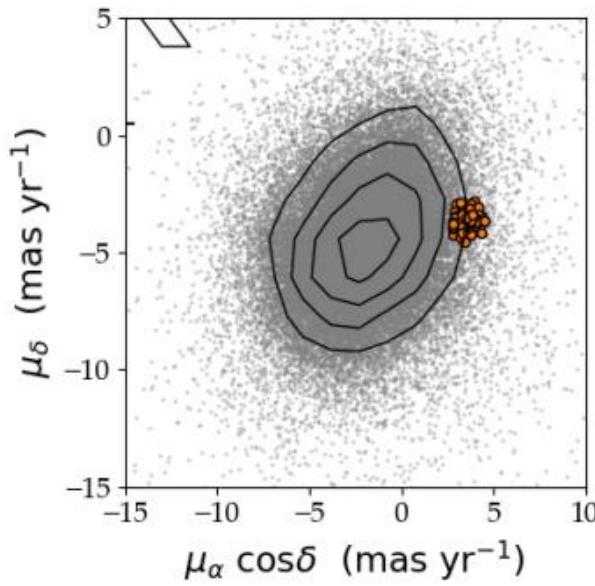
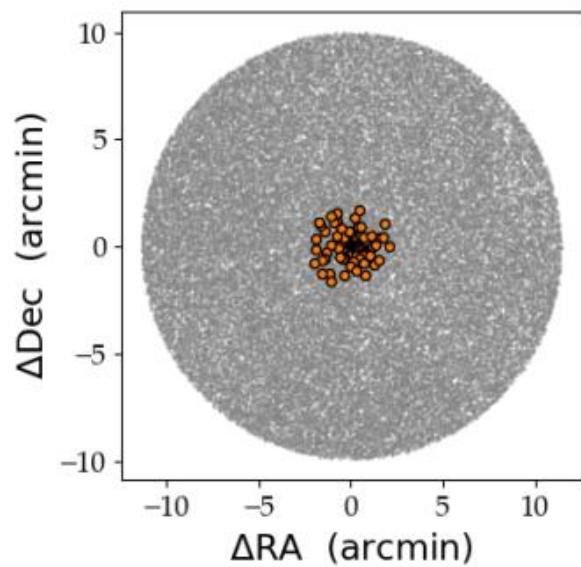
Clustering requirements:

- Grouped in space (ℓ, b)
- Coherent motion (PMs)
- Old stellar sequences

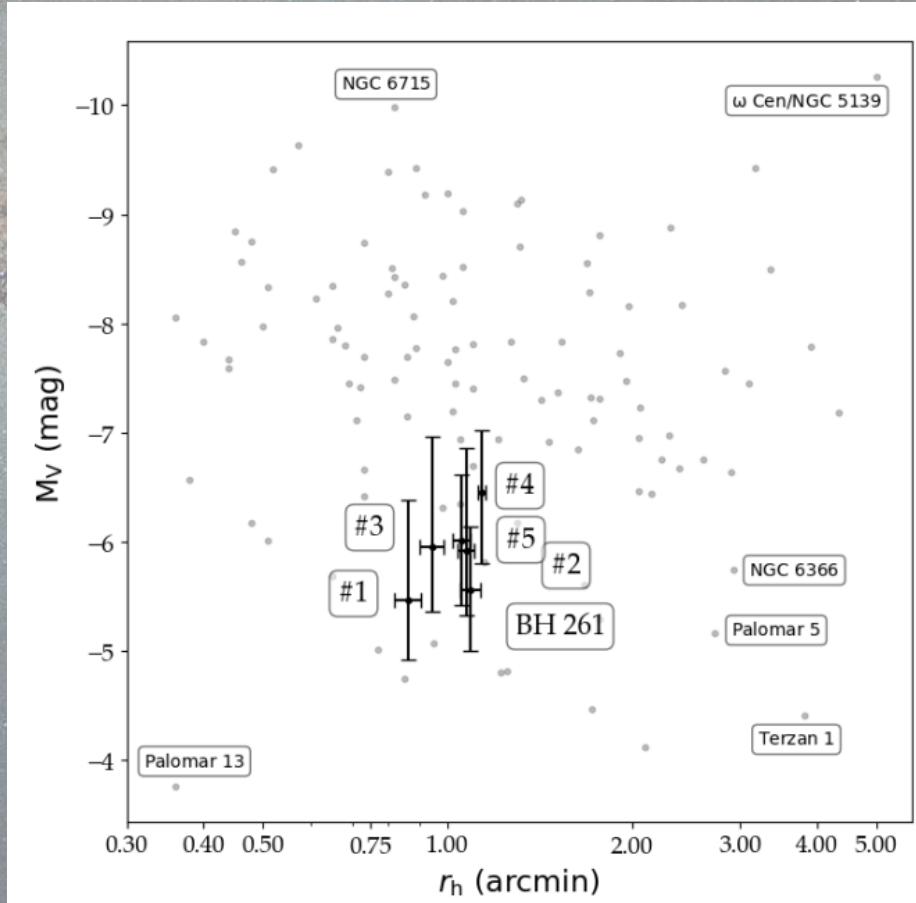
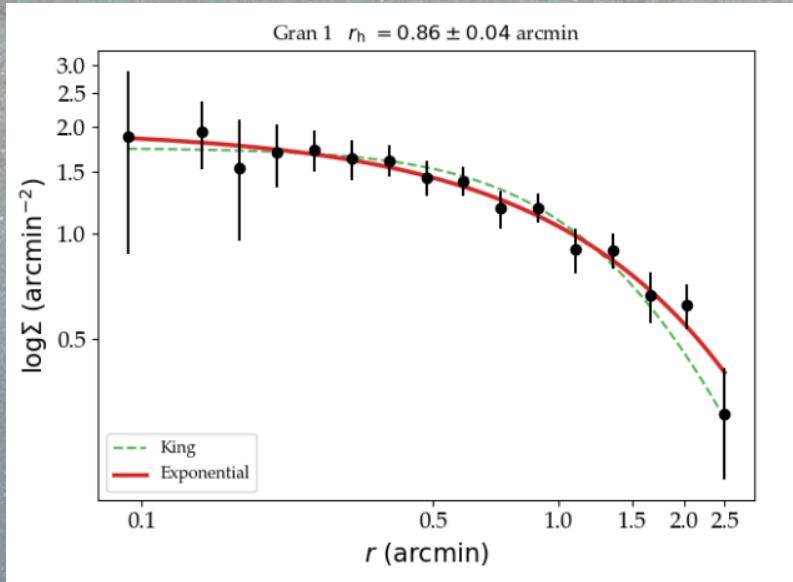
Cluster parameters:

- Age ~ 12 Gyr
- Distance ~ 22 kpc
- $[Fe/H] \sim -2.4$ dex
- $r_h \sim 1.15$ arcmin
- $M_{dyn} \sim 4 \times 10^5 M_\odot$

New GCs: side products



New GCs: full characterisation



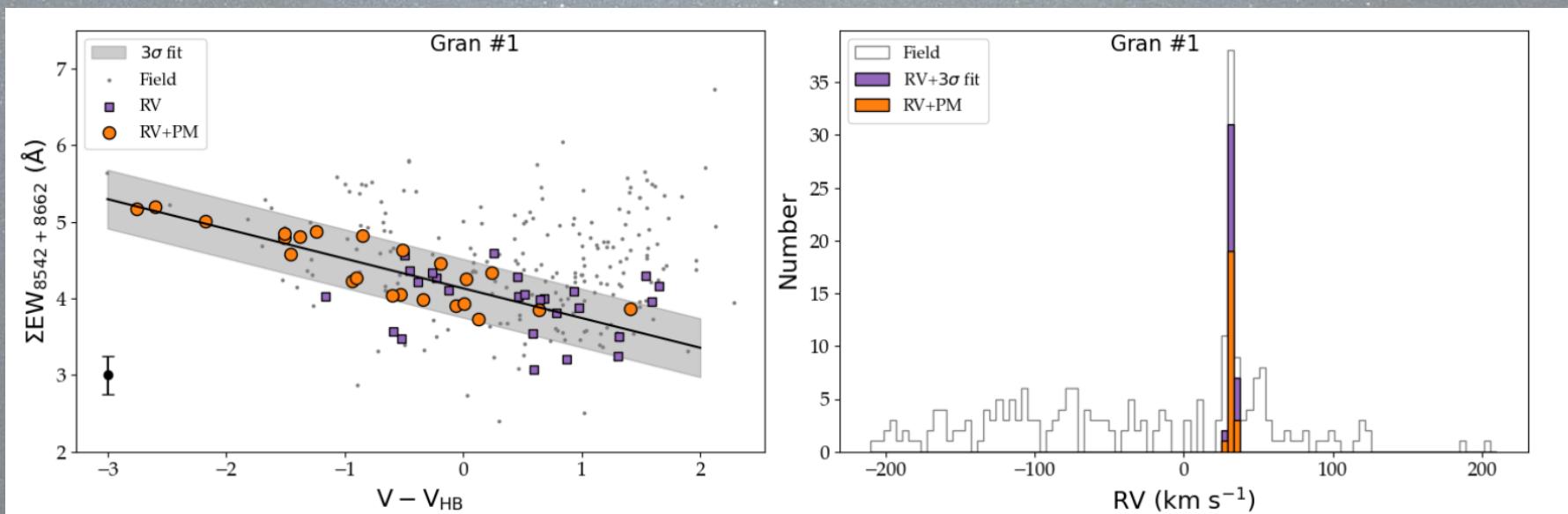
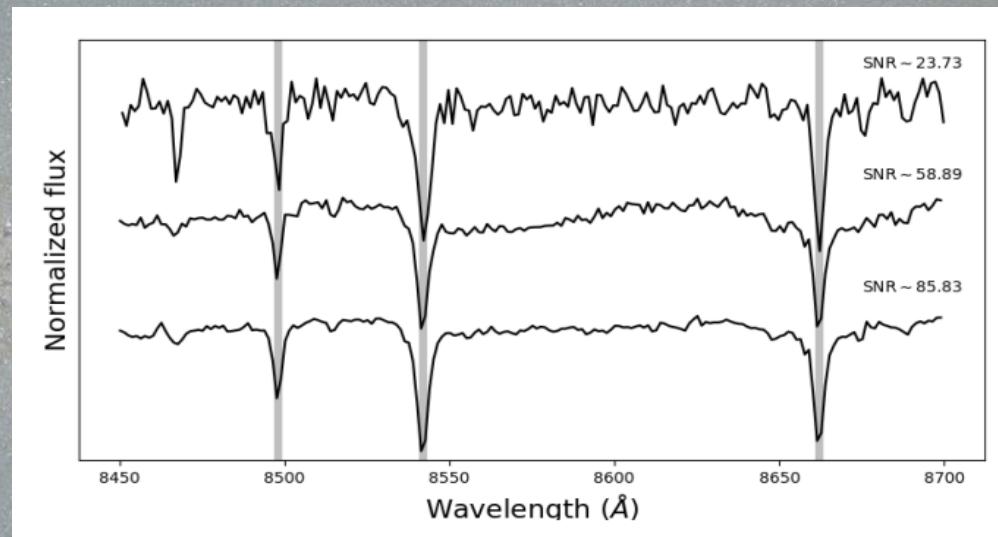
Gran et al. 2021

New GCs: full characterisation

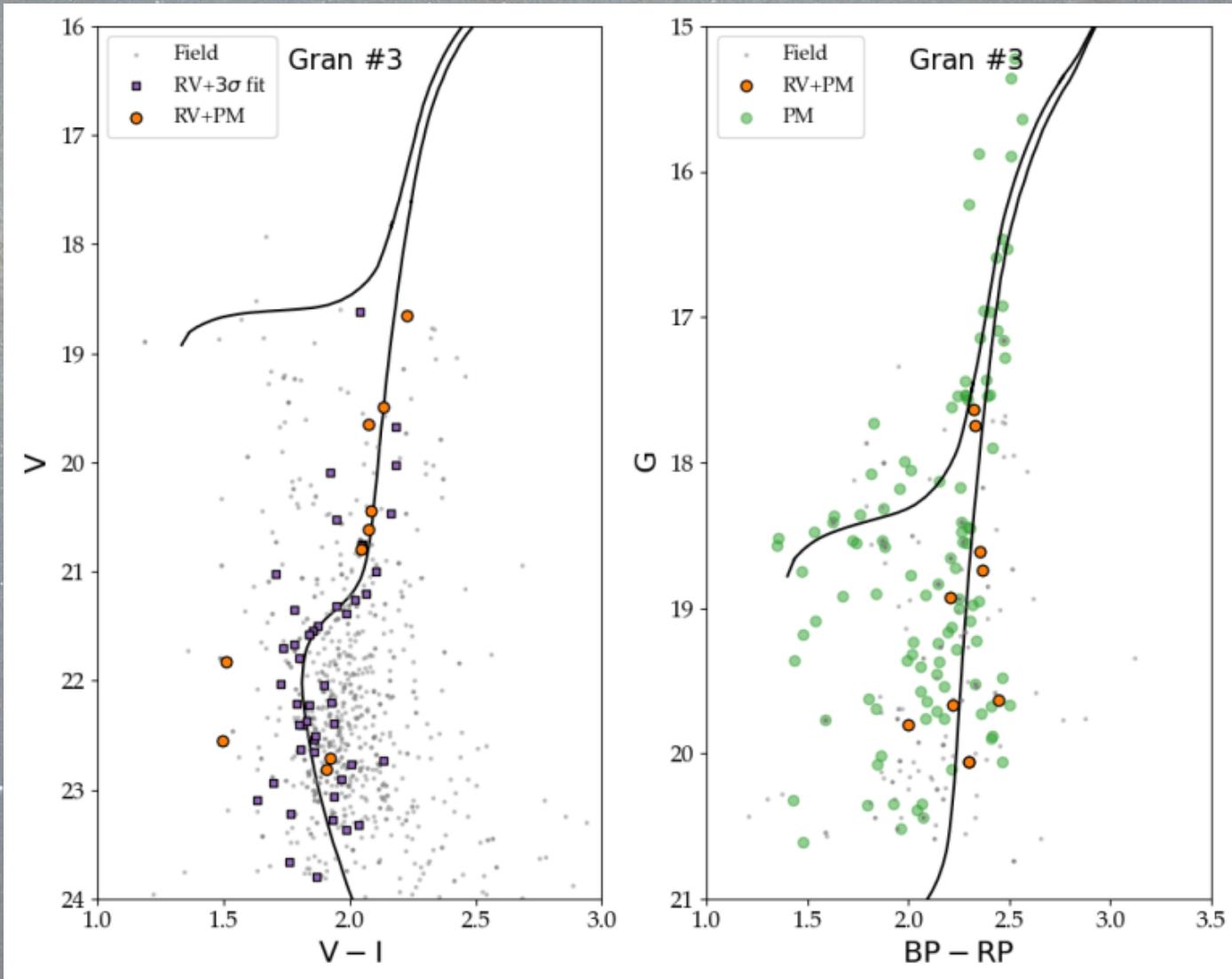
GC	ℓ (deg)	b (deg)	RA (deg)	Dec (deg)	$\mu_\alpha \cos(\delta)$ (mas yr $^{-1}$)	μ_δ (mas yr $^{-1}$)	$\mu_\ell \cos(b)$ (mas yr $^{-1}$)	μ_b (mas yr $^{-1}$)	N_{members} (number)
Gran 1	-1.233	-3.977	269.651	-32.020	-8.10	-8.01	-10.94	3.03	57
Gran 2	-0.771	8.587	257.890	-24.849	0.19	-2.57	-1.86	-1.76	102
Gran 3	-10.244	3.424	256.256	-35.496	-3.78	0.66	-1.76	3.71	118
Gran 4	10.198	-6.388	278.113	-23.114	0.46	-3.49	-2.88	-2.01	155
Gran 5	4.459	1.838	267.228	-24.170	-5.32	-9.20	-10.55	-0.10	76
Cluster candidates									
C1	-3.589	4.174	260.151	-29.673	-2.90	-6.11	-6.61	-1.07	113

GC	dm (mag)	Distance (kpc)	E(J – K _s) (mag)	A _{K_s} (mag)	A _G (mag)	A _V (mag)	V _t (mag)	M _V (mag)	r _h (arcmin)	[Fe/H] (dex)
Gran 1	14.60	7.94	0.45	0.24	2.70	3.38	12.41	-5.46	0.86	-1.19
Gran 2	16.10	16.60	—	—	1.90	2.37	12.56	-5.92	1.07	-2.12
Gran 3	15.40	12.02	—	—	2.60	3.25	12.63	-6.02	1.05	-2.33
Gran 4	16.84	22.49	0.20	0.14	1.20	1.50	11.81	-6.45	1.14	~ -2.4
Gran 5	13.25	4.47	0.63	0.43	3.24	4.05	12.11	-5.95	0.94	-1.56

New GCs: MUSE observations

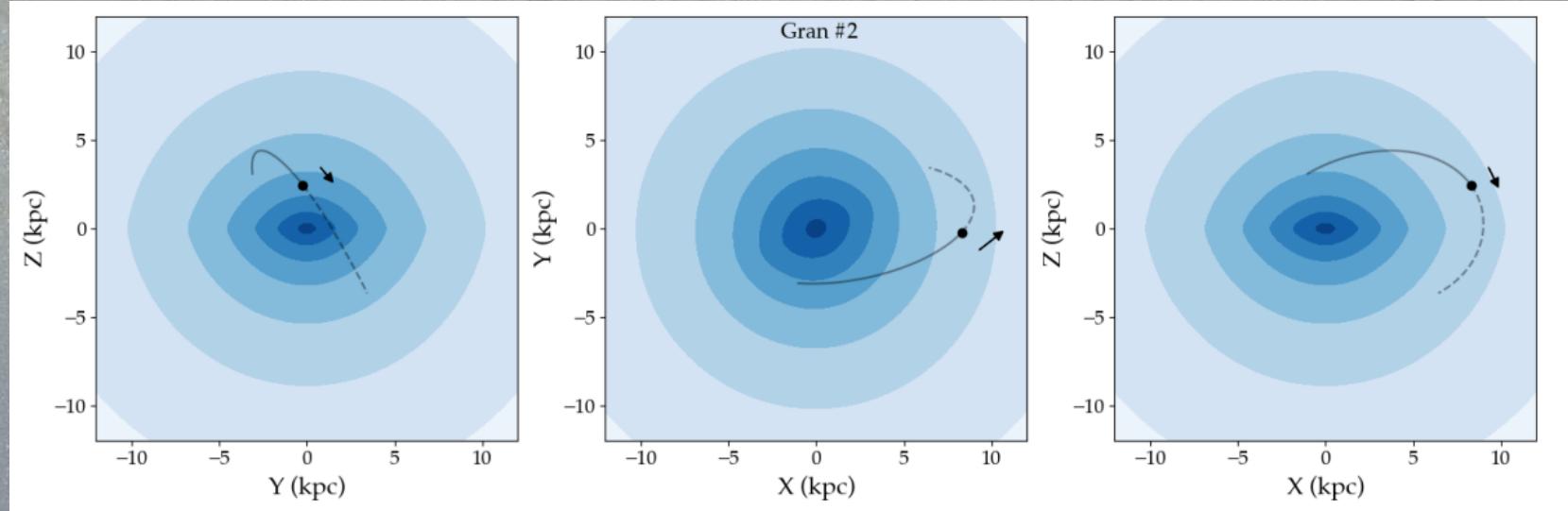


New GCs: MUSE observations



Gran et al. 2021

New GCs: MUSE observations



Gran et al. 2021

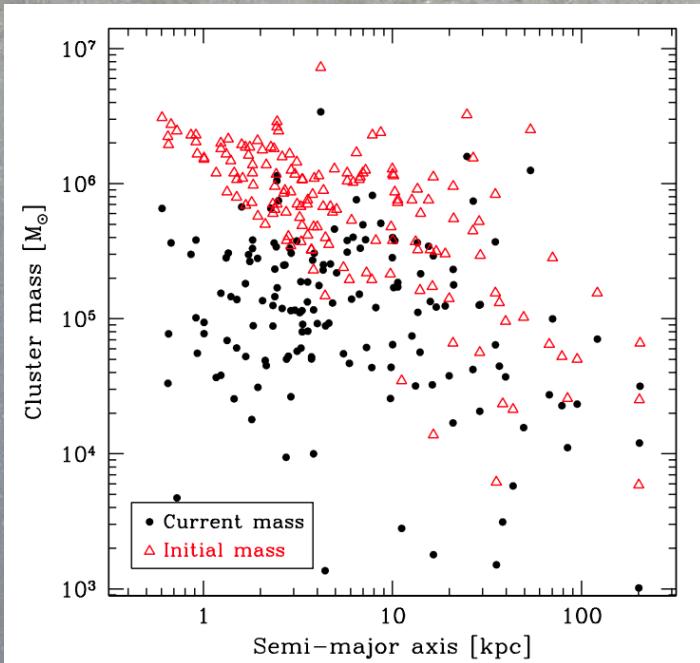
New GCs: MUSE observations

GC	σ_0 (km s $^{-1}$)	$M^{\text{dyn}}(< 1.8r_h)$ ($10^5 M_\odot$)	Υ ($M_\odot L_\odot^{-1}$)
Gran 1	3.96 ± 0.29	0.45 ± 0.08	3.61 ± 3.12
Gran 2	4.93 ± 0.47	1.84 ± 0.40	9.50 ± 8.51
Gran 3	4.79 ± 0.41	1.24 ± 0.25	5.84 ± 3.45
Gran 4	6.18 ± 0.33	4.16 ± 0.61	13.15 ± 7.14
Gran 5	3.68 ± 0.32	0.37 ± 0.08	1.85 ± 1.77

GC	RV (km s $^{-1}$)	[Fe/H] (dex)	V_{HB} (mag)	e	z_{max} (kpc)	r_{peri} (kpc)	r_{apo} (kpc)	L_z (kpc 2 Myr $^{-1}$)	E_{tot} (kpc 2 Myr $^{-2}$)
Gran 1	32.30 ± 1.87	-1.19 ± 0.19	19.08	0.76	0.38	0.31	2.22	0.03	-0.21
Gran 2	53.22 ± 1.67	-2.07 ± 0.17	18.59	0.34	5.44	4.59	9.24	0.79	-0.16
Gran 3	74.32 ± 2.70	-2.37 ± 0.18	18.65	0.08	3.88	4.66	5.47	0.69	-0.17
Gran 5	-90.40 ± 1.93	-1.56 ± 0.17	18.04	0.90	0.13	0.20	3.75	-0.04	-0.19

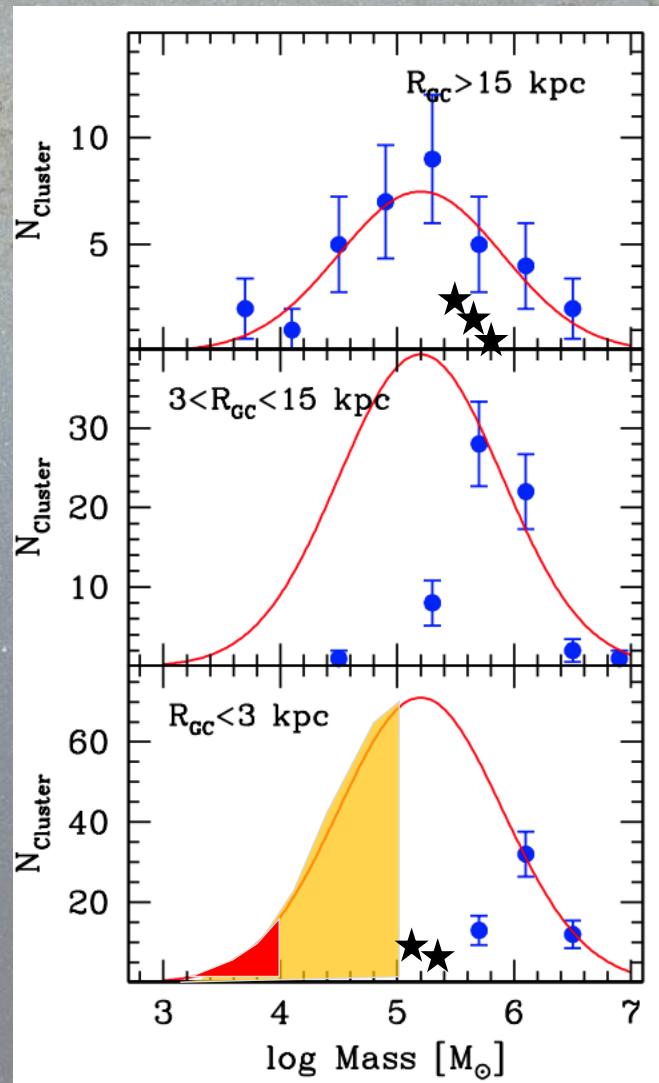
New GCs: Galactic context

Initial mass distribution



Baumgardt et al. 2018

Gran 2 + 3 + 4
Gran 1 + 5



← ~Halo GCs

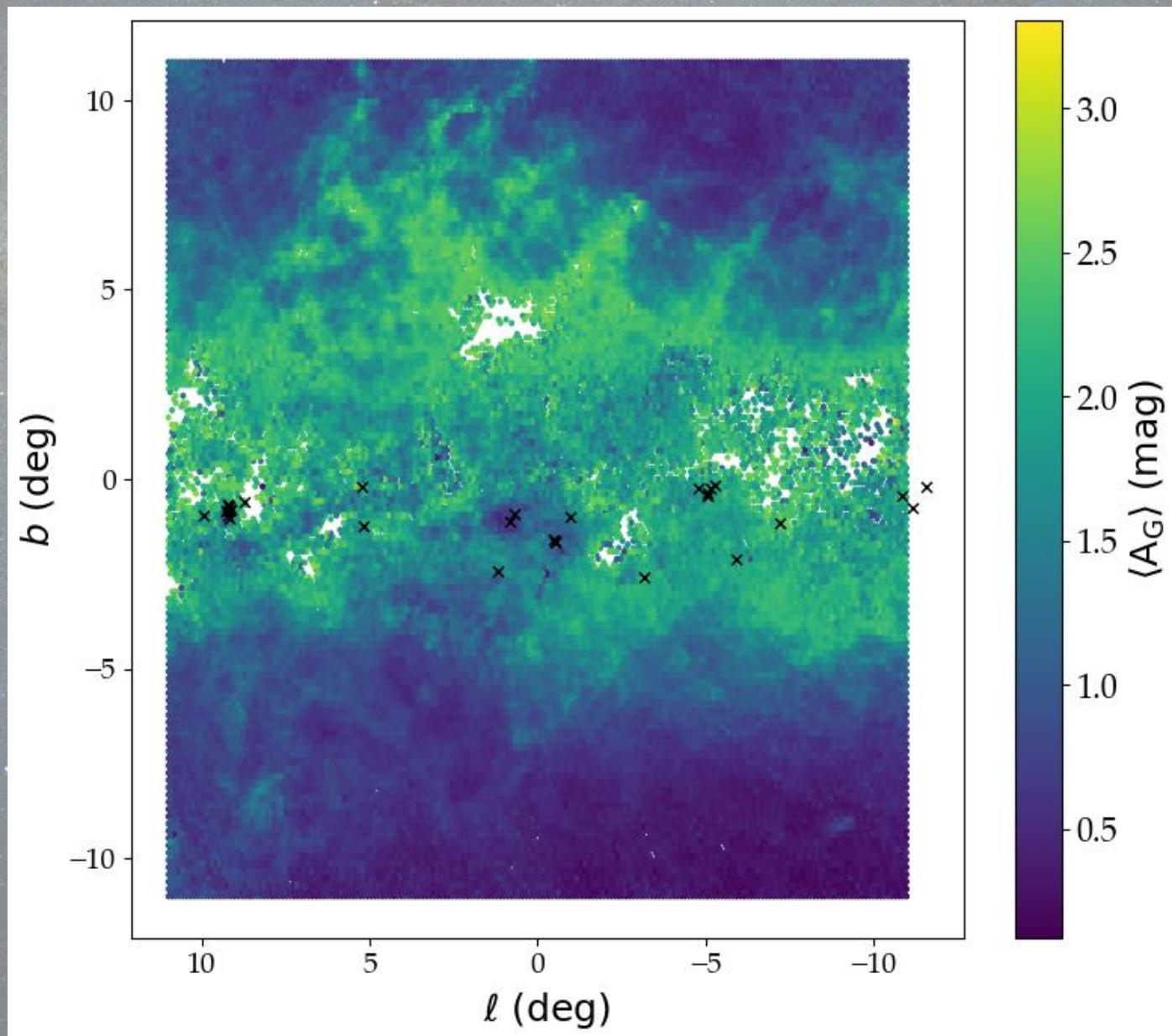
← ~Disk GCs

← ~Bulge GCs

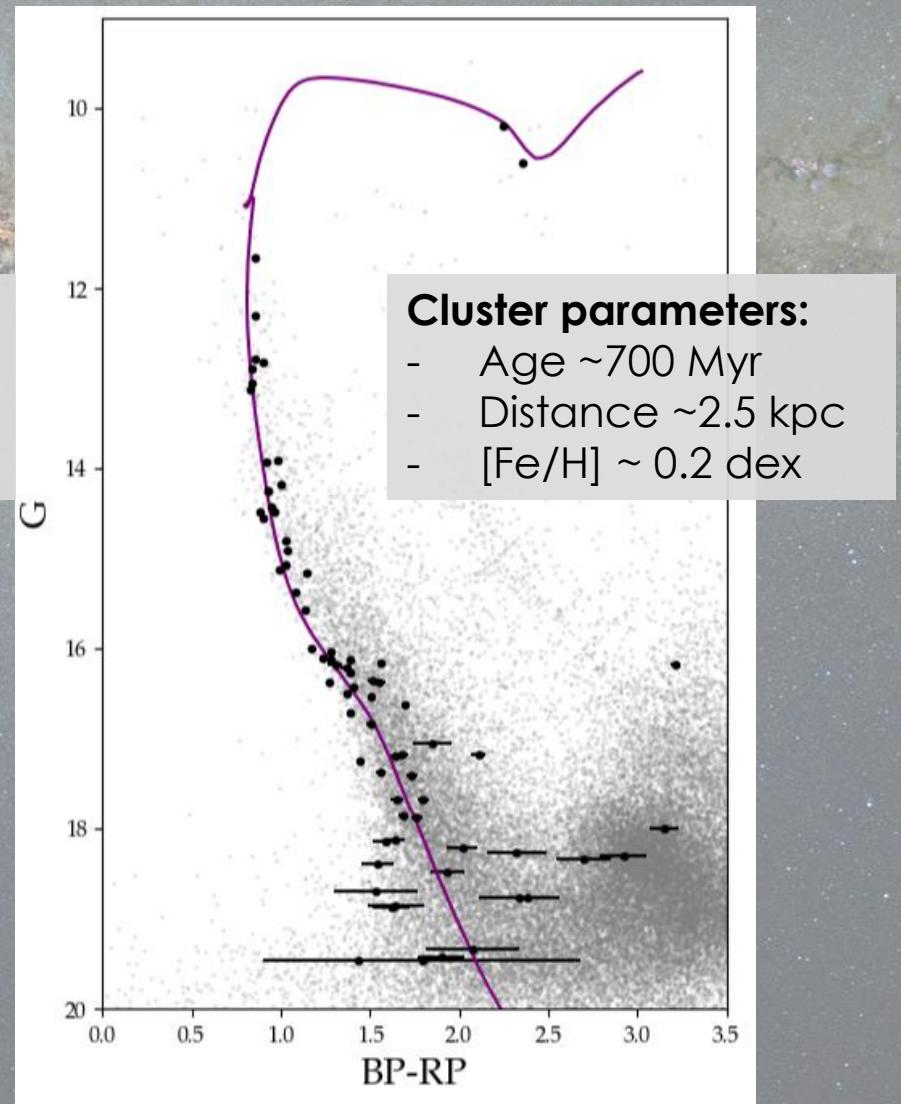
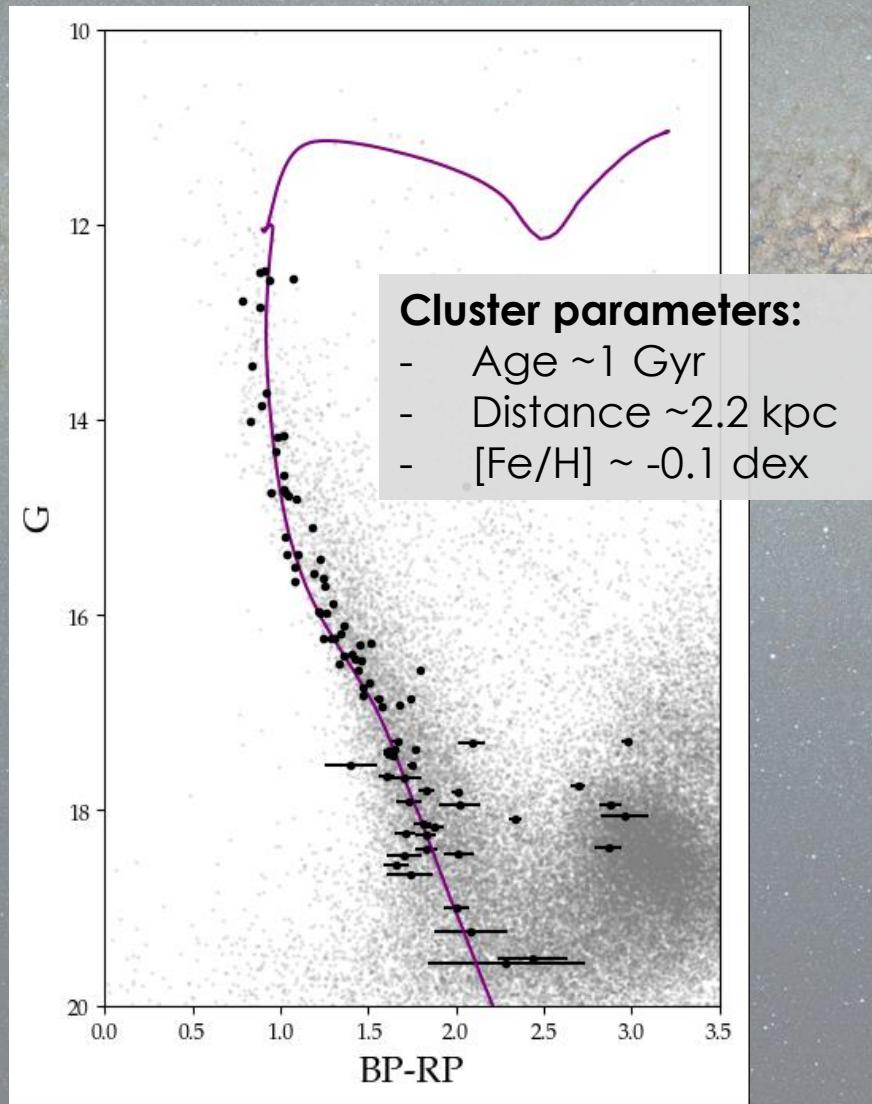
Summary #2

- ★ Bulge GCs are tracers of the **MW formation and evolution**: *in situ* component (Myeong et al. 2018).
- ★ No consensus has been reached on the total number of **bulge GCs**.
- ★ Using a clustering algorithm, we were able to discover **5 new** clusters with old stellar sequences.
- ★ Orbital parameters and metallicities from the analysis of **5 MUSE** cubes.
- ★ Key observable: **proper motions!**

Future work: new OCs



Future work: new OCs



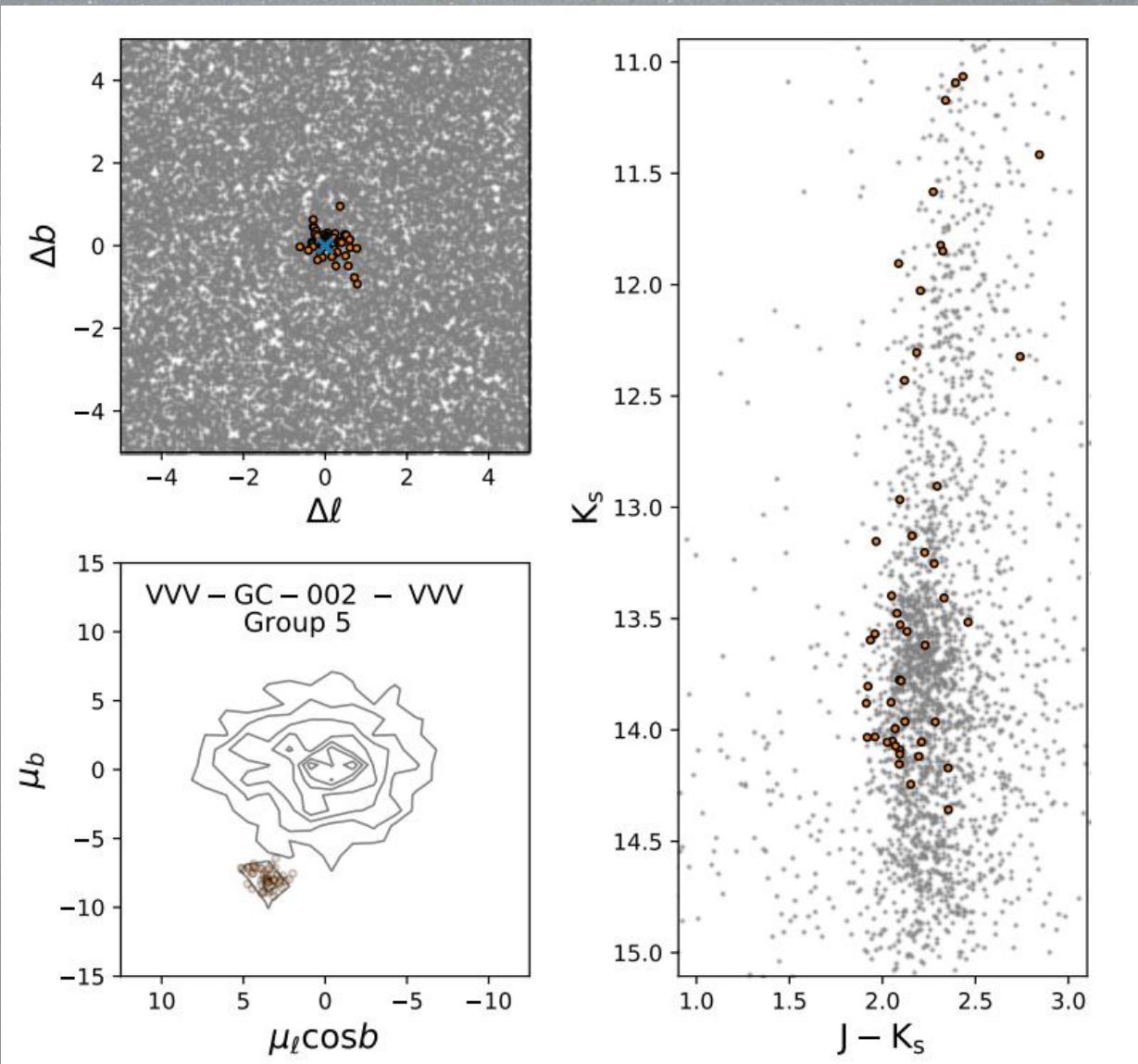
Thanks for your attention!

fegran@uc.cl

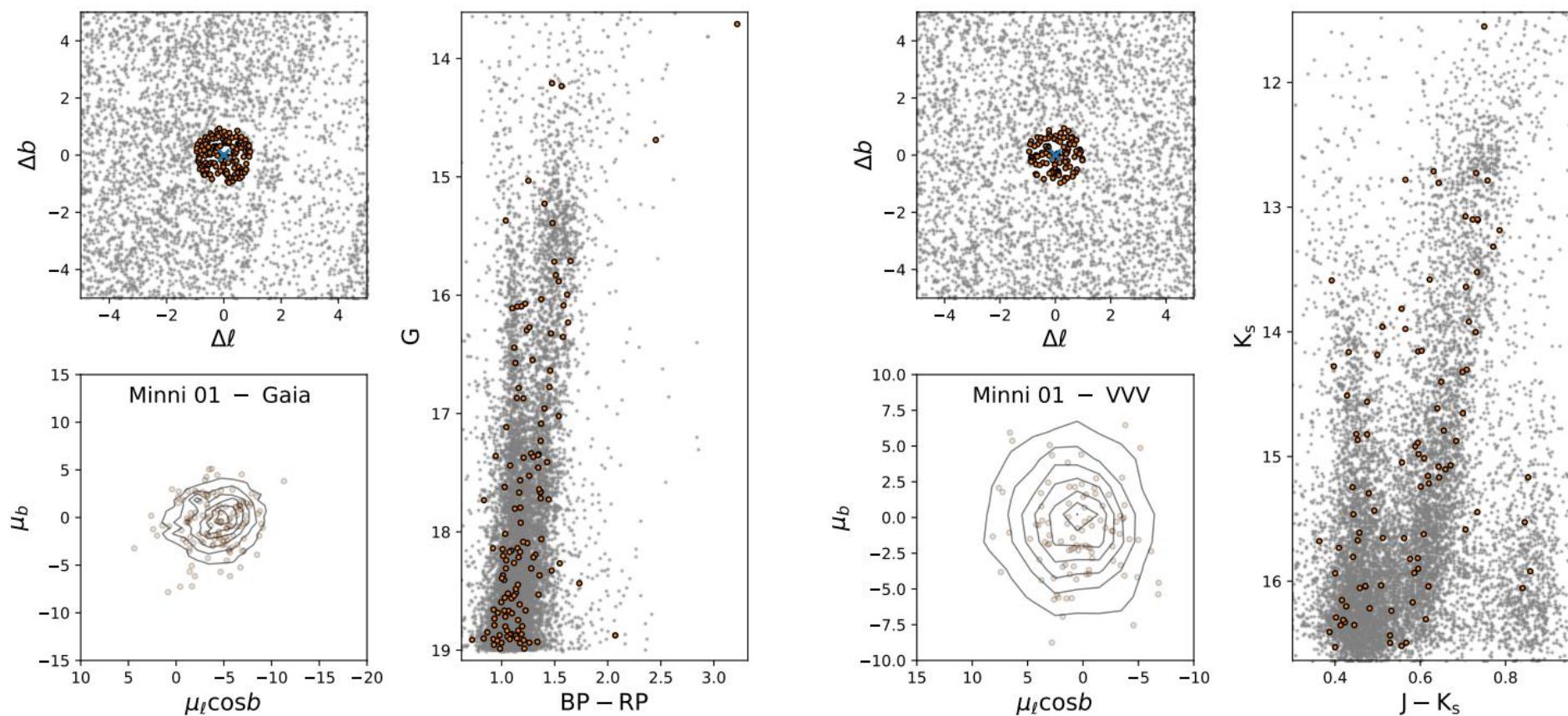
@fegramm fegran.github.io



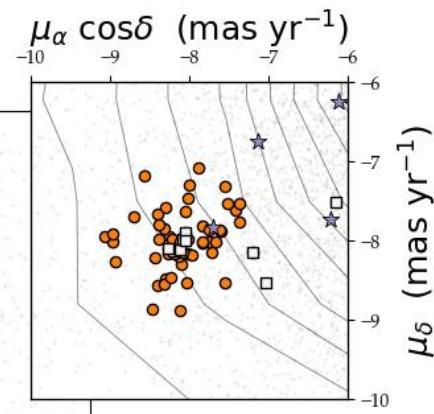
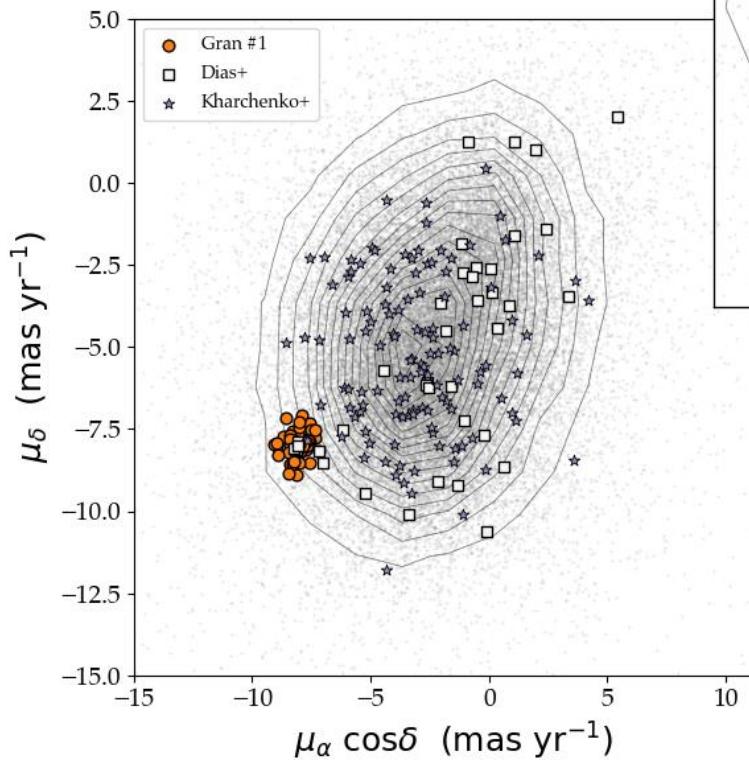
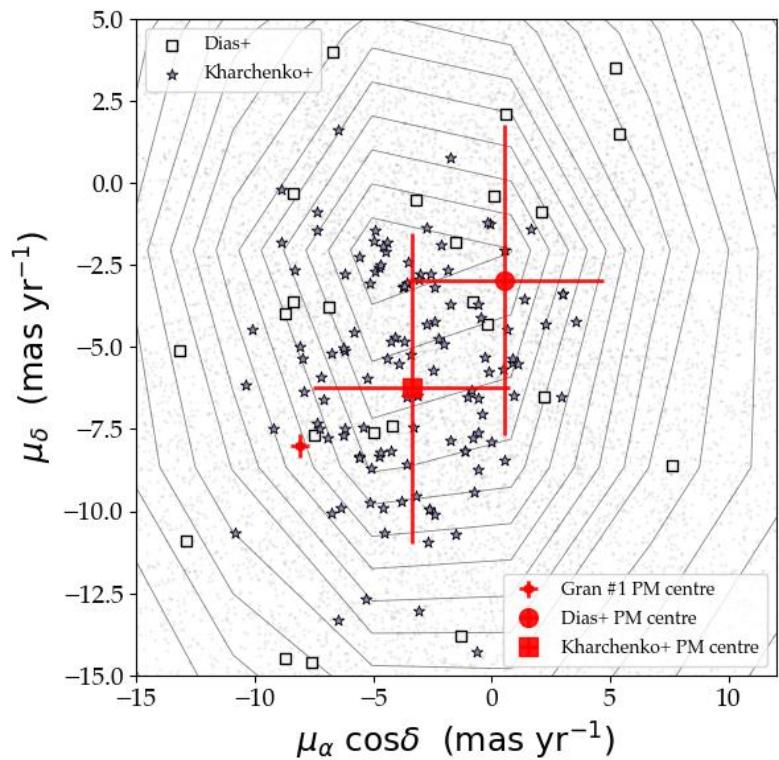
Backup sludes :)



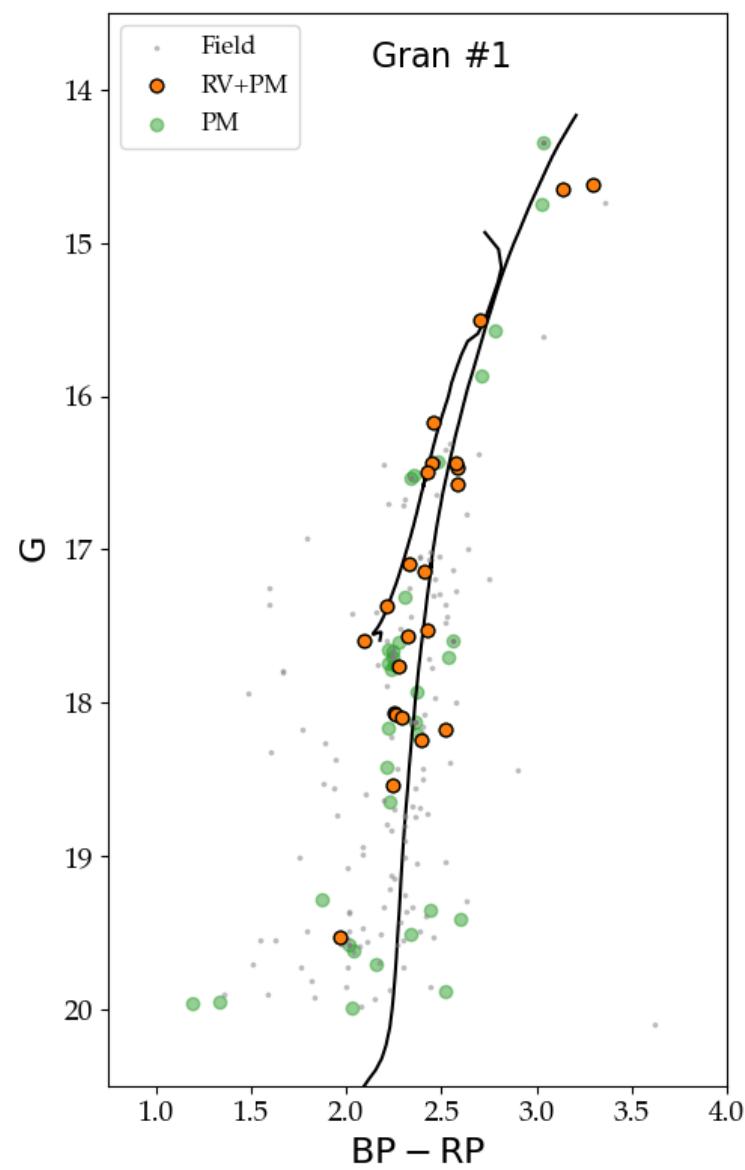
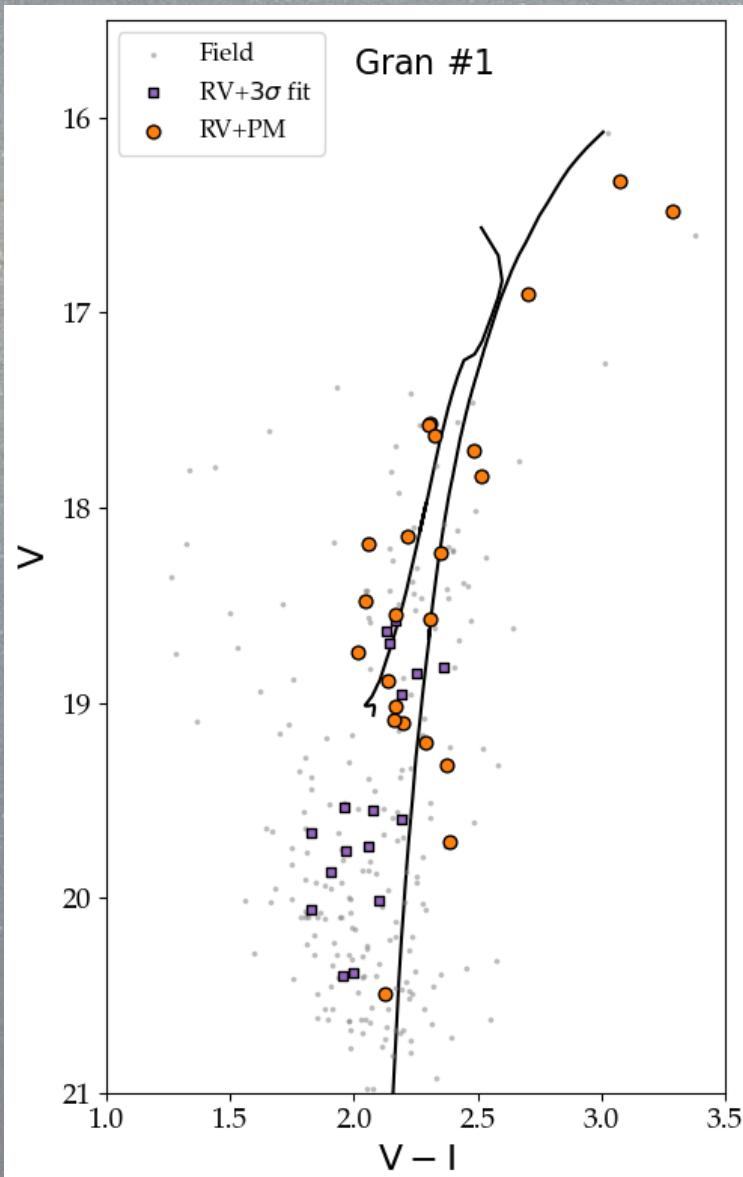
Backup slides :)



Backup sludes :)



Backup sludes :)



Backup sludes :)

