Hidden in the haystack: low-luminosity globular clusters towards the Milky Way bulge

Felipe Gran (OCA)
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Slides available at:
fegran.github.io/files/FGran-OCA-Seminar.pdf

OCA/Lagrange Seminar – December 13, 2022

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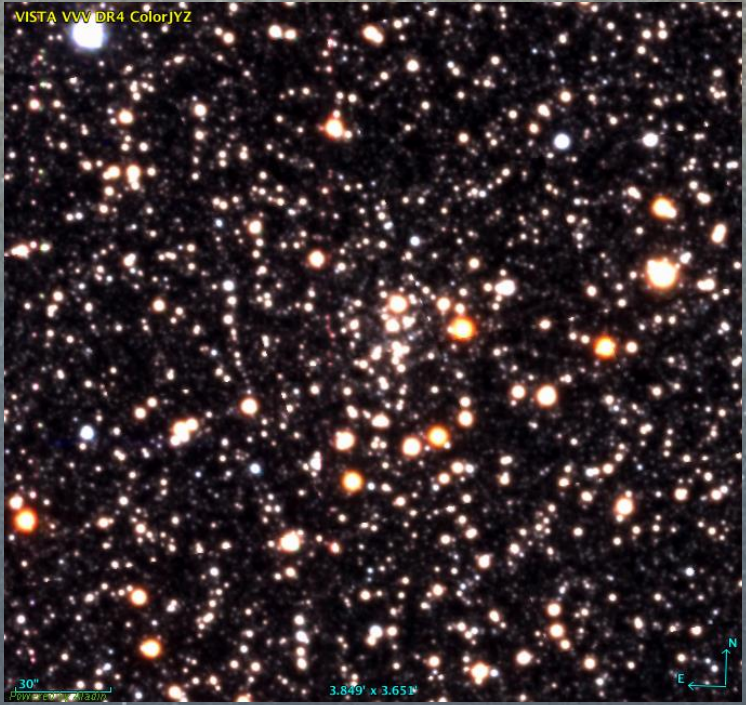


Gran et al. 2019

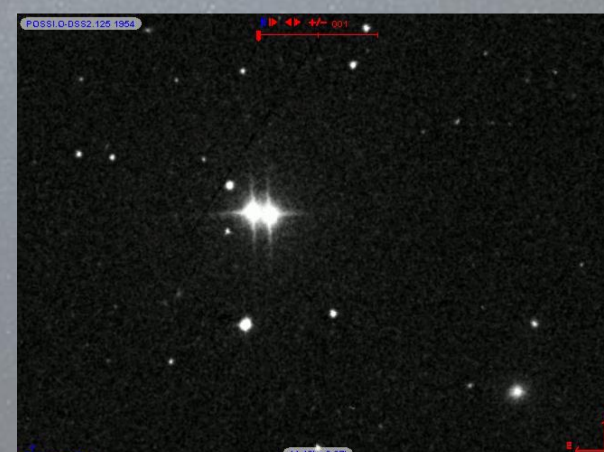
F. Gran, G. Kordopatis, V. Hill,
M. Zoccali, I. Saviane, E. Valenti, R. Contreras Ramos,
A. Rojas-Arriagada, J. Hartke, J. A. Carballo-Bello,
C. Navarrete, M. Rejkuba, J. Olivares

More than ~48 globular clusters are known towards the bulge area

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 *Ptolomy*, in the 3*d* Chapter of the 7*th* 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

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
- ★ Ground-based observations until 1995: ~**8000** stars

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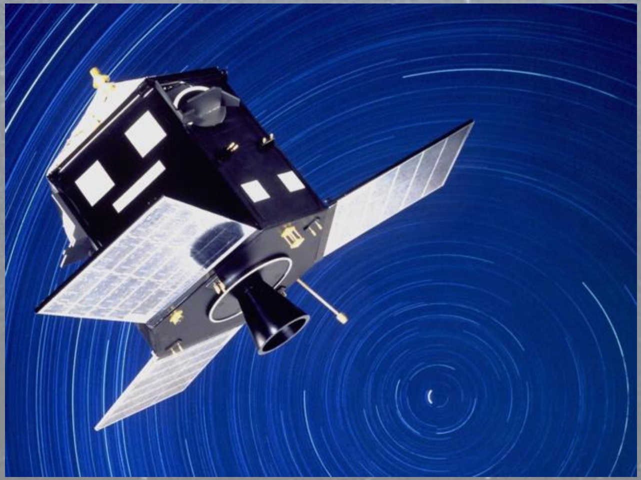


ESA, Hipparcos

Steve Quirk, Wikipedia Commons

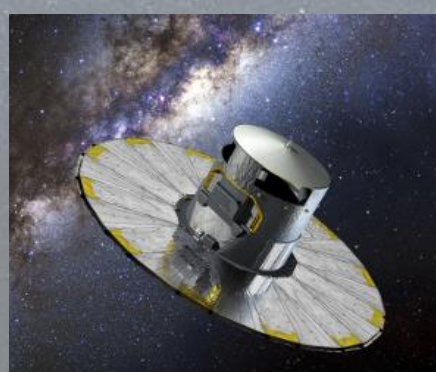
Key concept #1: stellar proper motions

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

- ★ Halley 1717: ~**few** stars
- ★ Ground-based observations until 1995: ~**8 000** stars
- ★ ESA Hipparcos space mission (early 90s): ~**115 000** stars
- ★ ESA Gaia space mission (active):
  ~**1.801 billion** stars
  ~**1 801 000 000** stars

POSS1, POSS2, DSS

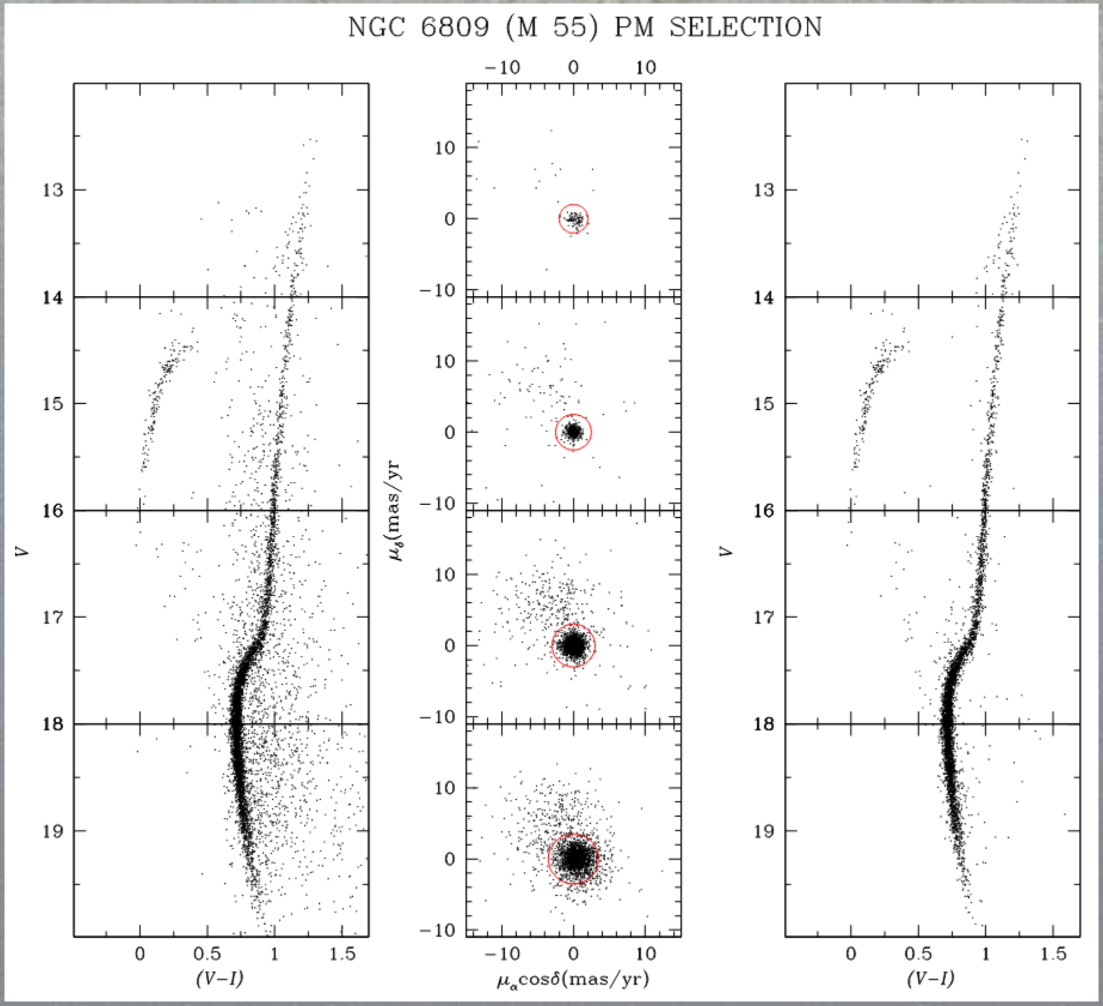
Steve Quirk,
Wikipedia Commons



ESA, Gaia

Key concept #2: globular clusters as a "simple" stellar population

★ From "simple stellar population" to the Pandora's box: photometrical and spectroscopical differences.



Sariya et al. 2012

Key concept #2: multiple stellar populations within globular clusters

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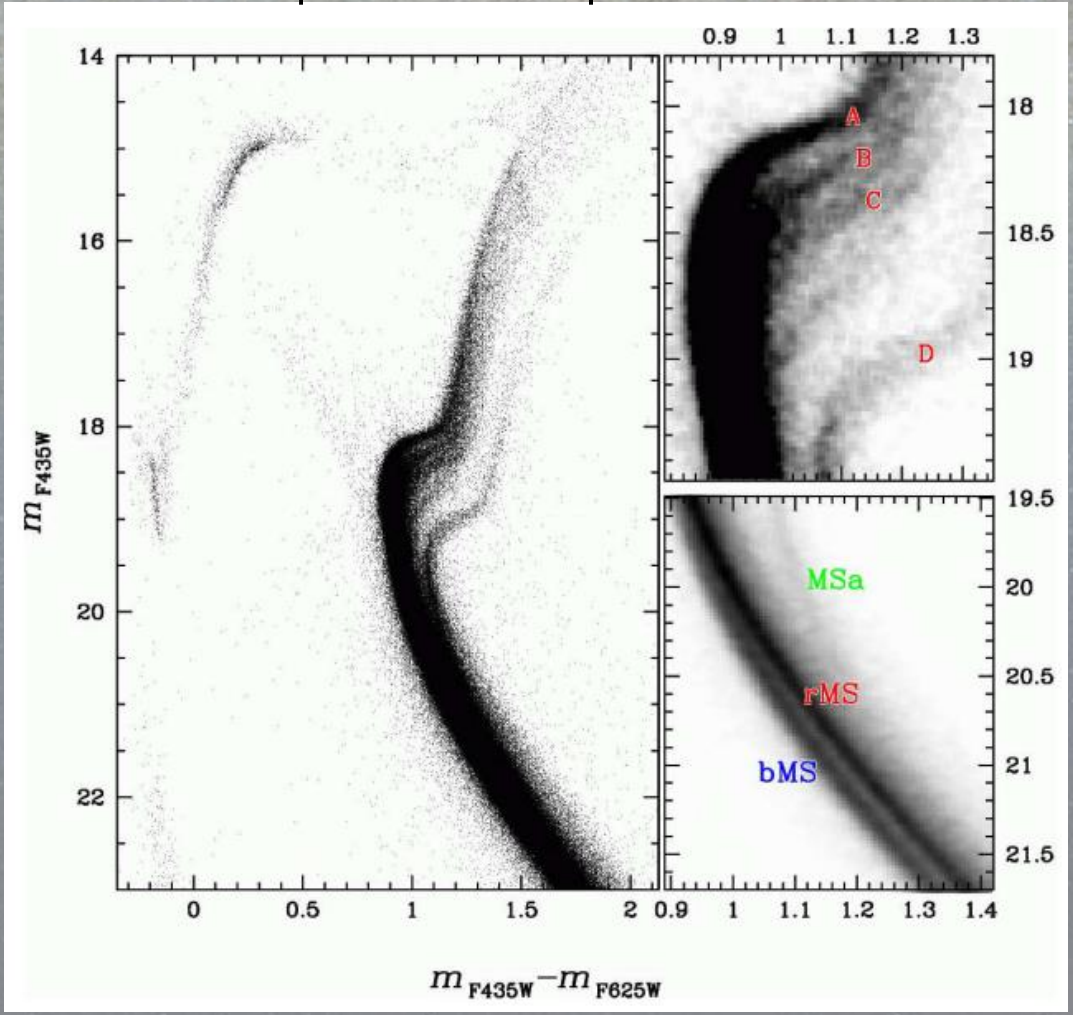

Bellini et al. 2010, 2017

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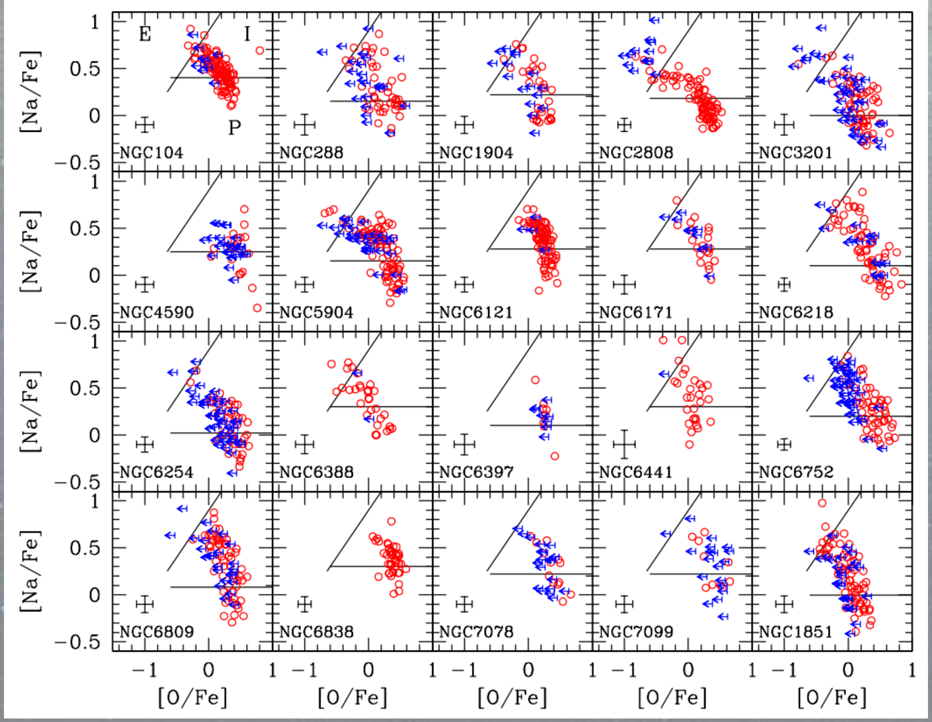


Carretta et al. 2009

★ Fe enrichment in only a limited cases: massive clusters

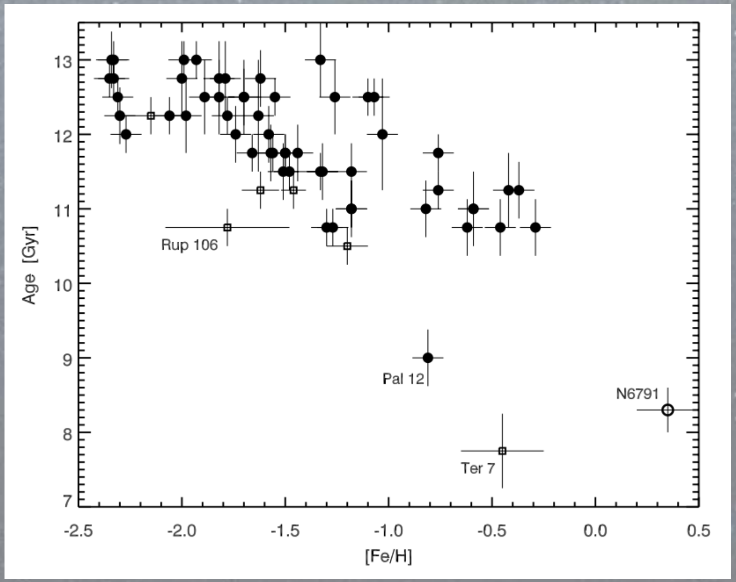
★ Light-element (proton capture) variations:
  ★ C, N, O, Na, Mg, Al, Si, … among others!

★ AGB and massive fast rotators: most likely contributors

Key concept #3: the Galaxy evolution told by its globular clusters

- ★ **Globular clusters** are one of the most valuable **tracers** when trying to understand **galaxy evolution** (Kruijssen et al. 2019). But also see Pagnini et al. 2022 as a cautionary tale.

- ★ We can constrain **ages**, **masses**, and **distances**: the primary laboratory of stellar evolution including **chemical** and **enrichment processes**.



Leaman et al. 2013

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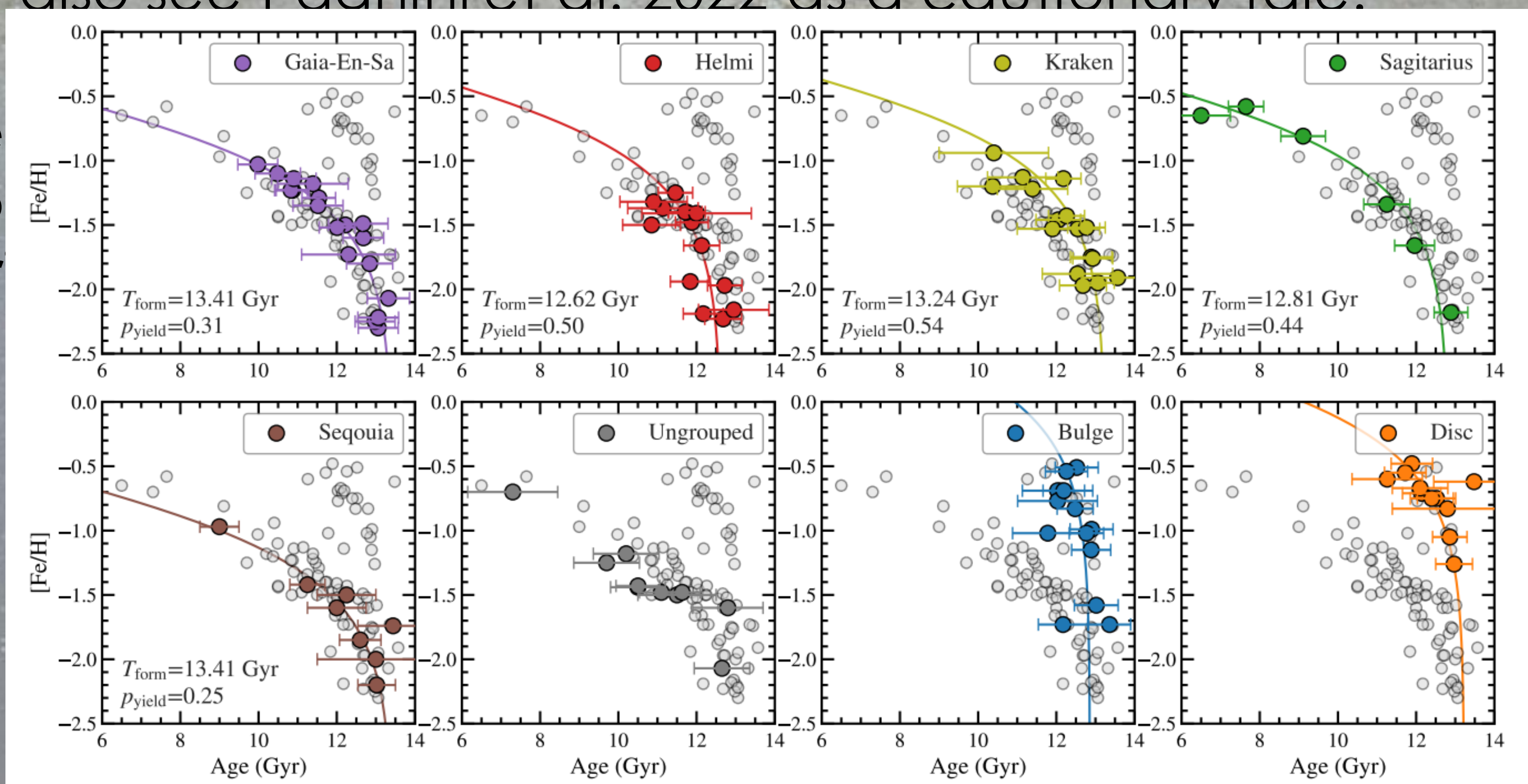
★ We ... ry lab ... **enr**



Callingham et al. 2022

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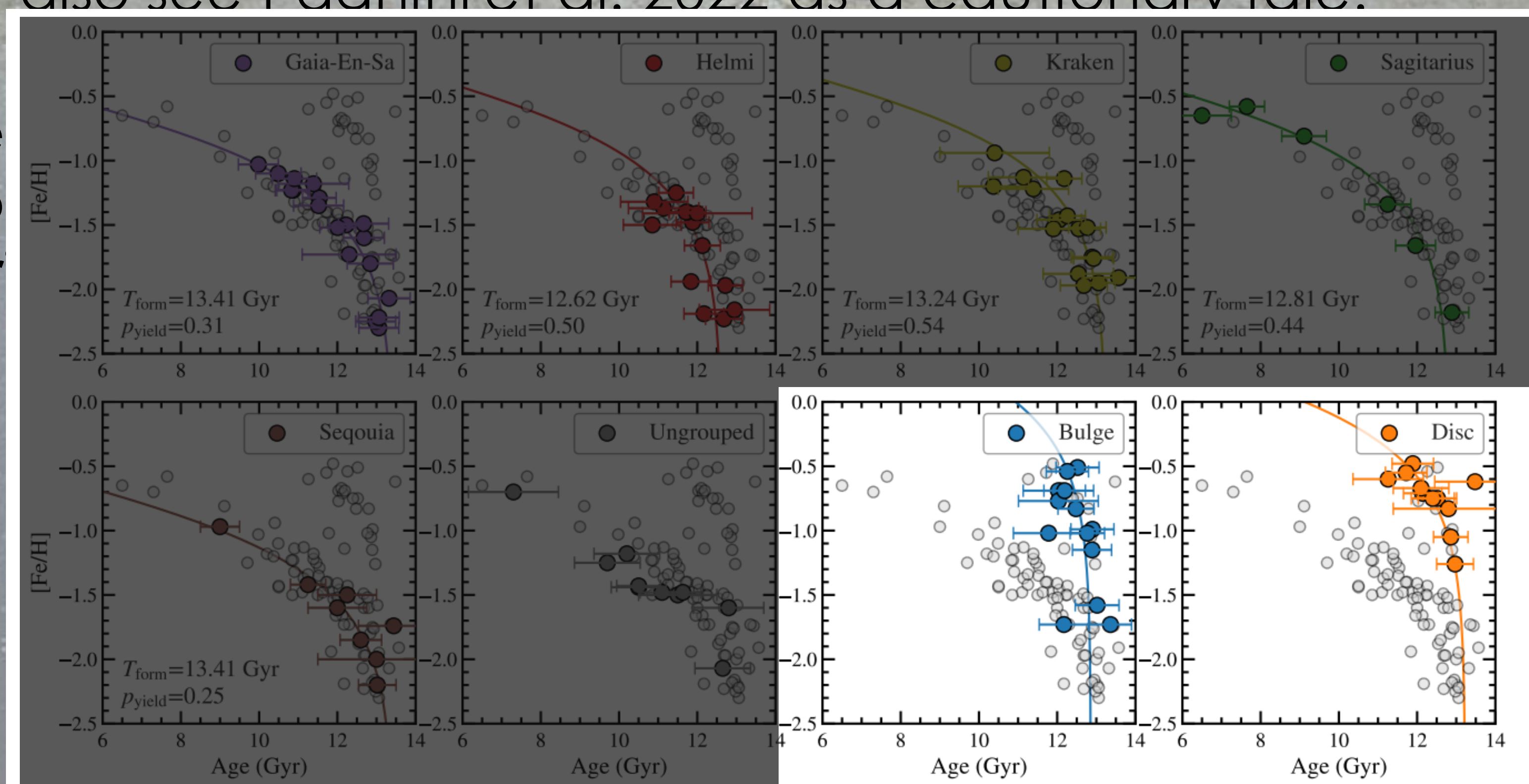


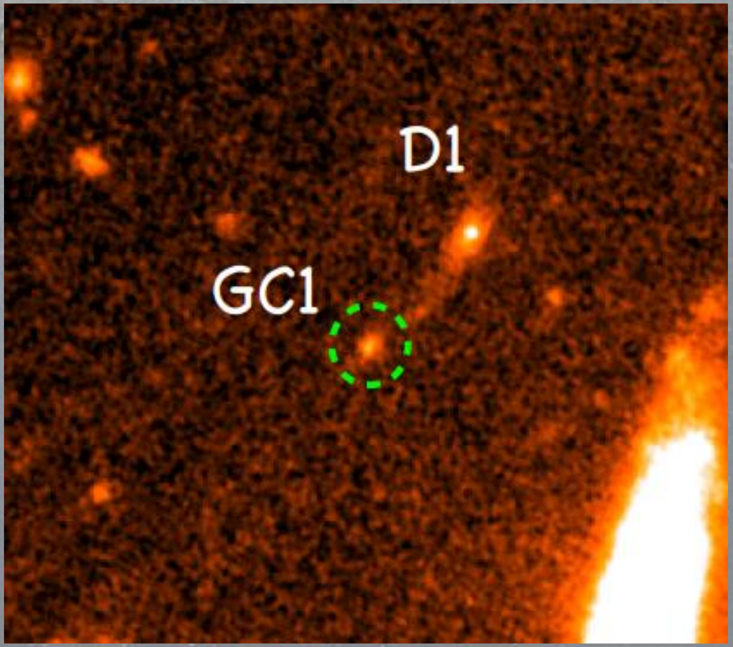
Callingham et al. 2022

Key concept #3: 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**.

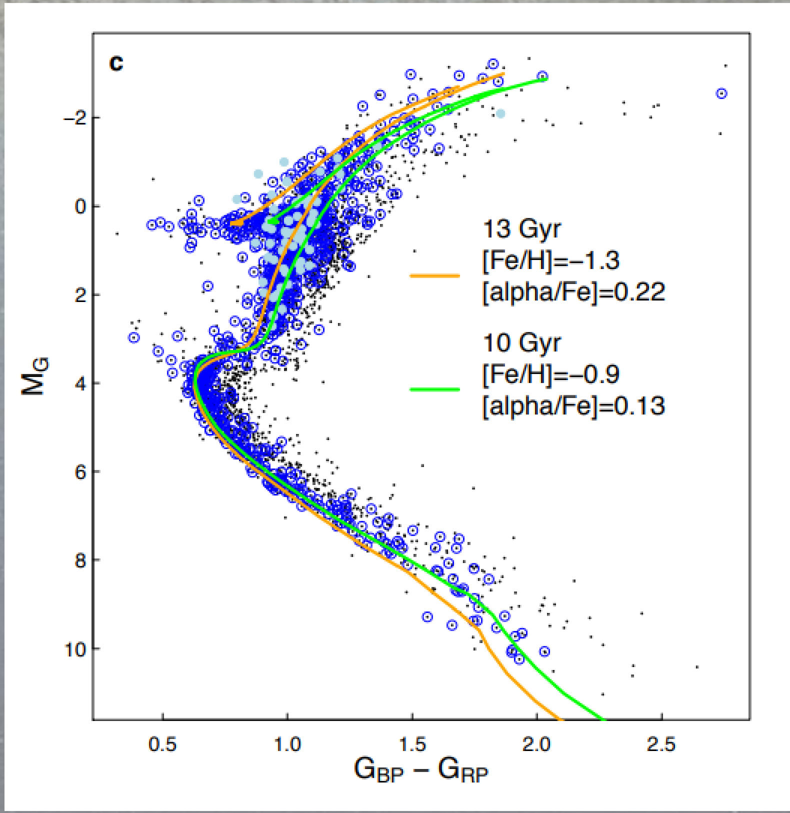


Vanzella et al. 2017

Key concept 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



Helmi et al. 2018;
Belokurov et al. 2018

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

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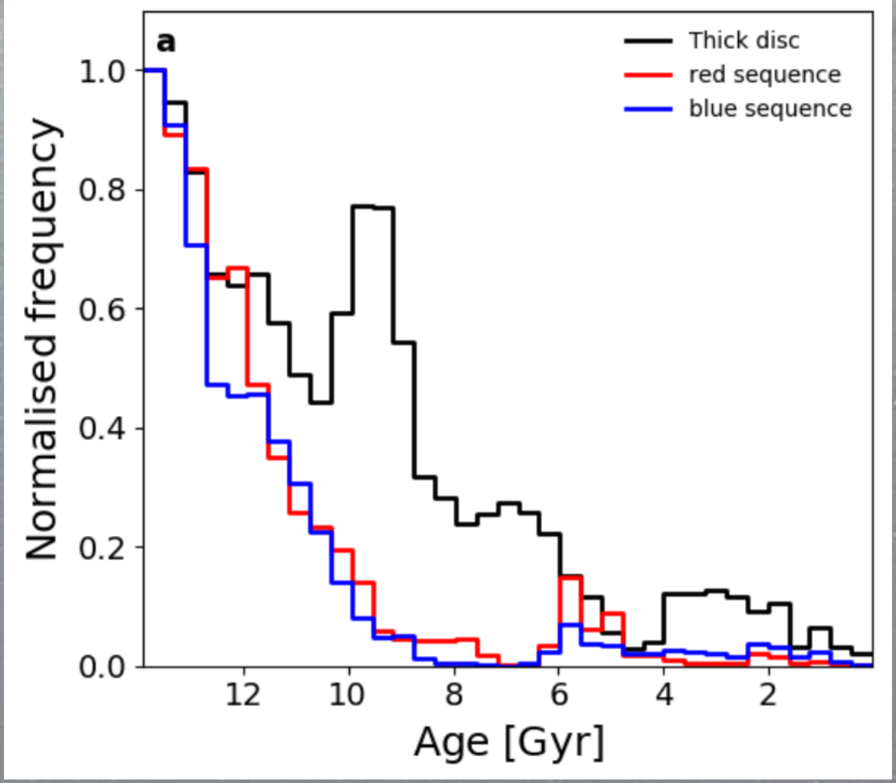

Gallart et al. 2019

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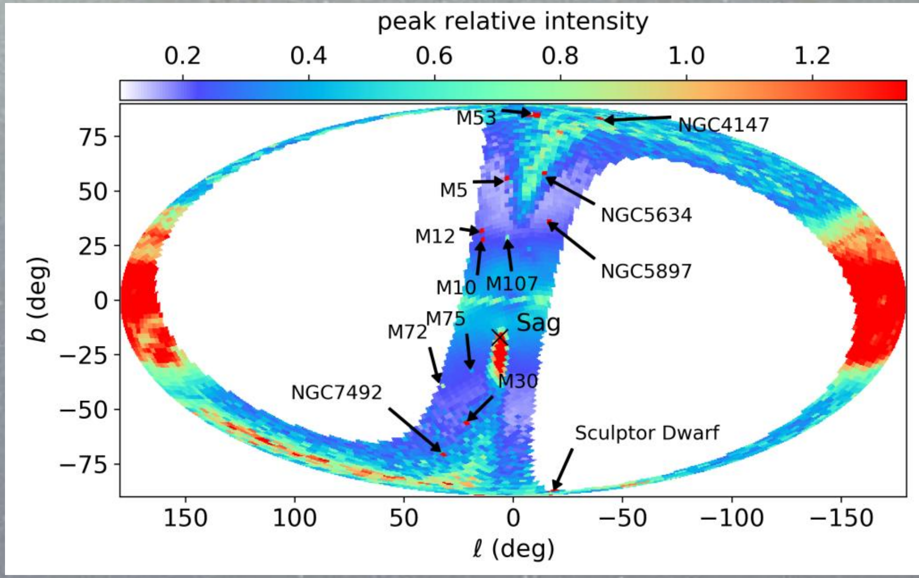

Antoja et al. 2020;
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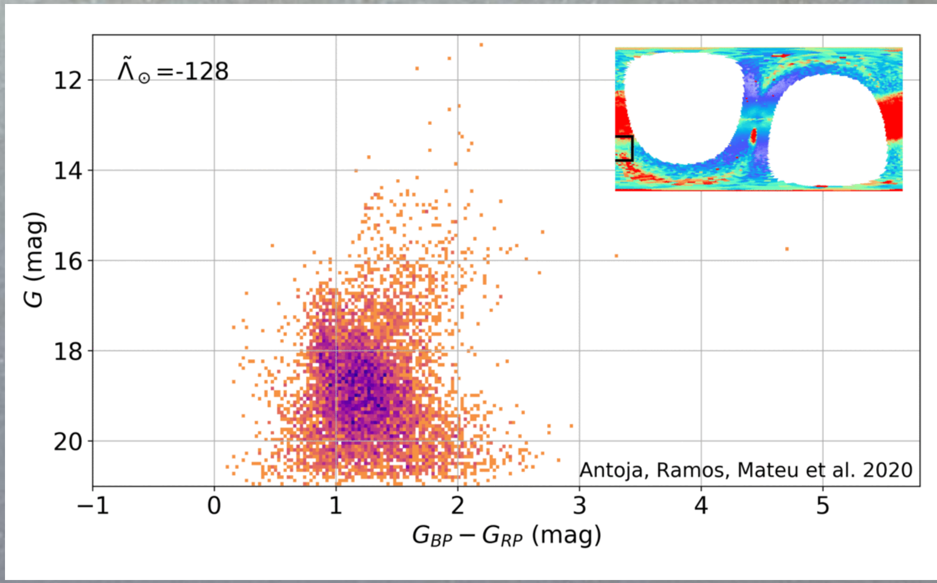

Antoja et al. 2020;
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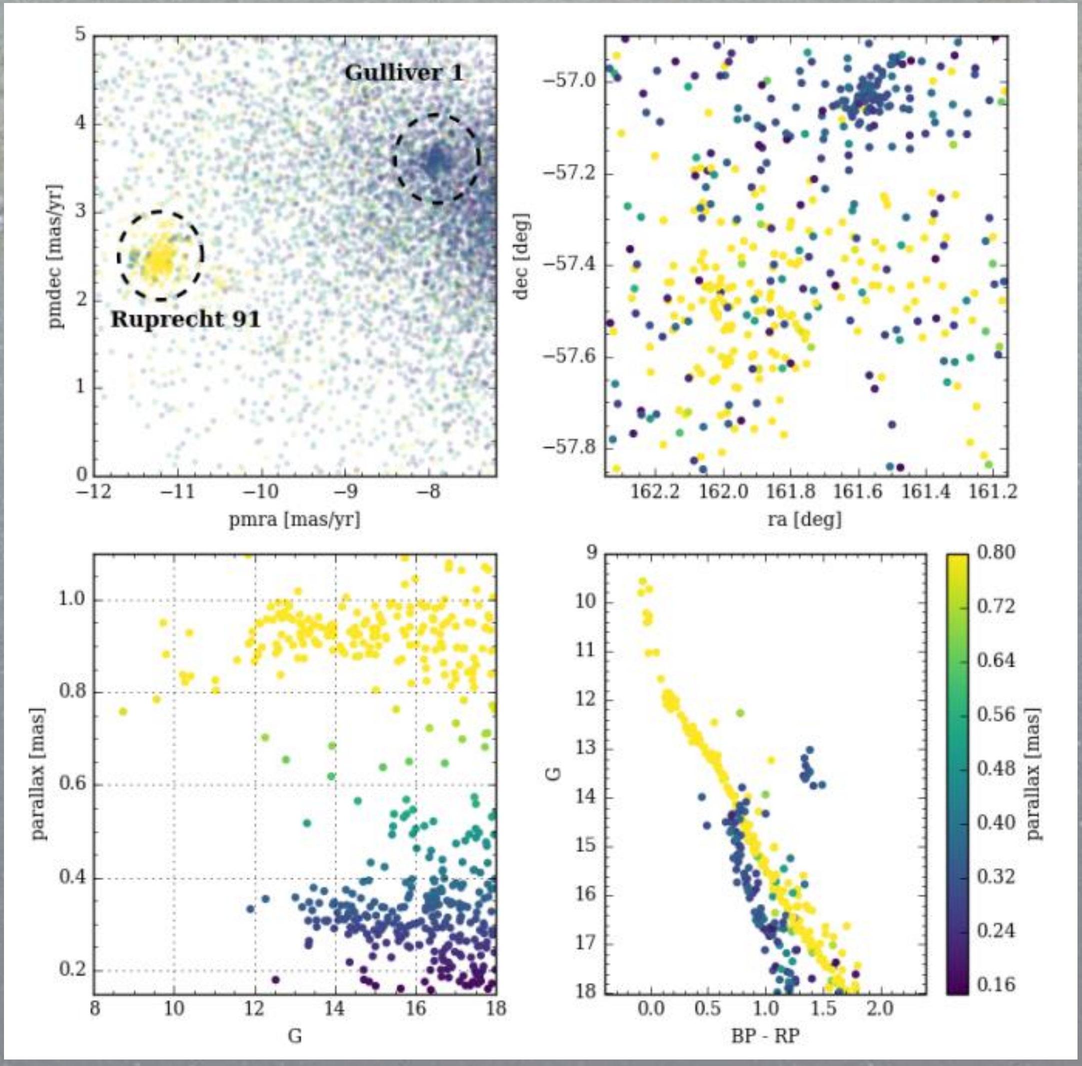
Key concept 1+2+3 = #6: proper motions to isolate different stellar populations

★ **CLUSTER SCIENCE!**



Cantat-Gaudin et al. 2018

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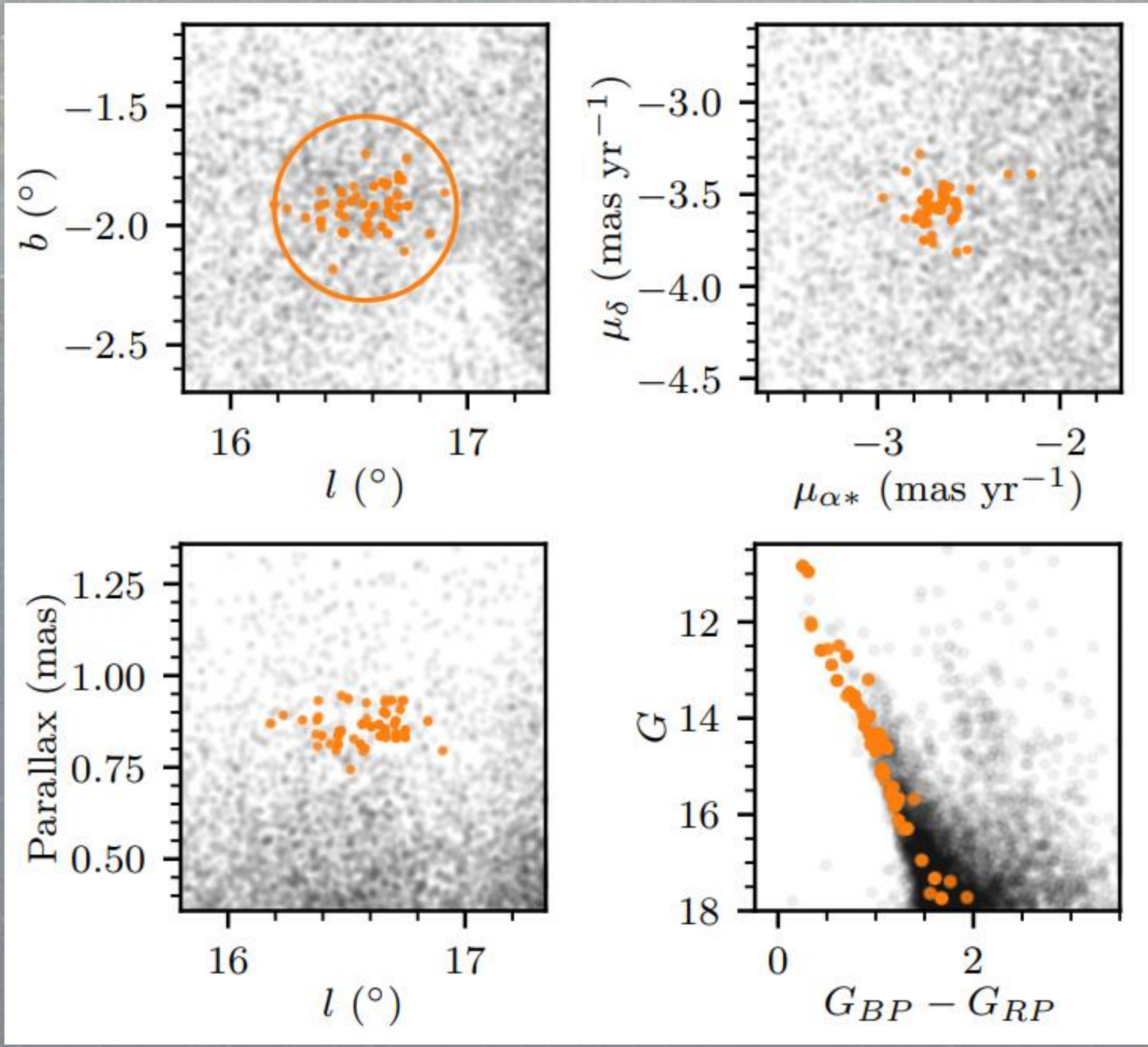
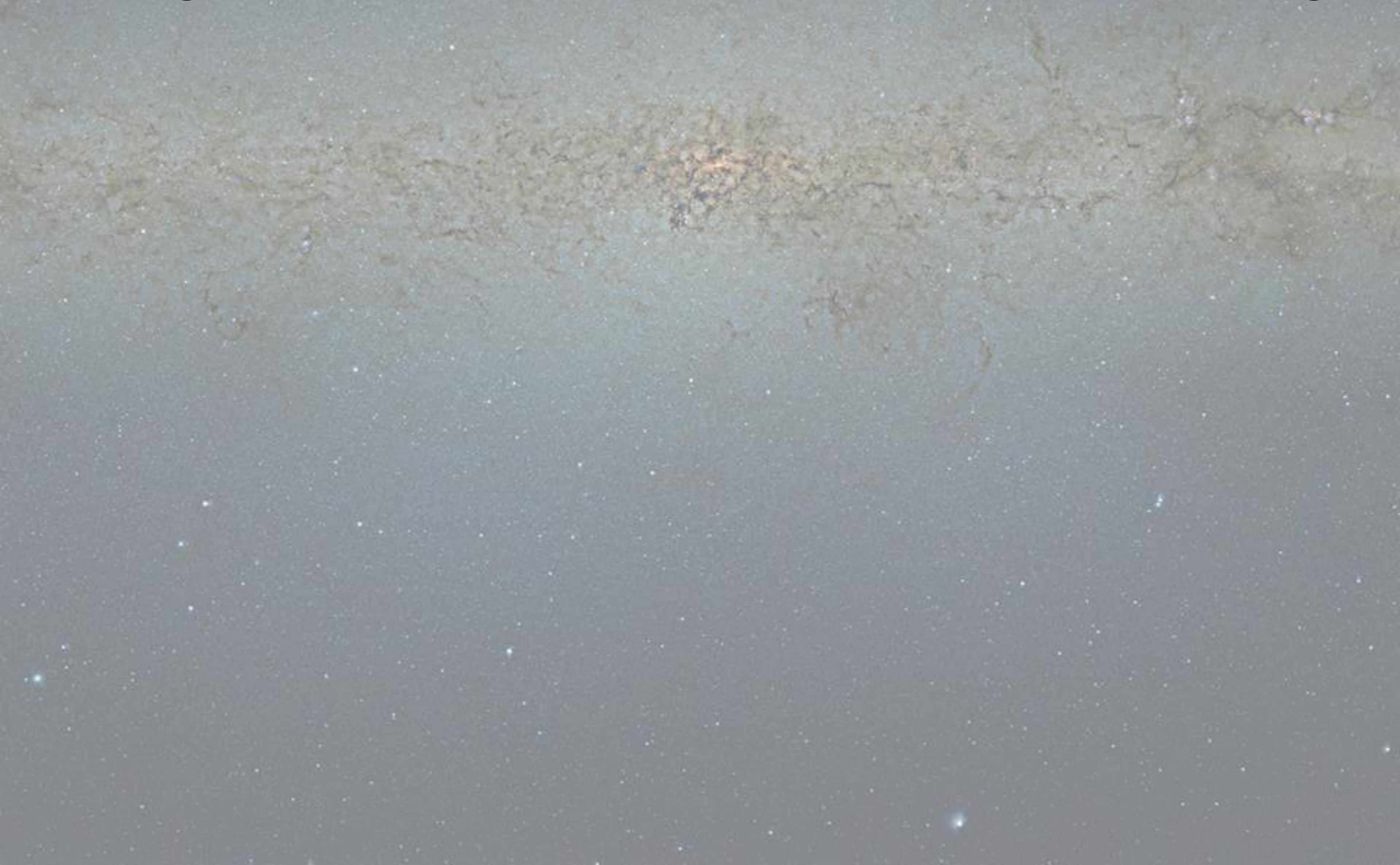


Hunt & Reffert 2021

Hidden in the haystack:

New globular clusters towards the Milky Way bulge



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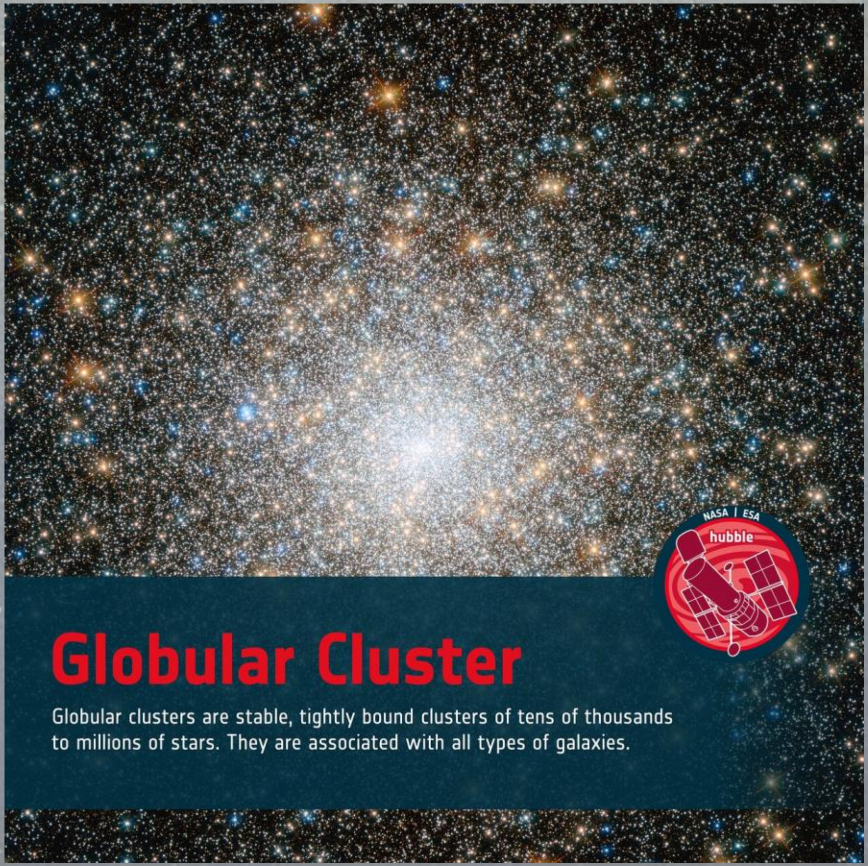

Credit: NASA & ESA

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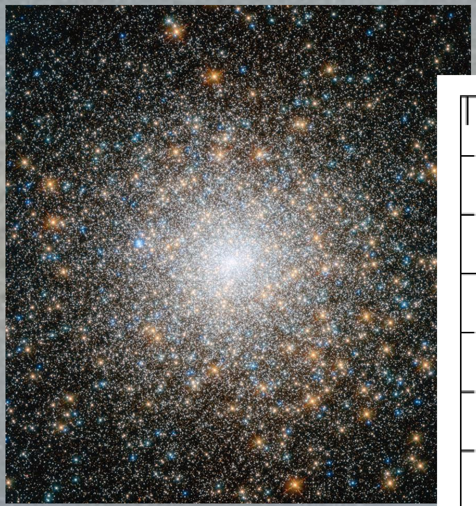
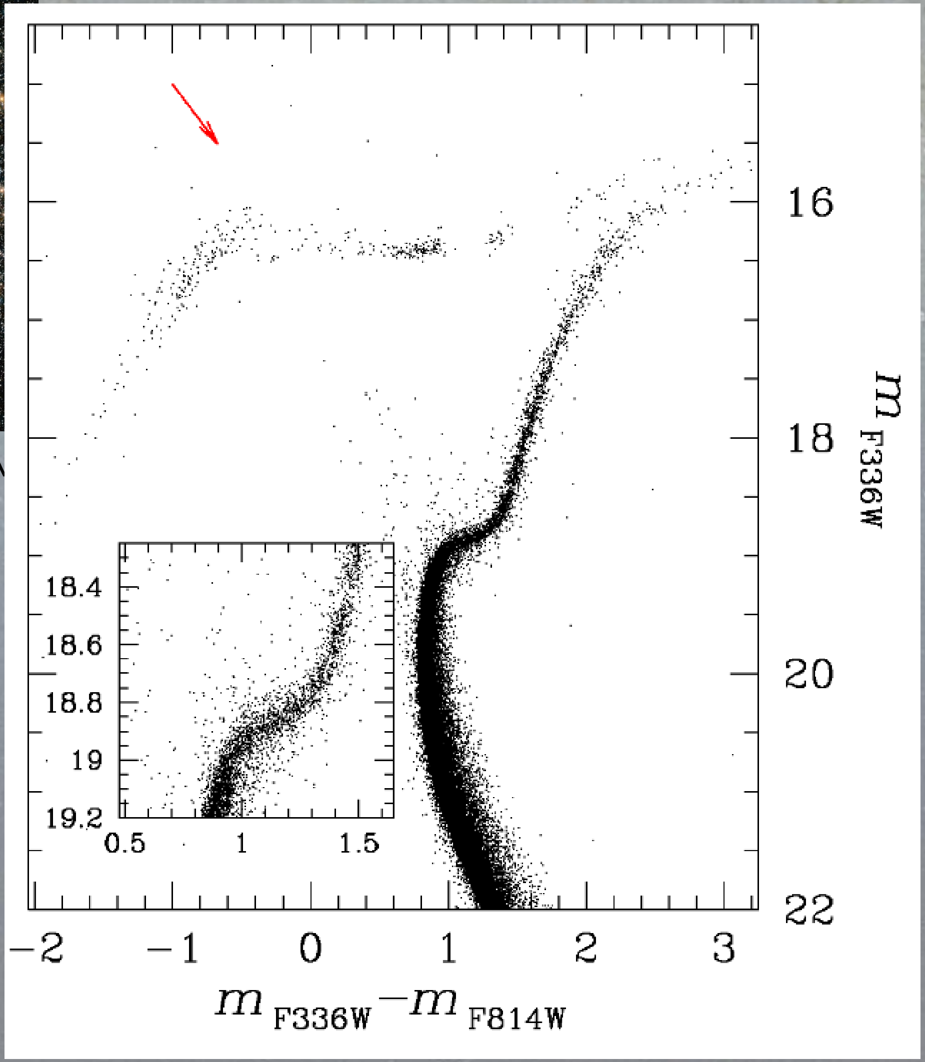

Credit: NASA & ESA



Nardiello et al. 2018

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Aladin Sky Atlas (Bonnarel et al. 2000, Boch & Fernique 2014)

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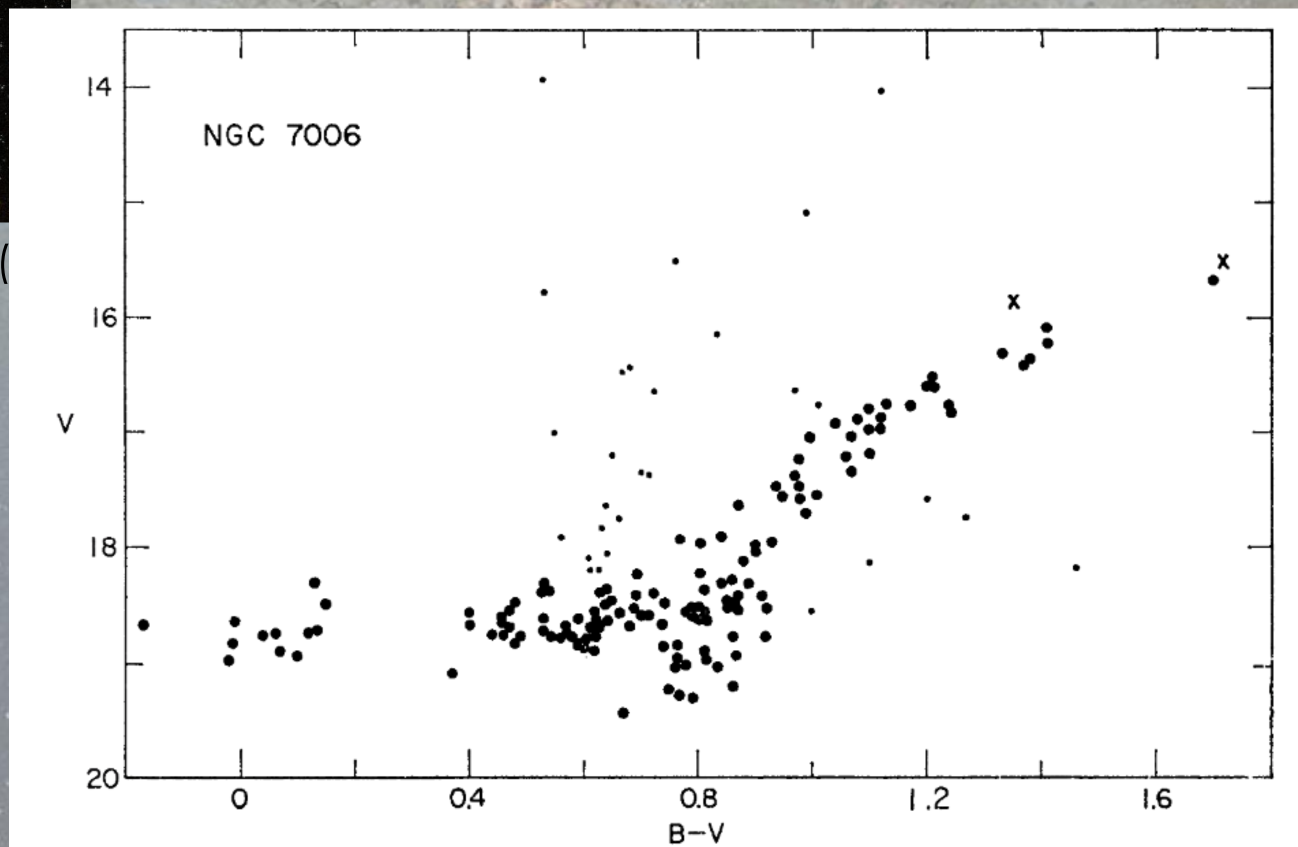

Sandage & Widley 1967

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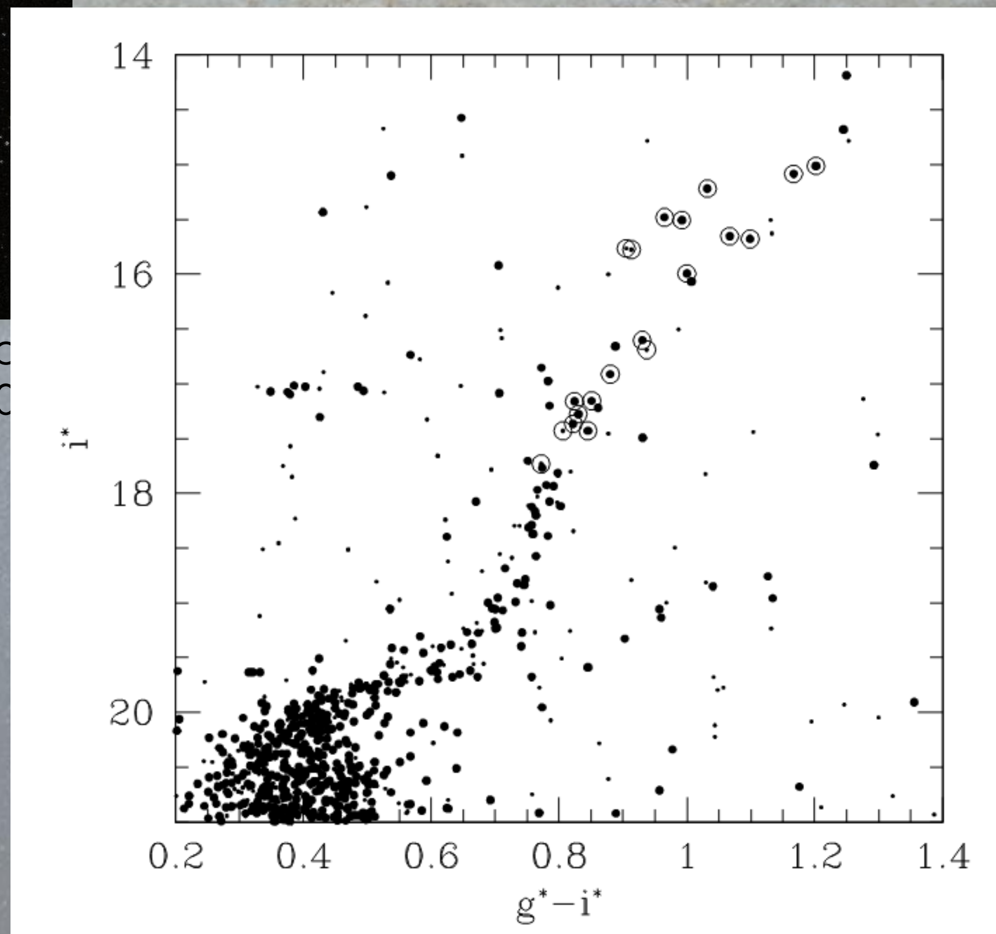

Odenkirchen et al. 2002

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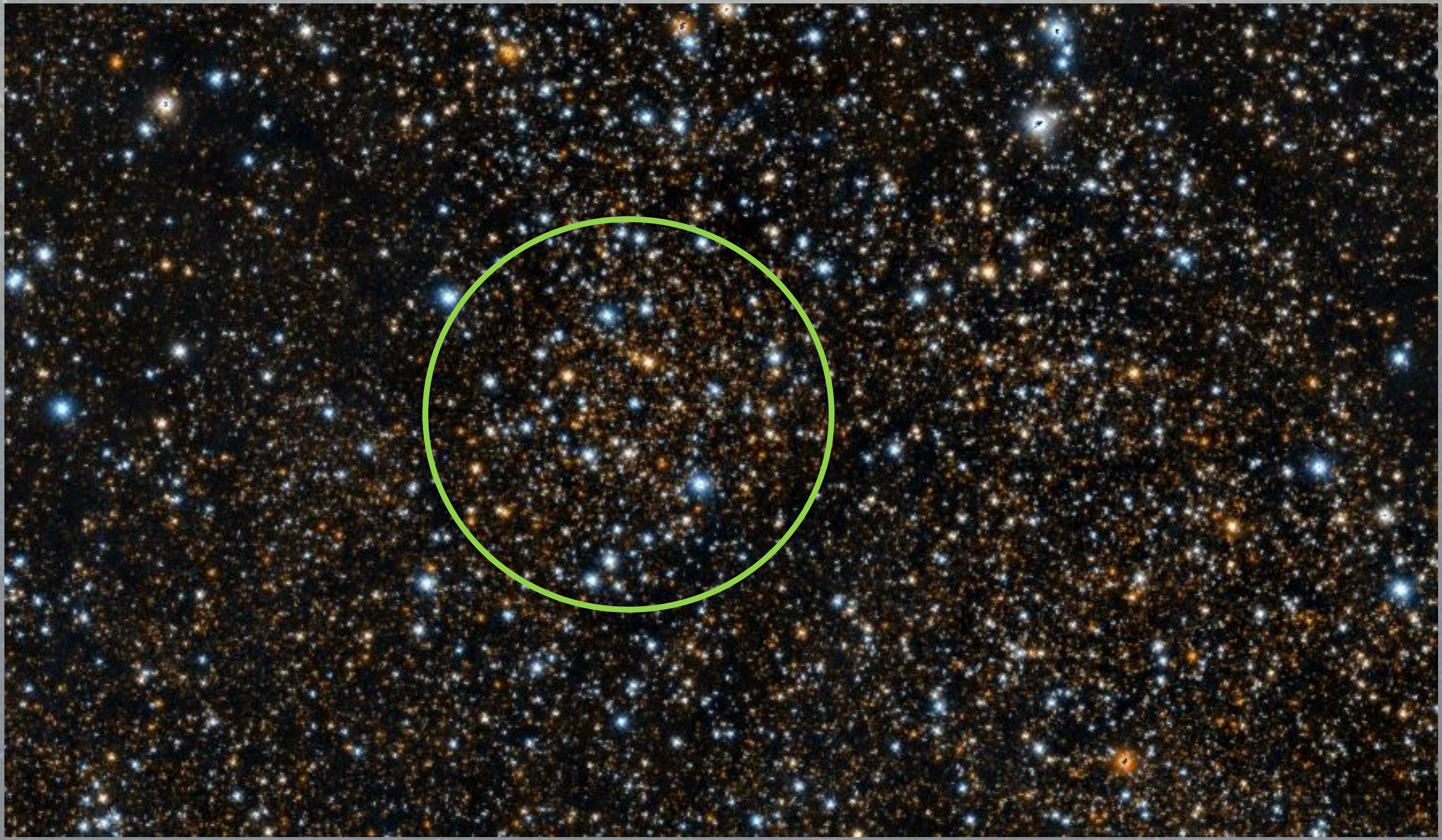

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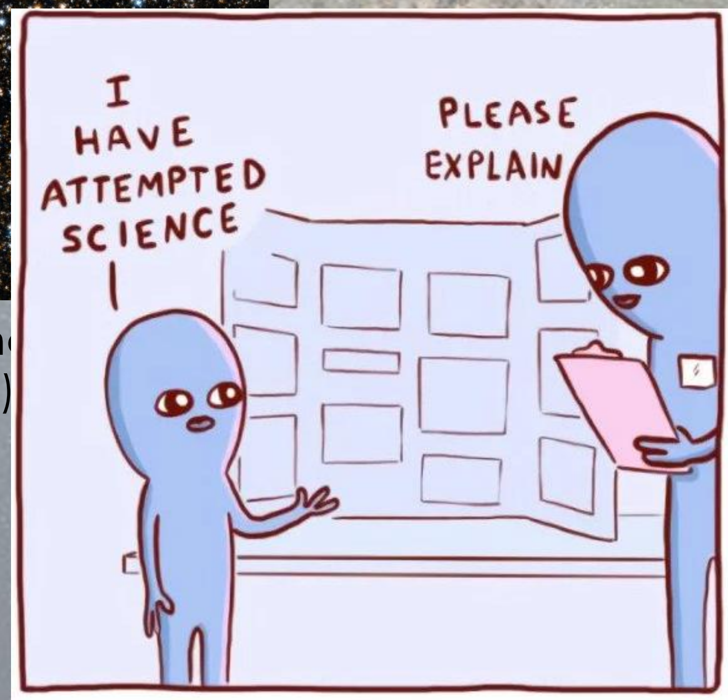

@nathanwpyle: STRANGE PLANET

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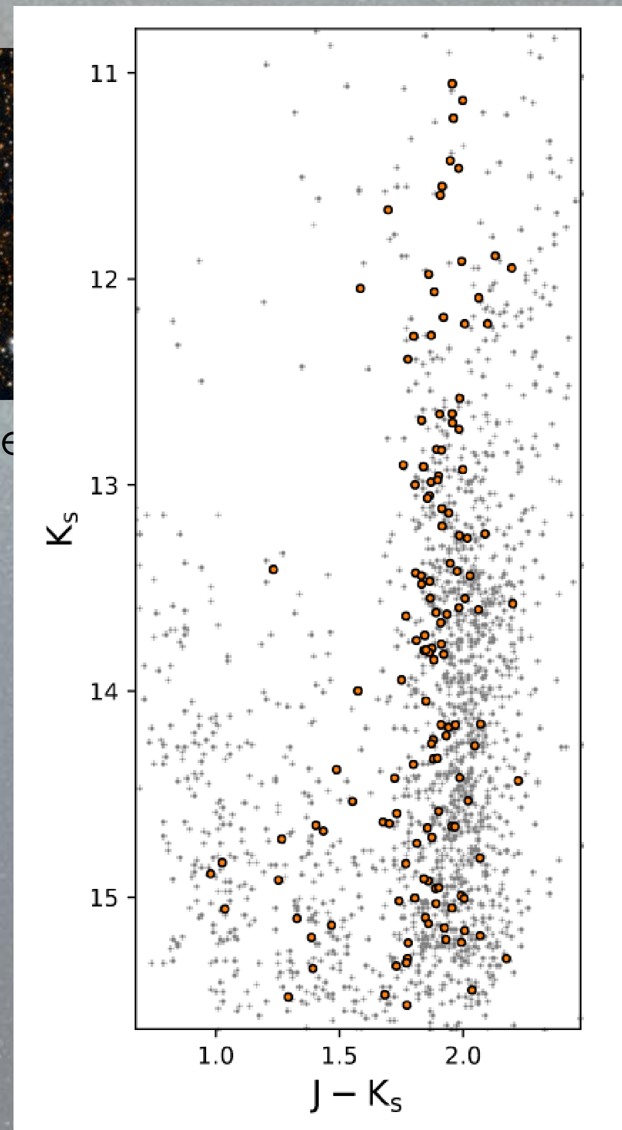

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- ★ Valuable tracers of understand the Milky Way evolution
- ★ Galactic bulge GCs compose a major part of the ***in situ*** component (Myeong et al. 2018)
- ★ The total number of GCs in the Milky Way is still **unknown**

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 Sesar[2], Edouard J. Bernard[3], Hans-Walter Rix[2], Colin T. Slater[4], Eric F. Bell[4], Annette M. N. Ferguson[3], Edward F. Schlafly[2], William S. Burgett[5], Kenneth C. Chambers[5], Larry Denneau[5], Peter W. Draper[6], Nicholas Kaiser[5], Rolf-Peter Kudritzki[5], Eugene A. Magnier[5], Nigel Metcalfe[6], Jeffrey S. Morgan[5], Paul A. Price[7], William E. Sweeney[5], John L. Tonry[5], Richard J. Wainscoat[5], and Christopher Waters[5]

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

S. Ortolani,[1,2] E. Bica[3] and B. Barbuy[4]†

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[3] *Universidade Federal do Rio Grande do Sul, Departamento de Astronomia, CP 15051, Porto Alegre 91501-970, Brazil*
[4] *Universidade 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

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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. Belokurov[1] and G. Torrealba[1]

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

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Received 2015 January 1; accepted 20...

A NEW DISTANT MILKY WAY GLOBULAR CLUST... RVEY

THE DISCOVERY OF TWO EXTREMELY LOW LUMINOSITY MILKY WAY GLOBULAR CLUSTERS

S. KOPOSOV,[1,2] J. T. A. DE JONG,[1] V. BELOKUROV,[2] H.-W. RIX,[1] D. B. ZUCKER,[2]

N. W. EVANS,[2] G. GILMORE,[2] M. J. IRWIN,[2] AND E. F. BELL[1]

Received 2007 March 1; accepted 2007 July 6

Segue 3: the youngest globular cluster in th...

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…AR CLUSTER IN THE… …US

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STAR CLUSTER IN THE CONSTELLATION OF URSA MINOR*

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…nology, Pasadena, CA 91125, USA

…: published 2012 June 15

…RY OF A FAINT O… …N THE SOUTHERN SKY

…ND GARY S. DA COSTA

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…KY WAY GLOB… …RVEY

CATS AND DOGS, HAIR AND A HERO: A QUINTET OF NEW MILKY WAY COMPANIONS[1]

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Received 2006 August 20; accepted 2006 September 20

THE DISC…

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[3] Herzbe…
[4] Observatori…
[5] Astr…

…bica[3] and B. Barbuy

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…o Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padua, Italy

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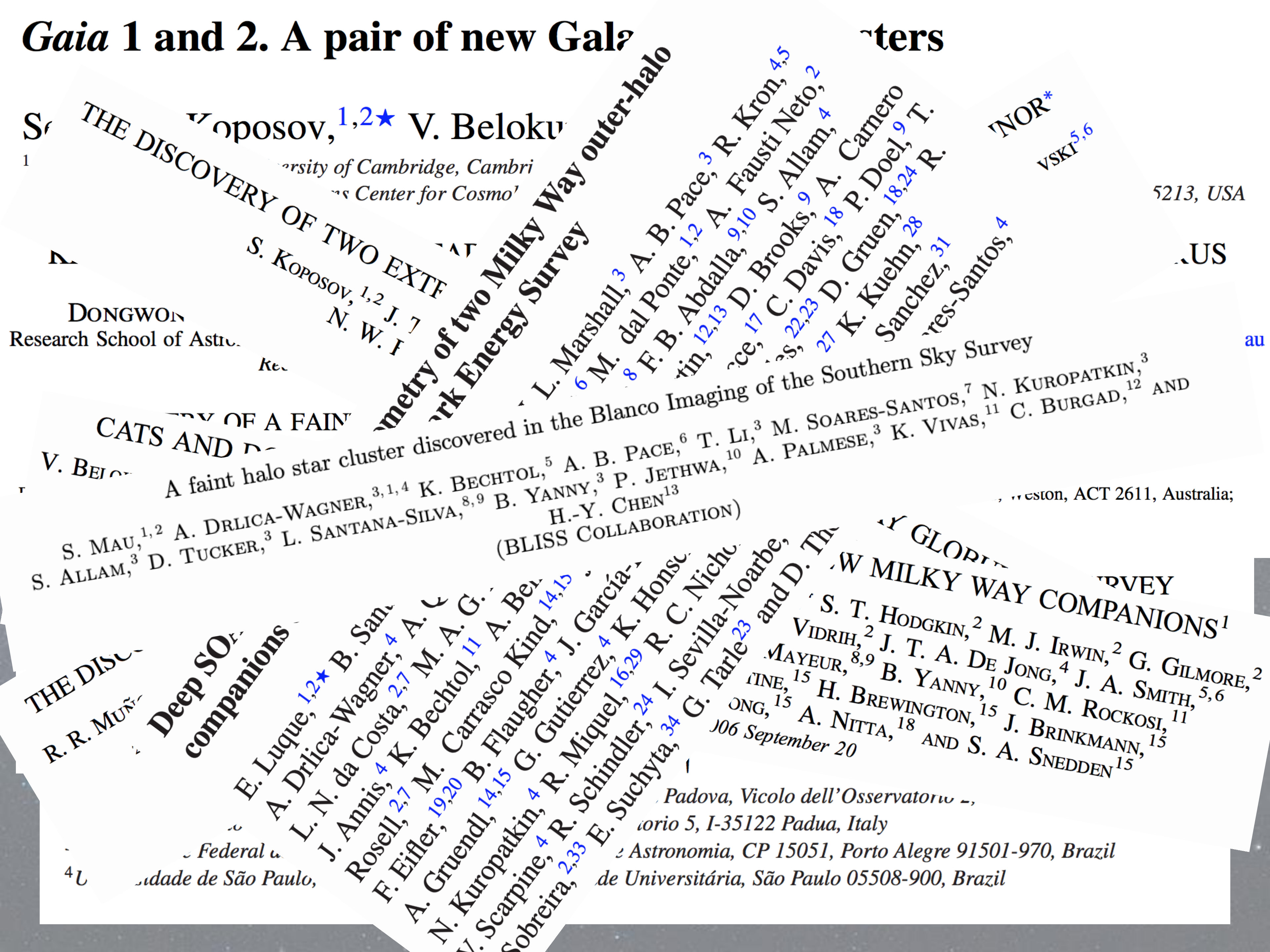


Gaia 1 and 2. A pair of new Gala
THE DISCOVERY OF TWO EXTR
S. Koposov, 1,2 J.
N. W.
metry of two Milky Way outer-halo
rk Energy Survey
L. Marshall, 3 A. B. Pace, 3 R. Kron, 4,5
M. dal Ponte, 1,2 A. Fausti Neto, 2
F. B. Abdalla, 9,10 S. Allam, 4
D. Brooks, 9 A. Carnero
C. Davis, 18 P. Doel, 9 T.
D. Gruen, 18,24 R.
K. Kuehn, 28
Sanchez, 31
res-Santos, 4
DONGWON
Research School of Astro
A faint halo star cluster discovered in the Blanco Imaging of the Southern Sky Survey
S. Mau, 1,2 A. Drlica-Wagner, 3,1,4 K. Bechtol, 5 A. B. Pace, 6 T. Li, 3 M. Soares-Santos, 7 N. Kuropatkin, 3
S. Allam, 3 D. Tucker, 3 L. Santana-Silva, 8,9 B. Yanny, 3 P. Jethwa, 10 A. Palmese, 3 K. Vivas, 11 C. Burgad, 12 and
H.-Y. Chen 13
(BLISS Collaboration)
CATS AND D
V. BEL
Weston, ACT 2611, Australia;
Deep SO
companions
E. Luque, 1,2★ B. Santiago
A. Drlica-Wagner, 4 A.
L. N. da Costa, 2,7 M. A. G.
J. Annis, 4 K. Bechtol, 11 A. Ben
Rosell, 2,7 M. Carrasco Kind, 14,15
F. Eifler, 19,20 B. Flaugher, 4 J. García-
A. Gruendl, 14,15 G. Gutierrez, 4 K. Honsc
N. Kuropatkin, 4 R. Miquel, 16,29 R. C. Nich
V. Scarpine, 4 R. Schindler, 24 I. Sevilla-Noarbe,
Sobreira, 2,33 E. Suchyta, 34 G. Tarle 23 and D. Th
W MILKY WAY COMPANIONS 1
S. T. Hodgkin, 2 M. J. Irwin, 2 G. Gilmore, 2
Vidrih, 2 J. T. A. De Jong, 4 J. A. Smith, 5,6
Mayeur, 8,9 B. Yanny, 10 C. M. Rockosi, 11
H. Brewington, 15 J. Brinkmann, 15
A. Nitta, 18 and S. A. Snedden 15
THE DISC
R. R. Mu
Padova, Vicolo dell'Osservatorio
orio 5, I-35122 Padua, Italy
Federal
Astronomia, CP 15051, Porto Alegre 91501-970, Brazil
dade de São Paulo,
de Universitária, São Paulo 05508-900, Brazil

Photometric searches of GCs

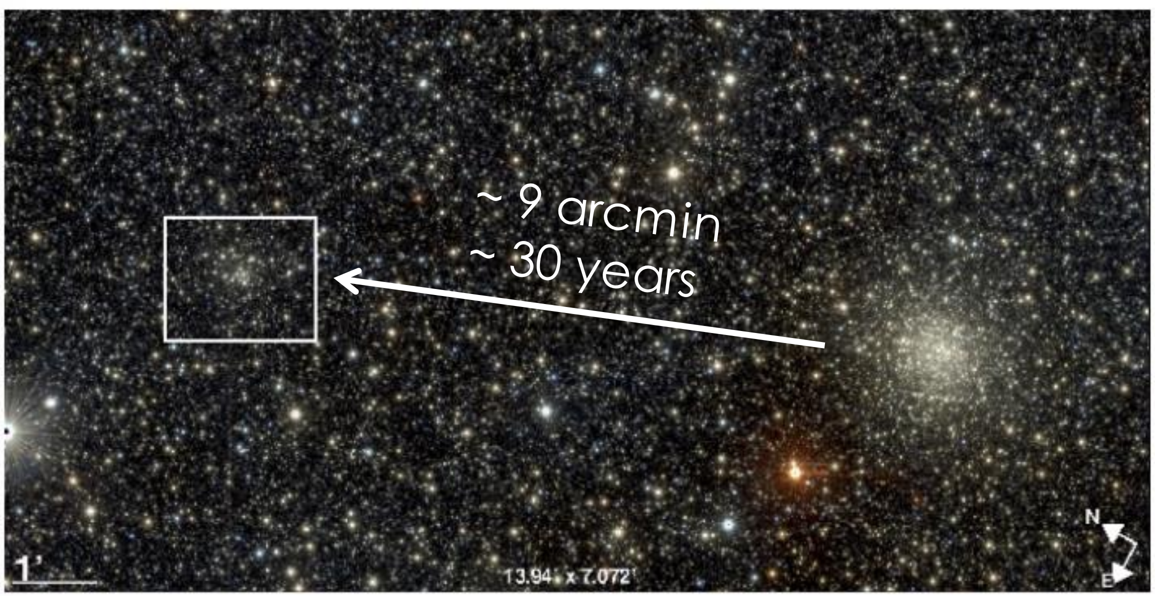
Thanks to the recent **near-IR photometric surveys**, the number of star cluster candidates has risen exponentially in the last few years in the **bulge region**.

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**.



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**.

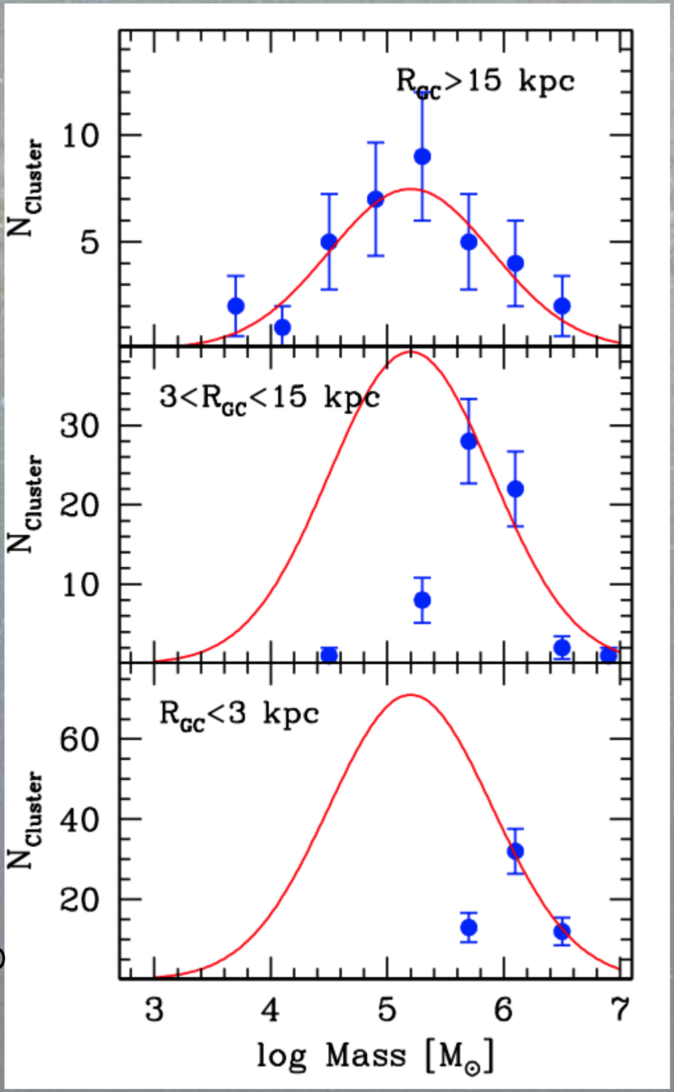
Unfortunately, most of them were recently **ruled out** using proper motions (**Gran et al. 2019**):

★ Spatial overdensities ☑

★ CMD different from field ⚠

★ Coherent space motion 🛑

Initial mass distribution of GCs in the MW



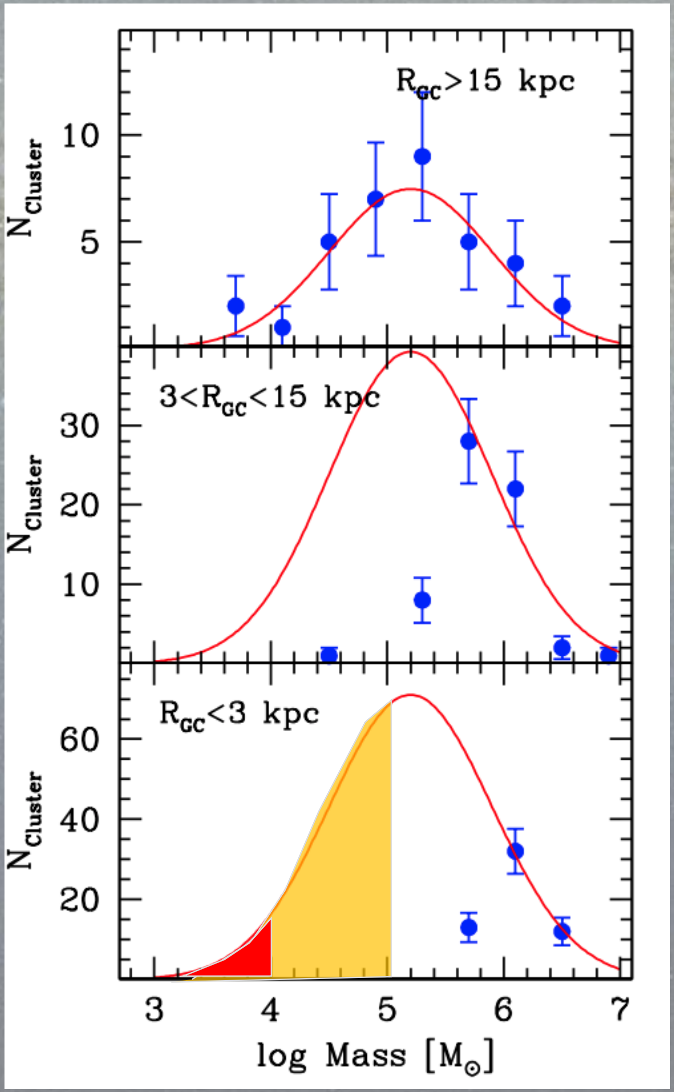
Baumgardt et al. 2018

~Halo GCs

~Disk GCs

~Bulge GCs

Initial mass distribution of GCs in the MW



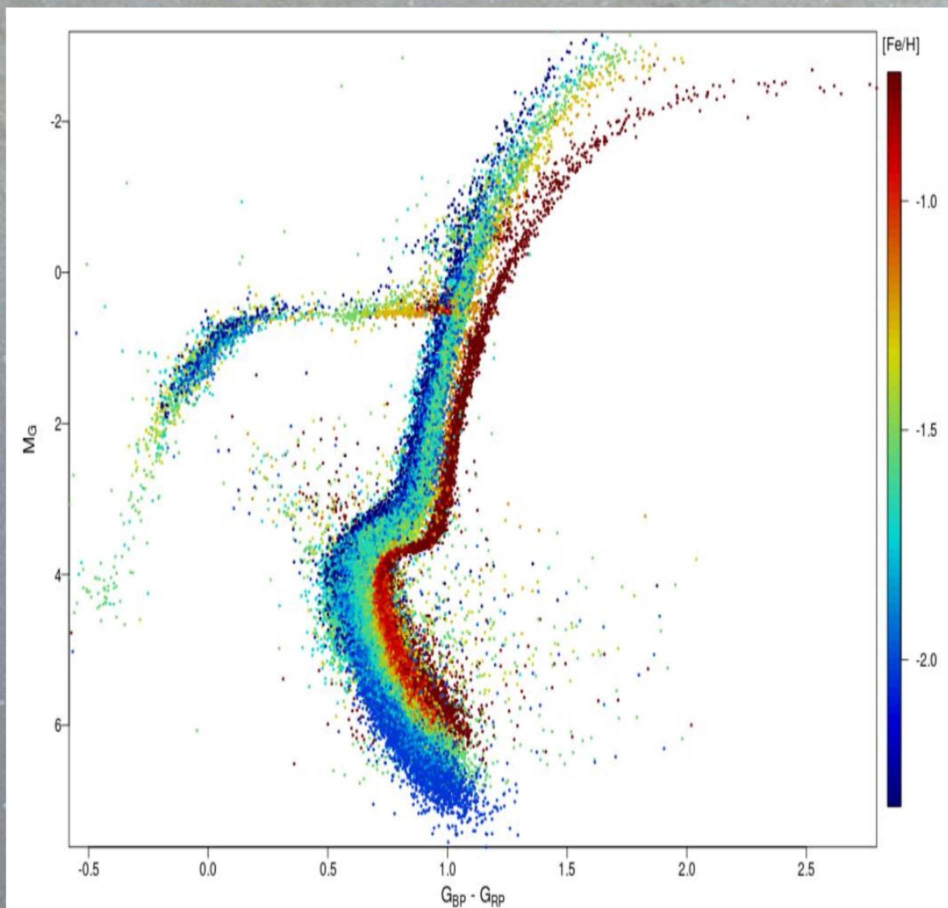
Baumgardt et al. 2018

~Halo GCs

~Disk GCs

~Bulge GCs

Gaia DR3 proper motion catalogue



Gaia Collaboration et al. 2018

Gaia DR3

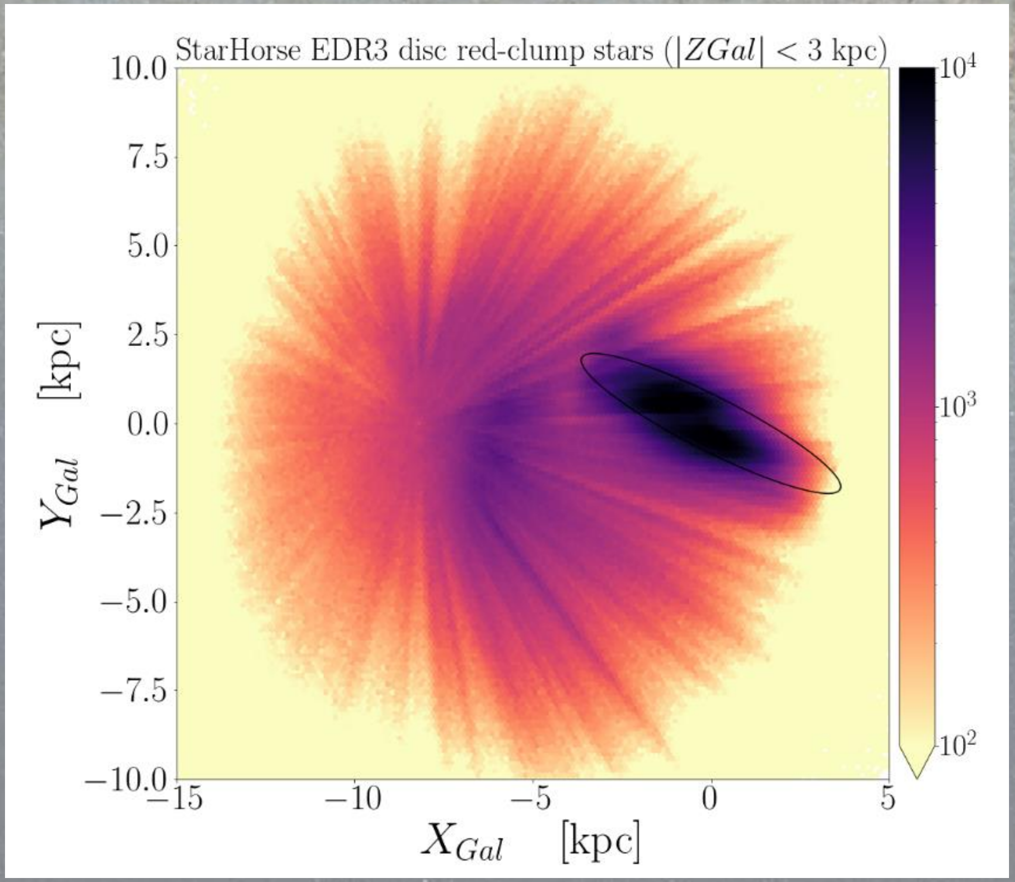
Optical survey (G, G_{BP}, G_{RP}, G_{RVS}, XP spectra)

Valid for $|b| \geq 2°$

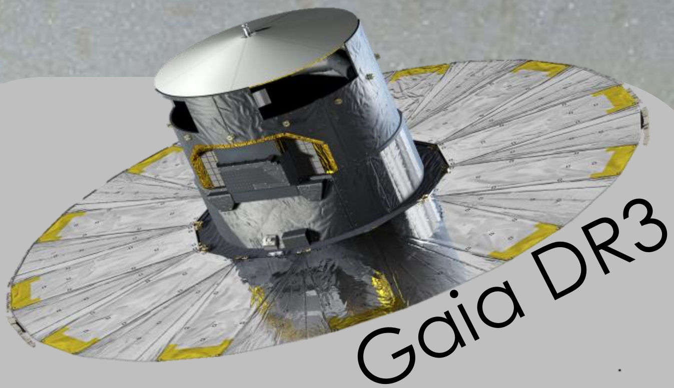
Absolute proper motions: $\mu_\alpha \cos(\delta)$, μ_δ

Gaia Collaboration 2022

Gaia DR3 proper motion catalog



Anders et al. 2021



Optical survey
(G, G_{BP}, G_{RP},
G_{RVS}, XP spectra)

Valid for $|b| \geq 2°$

Absolute proper motions:
$\mu_{\alpha} \cos(\delta)$, μ_{δ}

Gaia Collaboration 2018

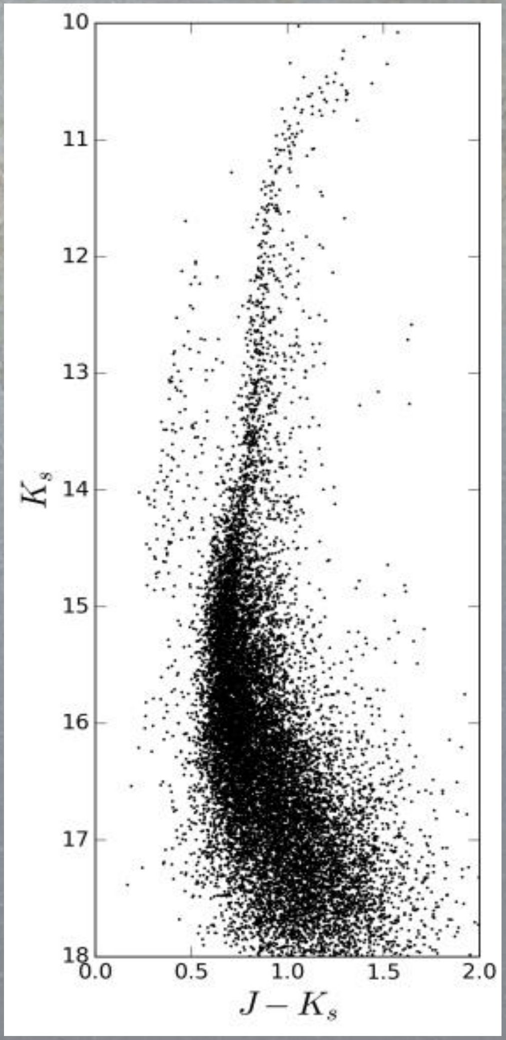
VVV survey catalogue

Survey

Near-IR survey
(ZYJH$\mathbf{K_s}$)

~100+ K_s epochs

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



Minniti et al 2010,
Contreras Ramos et al. 2017

Clustering on a 5-D phase-space

$-10 \leq l$ (deg) ≤ 10
$-10 \leq b$ (deg) ≤ 10

+

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

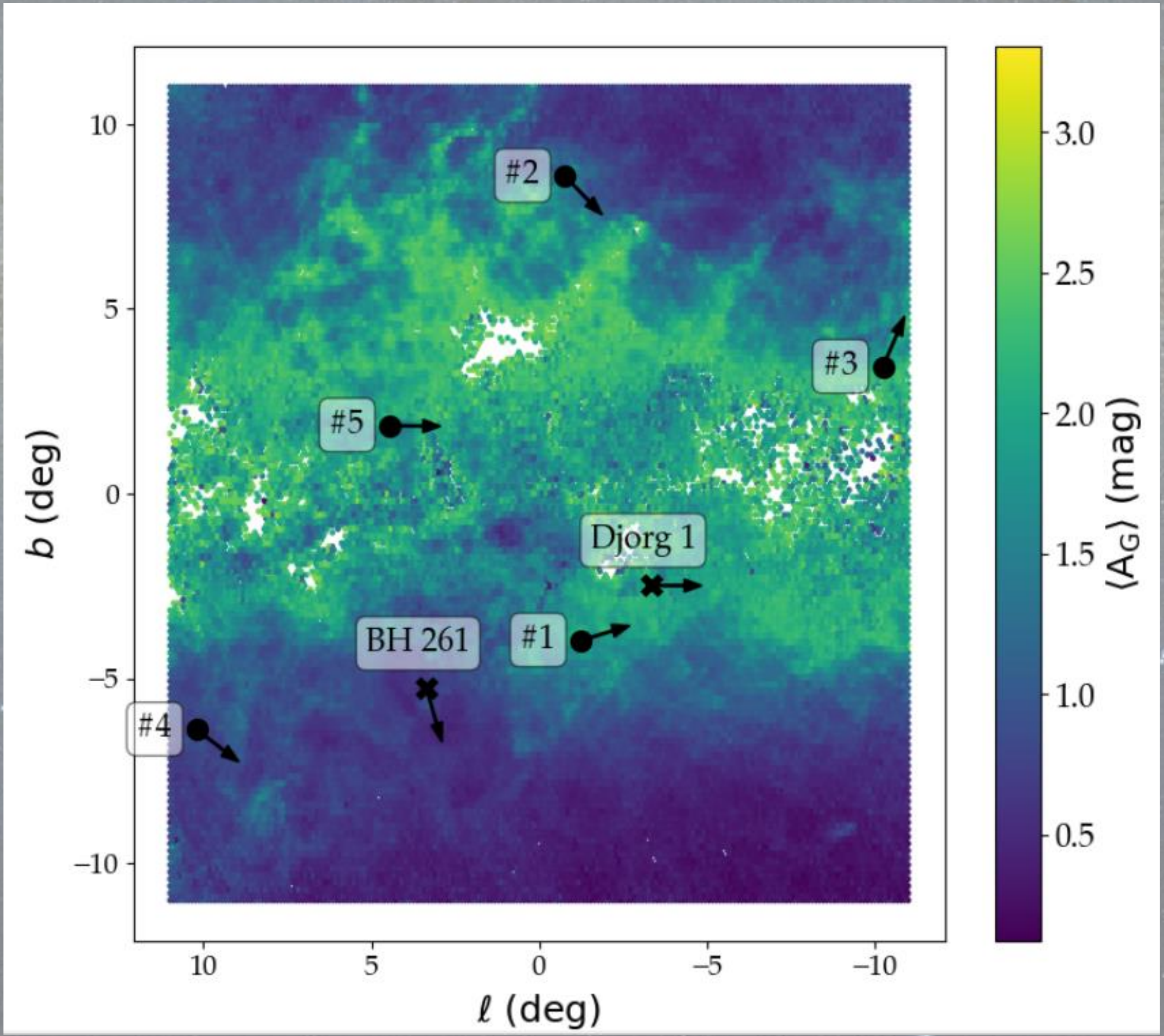
+

scikit learn: KDTree
and DBScan

Pedragosa et al 2011

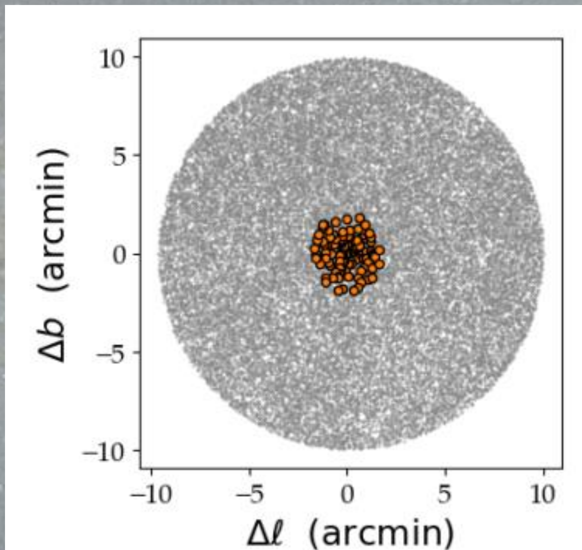
¡Candidate clusters in the 5-D phase space!

Map of the new GCs



Gran et al. 2022

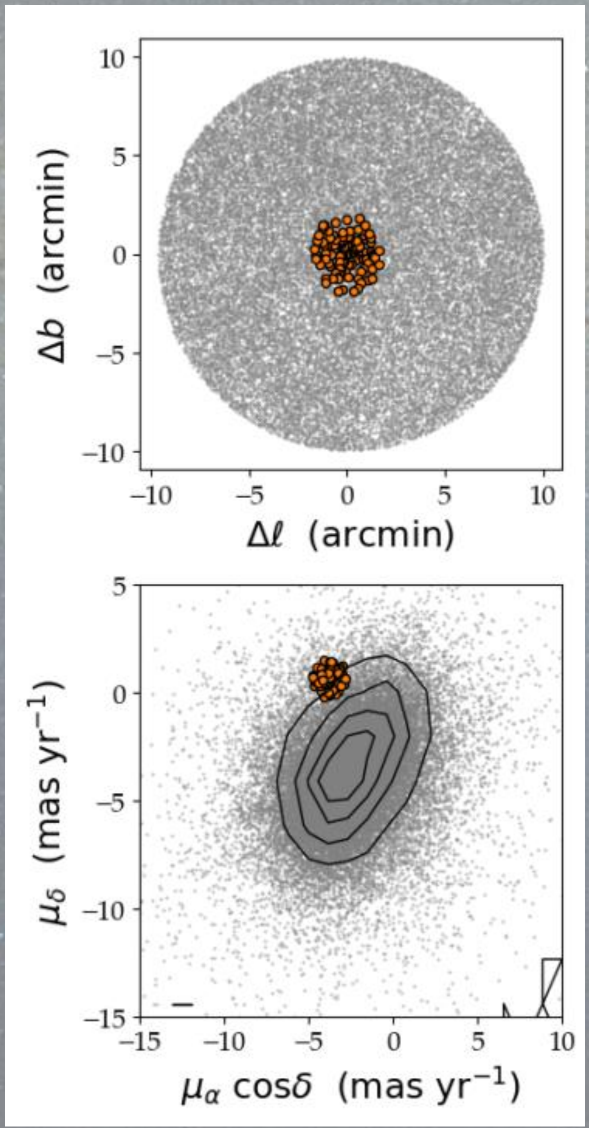
New GCs: the case of Gran 3



Clustering requirements:

- Grouped in space (ℓ,b)

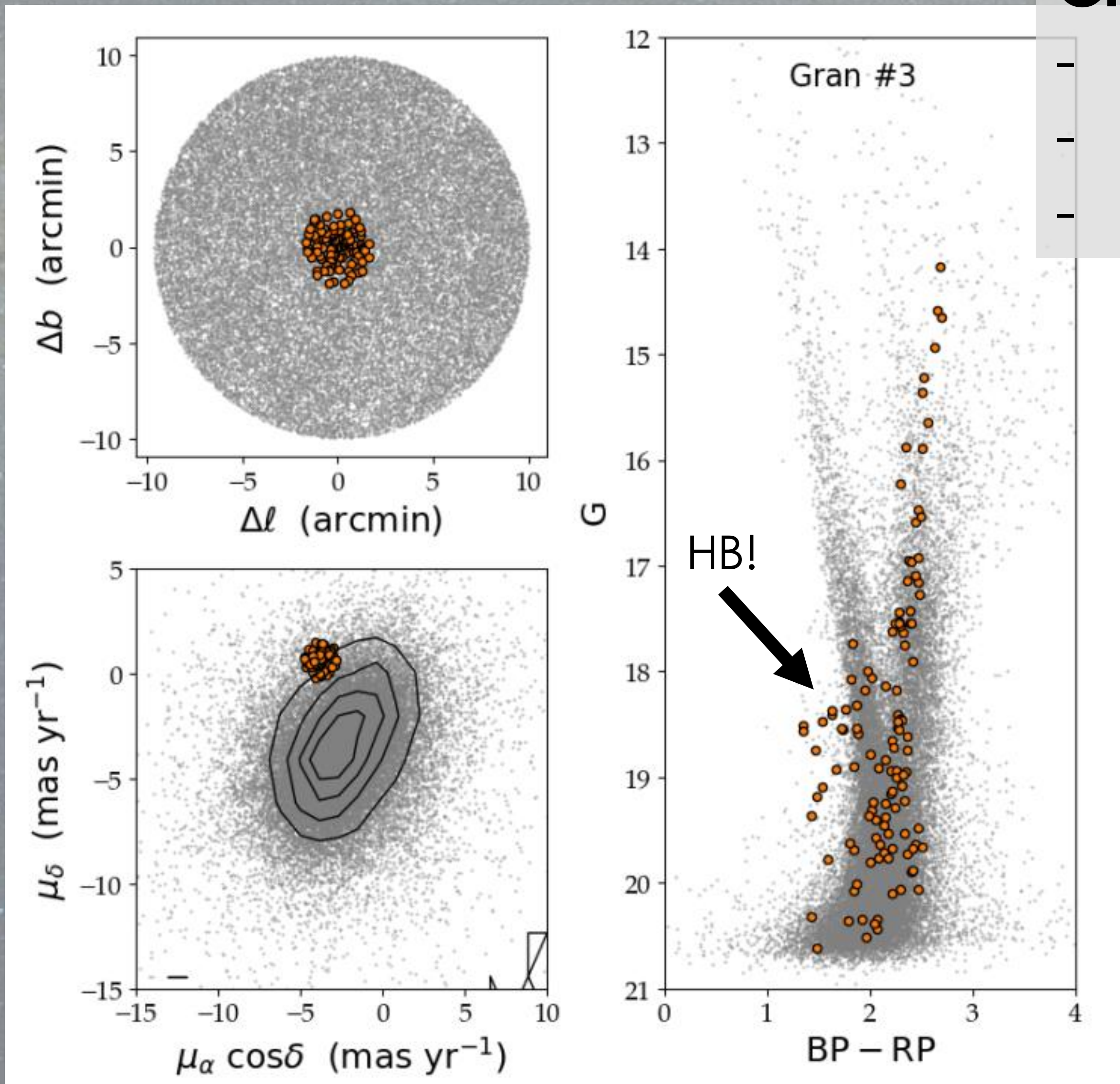
New GCs: the case of Gran 3



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

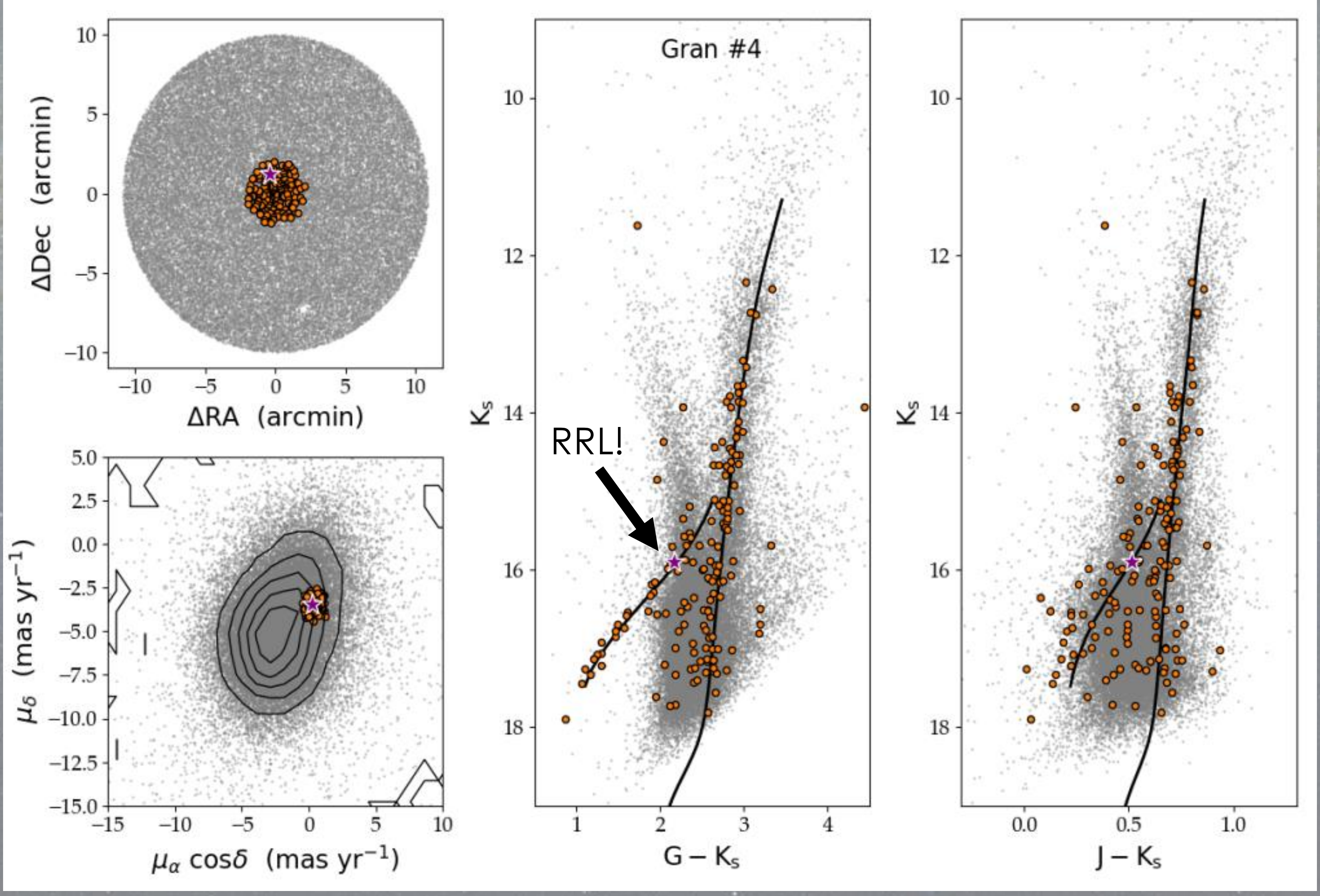
New GCs: the case of Gran 3

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



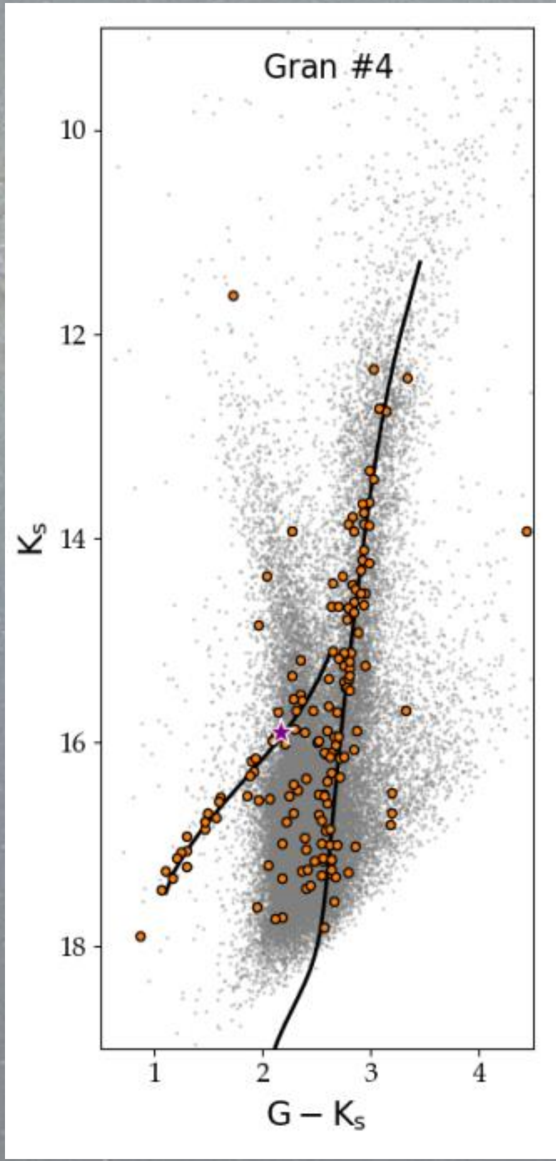
Gran et al. 2022

New GCs: the case of Gran 4



Gran et al. 2021

New GCs: the case of Gran 4



Gran et al. 2022

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

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

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

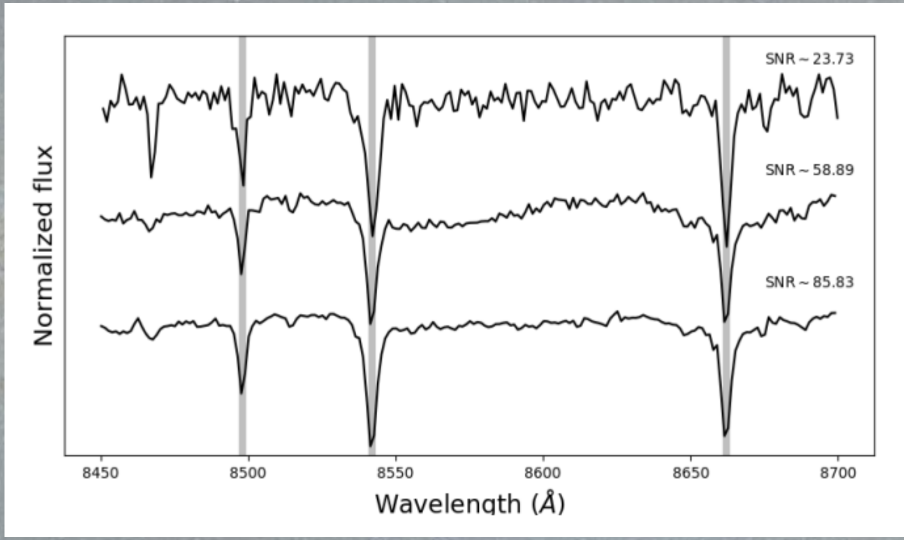
Gran et al. 2022

New GCs: MUSE observations

ESO P103-105
PI: F. Gran

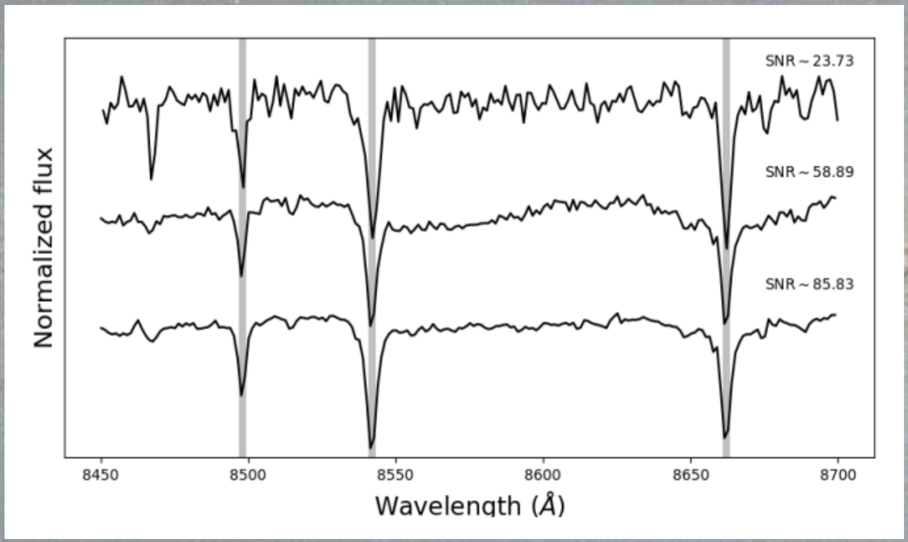
14 hours
WFM ~ 1 arcmin^2
4650 < λ (Å) < 9300
R @ 8800 Å ~ 4000

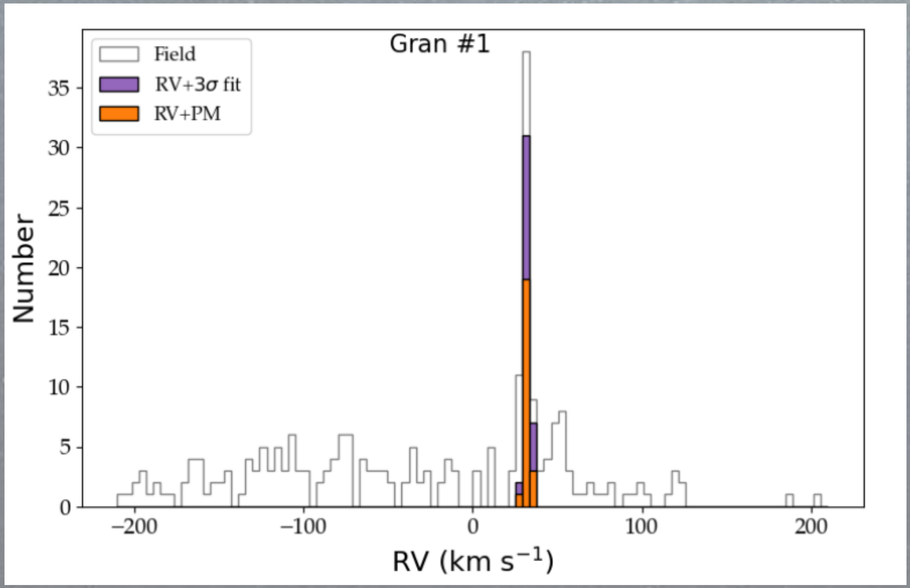
New GCs: MUSE observations



Gran et al. 2022

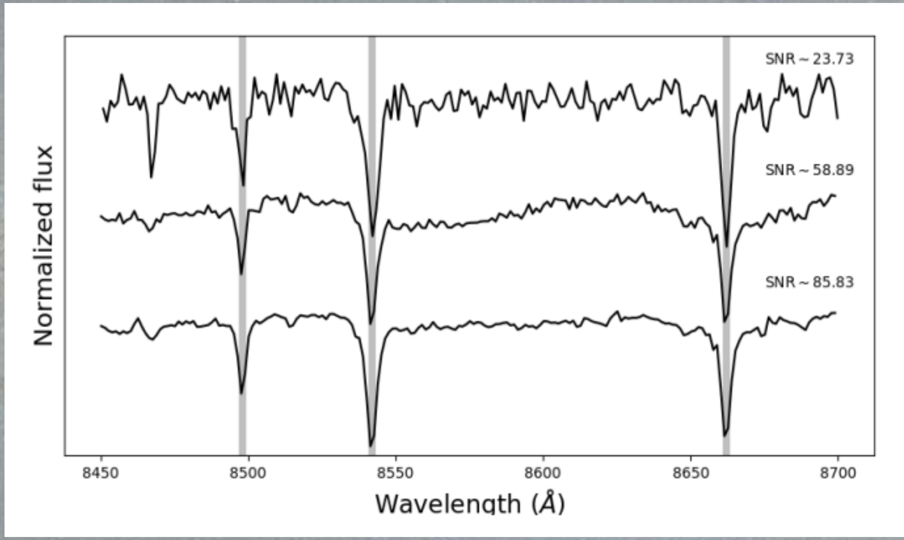
New GCs: MUSE observations

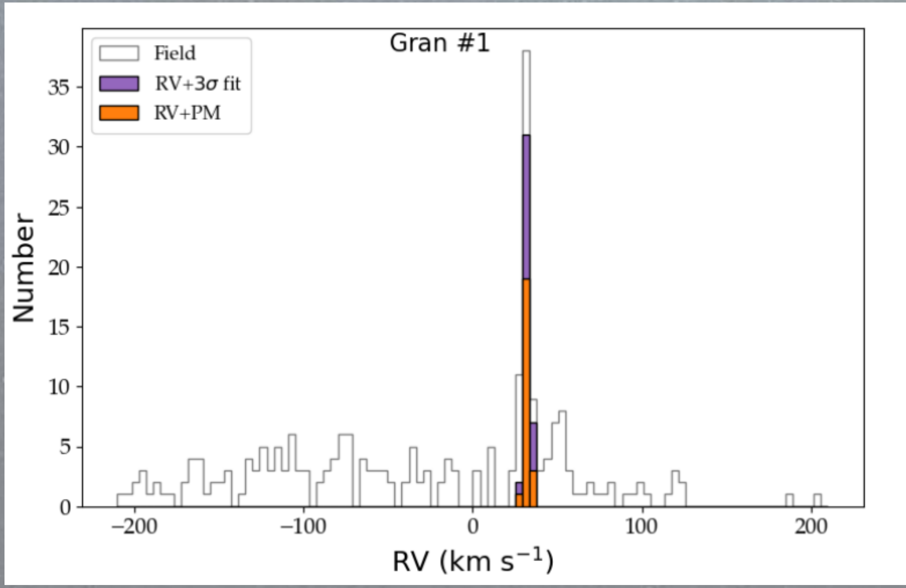


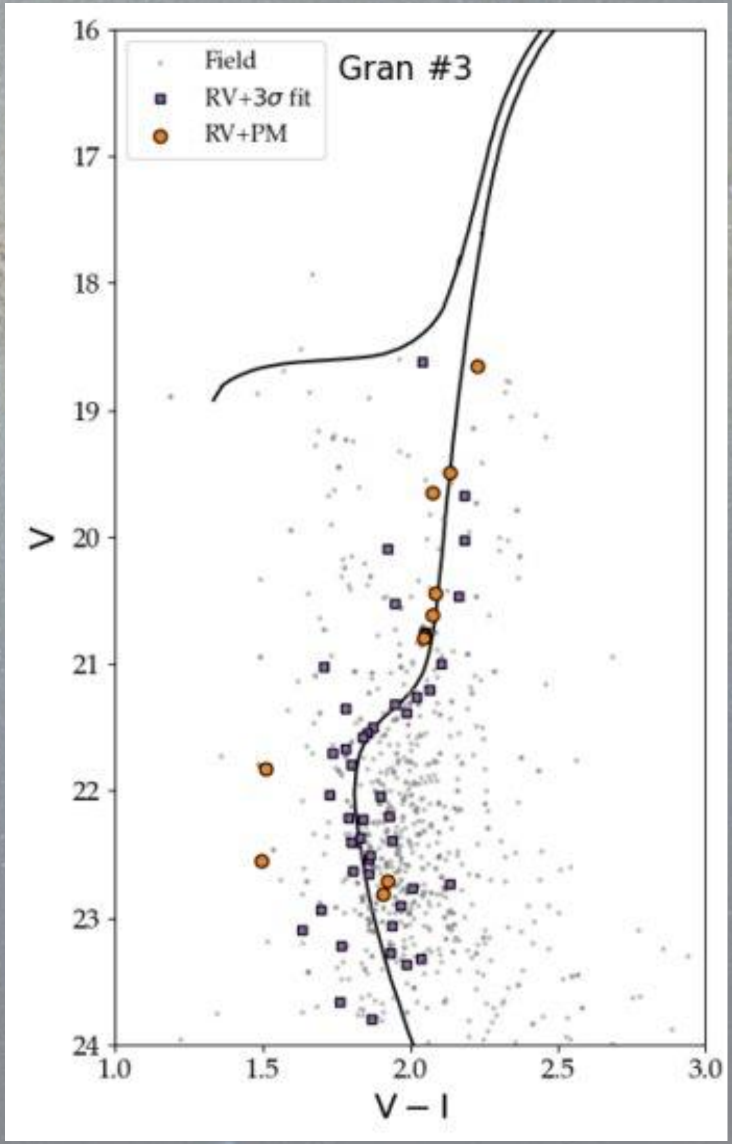


Gran et al. 2022

New GCs: MUSE observations

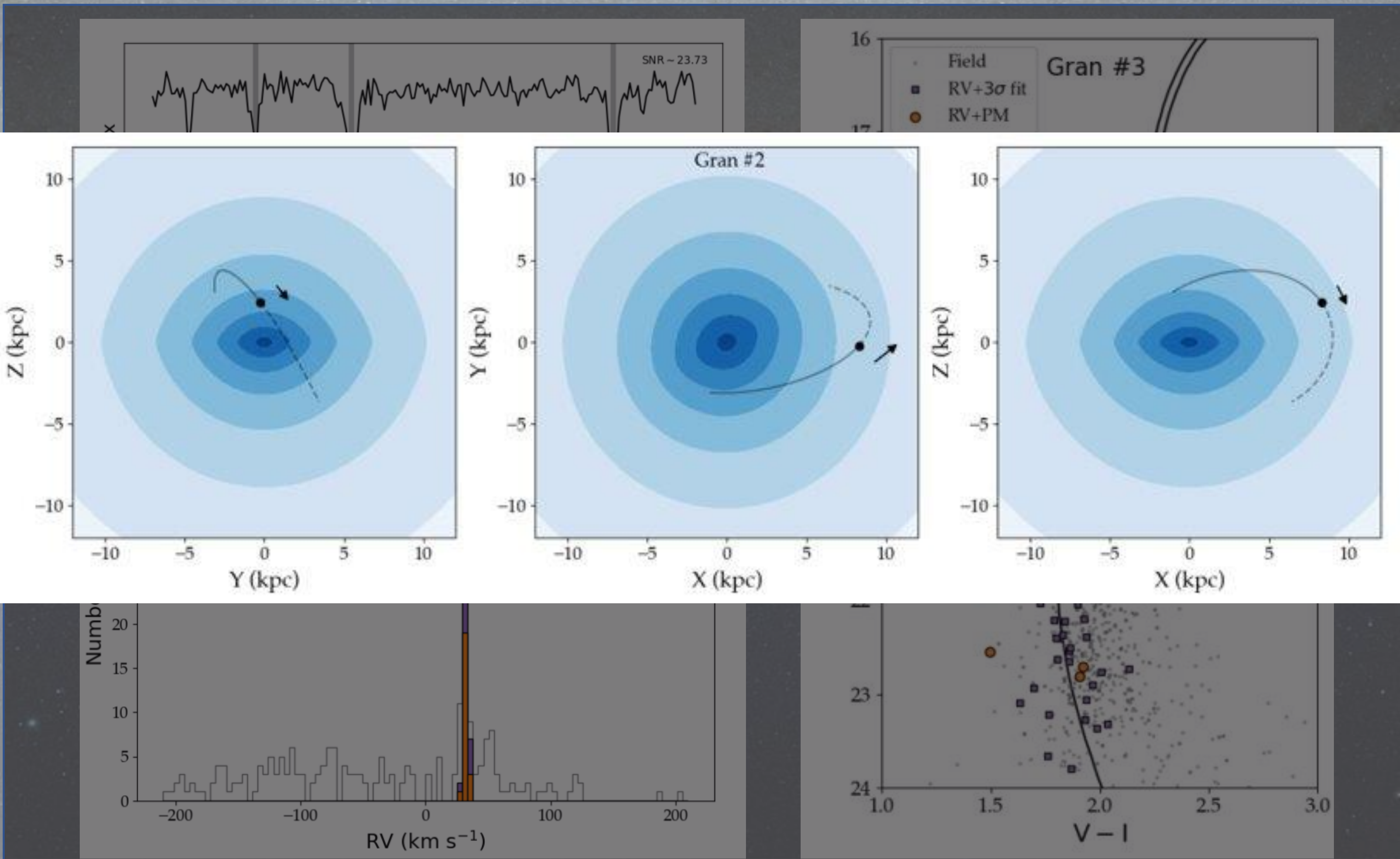






Gran et al. 2022

New GCs: MUSE observations



Gran et al. 2022

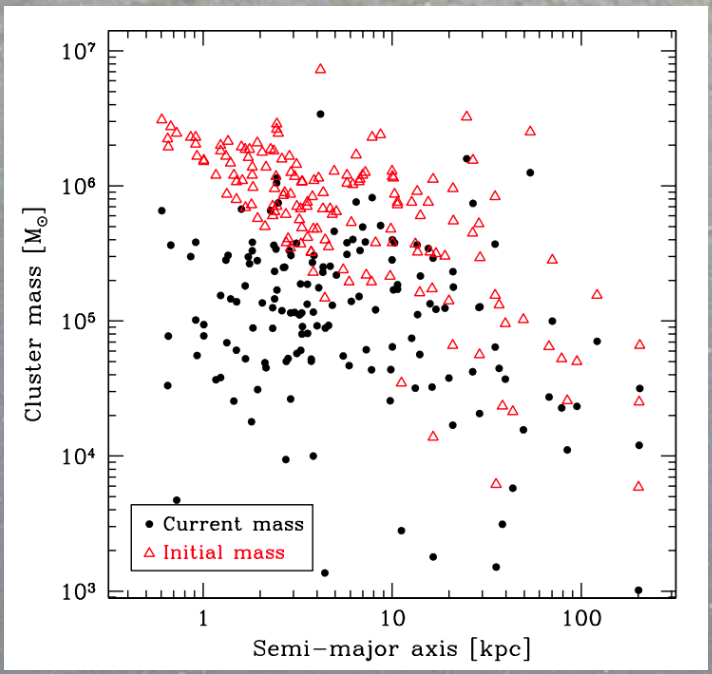
New GCs: MUSE observations

GC	σ_0 (km s^{-1})	$M^{\rm dyn}(< 1.8r_{\rm h})$ ($10^5 M_\odot$)	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

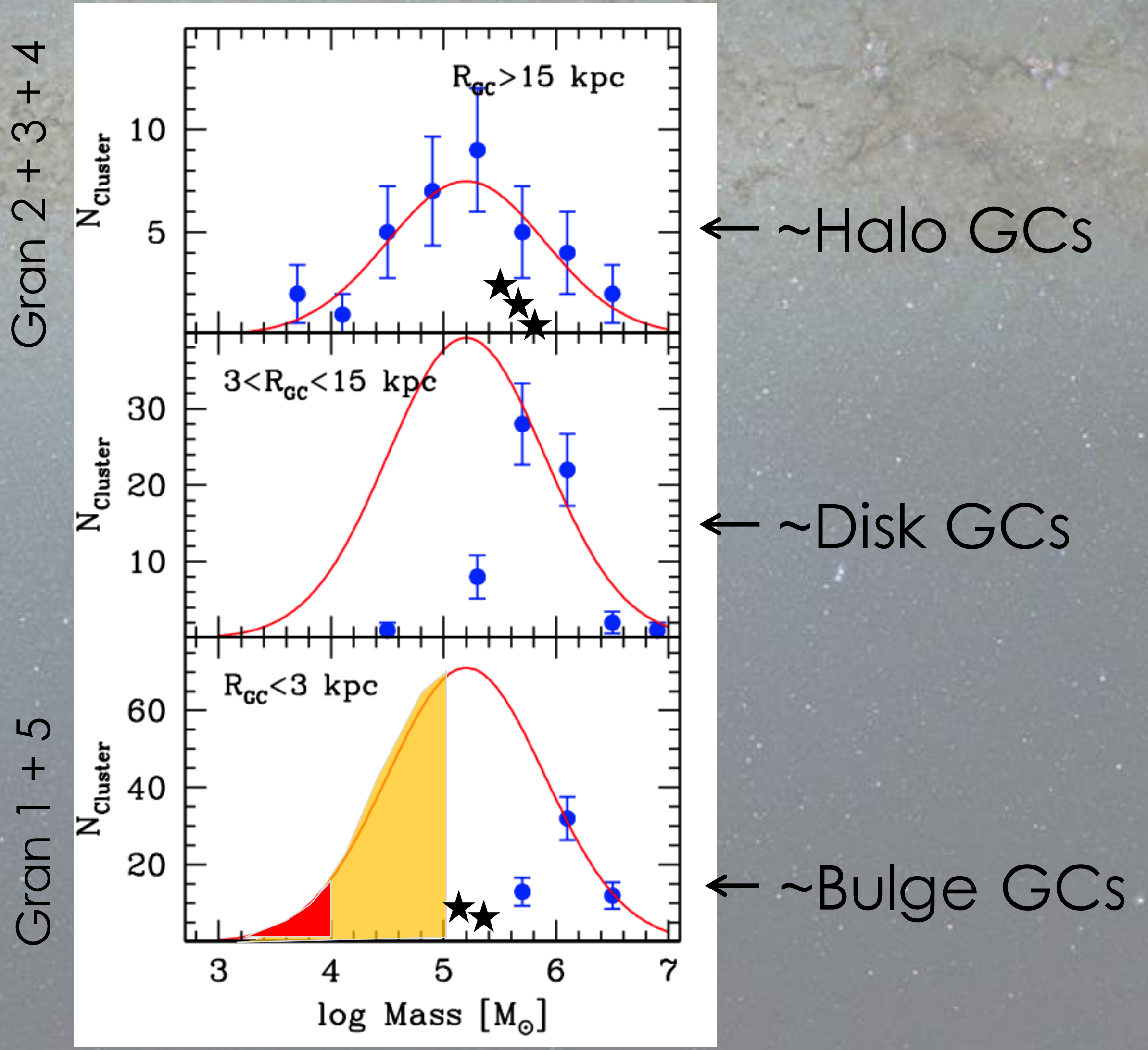
GC	RV (km s^{-1})	[Fe/H] (dex)	$V_{\rm HB}$ (mag)	e	$z_{\rm max}$ (kpc)	$r_{\rm peri}$ (kpc)	$r_{\rm apo}$ (kpc)	L_z (kpc^2 Myr^{-1})	$E_{\rm tot}$ (kpc^2 Myr^{-2})
Gran 1	32.30 ± 1.87	-1.19 ± 0.19	19.08	0.76	0.38	0.31	2.22	0.03	-0.21
Gran 2	53.22 ± 1.67	-2.07 ± 0.17	18.59	0.34	5.44	4.59	9.24	0.79	-0.16
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

Gran et al. 2022

New GCs: Galactic context
Initial mass distribution



Baumgardt et al. 2018

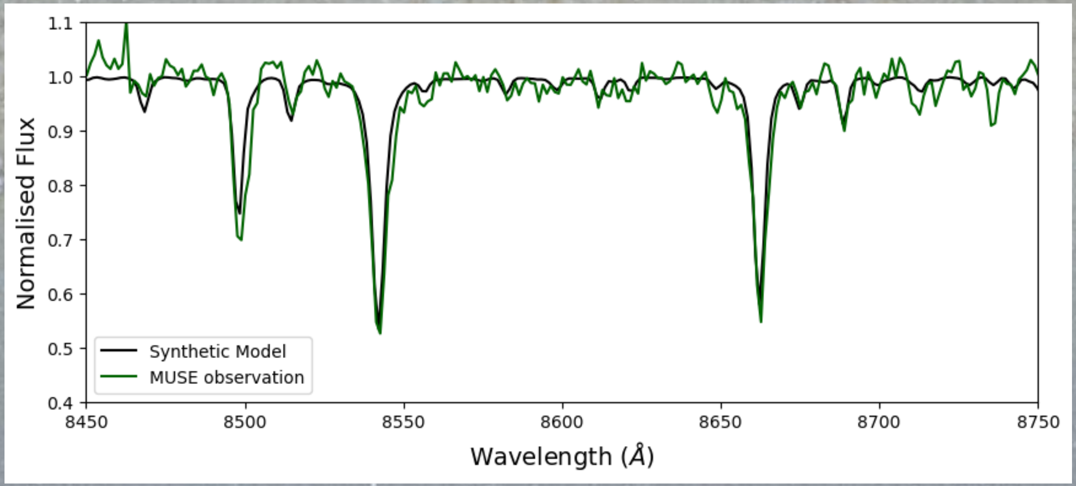


Summary

- ★ 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

★ Derive clusters metallicity via synthetic models



★ WEAVE survey: homogenisation of contributed catalogues into a common reference frame

Thanks for your attention!

fgran@oca.eu
fegran.github.io

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