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

Felipe Gran (OCA)
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CION –1 C1-20

Slides available at:
fegran.github.io/files/OCA-Seminar-FGran.pdf

OCA/Lagrange Seminar – December 13, 2022

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

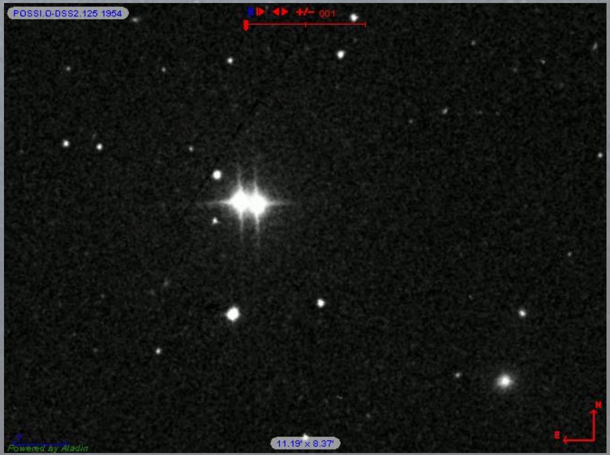
Gran et al. 2019

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

Key concept #1: stellar proper motions

POSS1, POSS2, DSS

Steve Quirk,
Wikipedia Commons

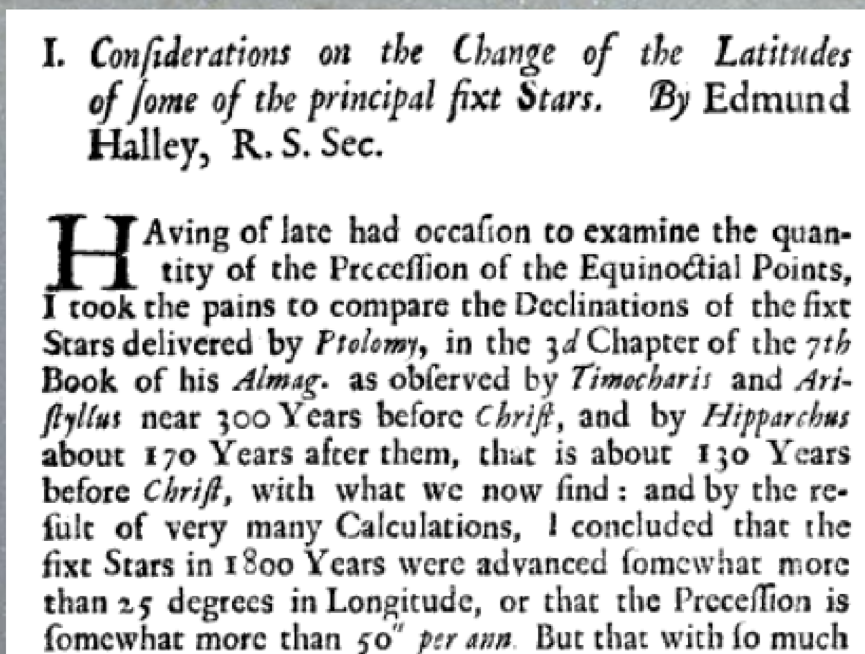


DSS/STScI

Key concept #1: stellar proper motions

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

- ★ Halley 1717: ~**few** stars



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

HAving of late had occafion to examine the quantity of the Preceffion 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 obferved by *Timocharis* and *Ariftyllus* near 300 Years before *Chrift*, and by *Hipparchus* about 170 Years after them, that is about 130 Years before *Chrift*, with what we now find: and by the refult of very many Calculations, I concluded that the fixt Stars in 1800 Years were advanced fomewhat more than 25 degrees in Longitude, or that the Preceffion is fomewhat more than 50″ *per ann.* But that with fo much

Halley 1717

POSS1, POSS2, DSS

Steve Quirk, Wikipedia Commons

Key concept #1: stellar proper motions

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

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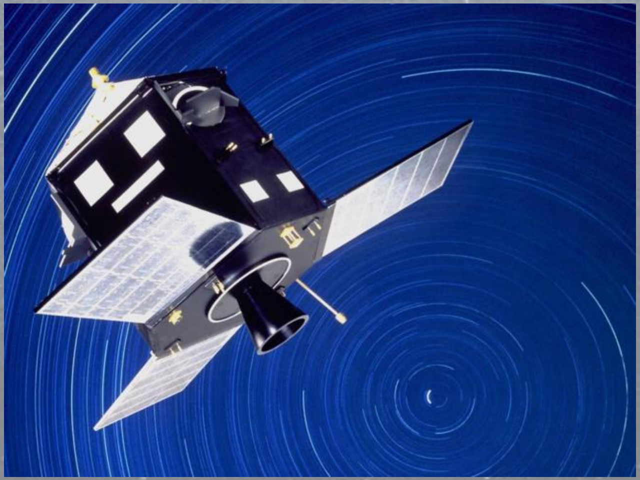
POSS1, POSS2, DSS



ESA, Hipparcos

Steve Quirk, Wikipedia Commons

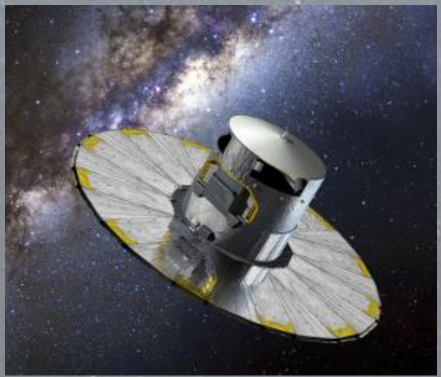
Key concept #1: stellar proper motions

★ 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

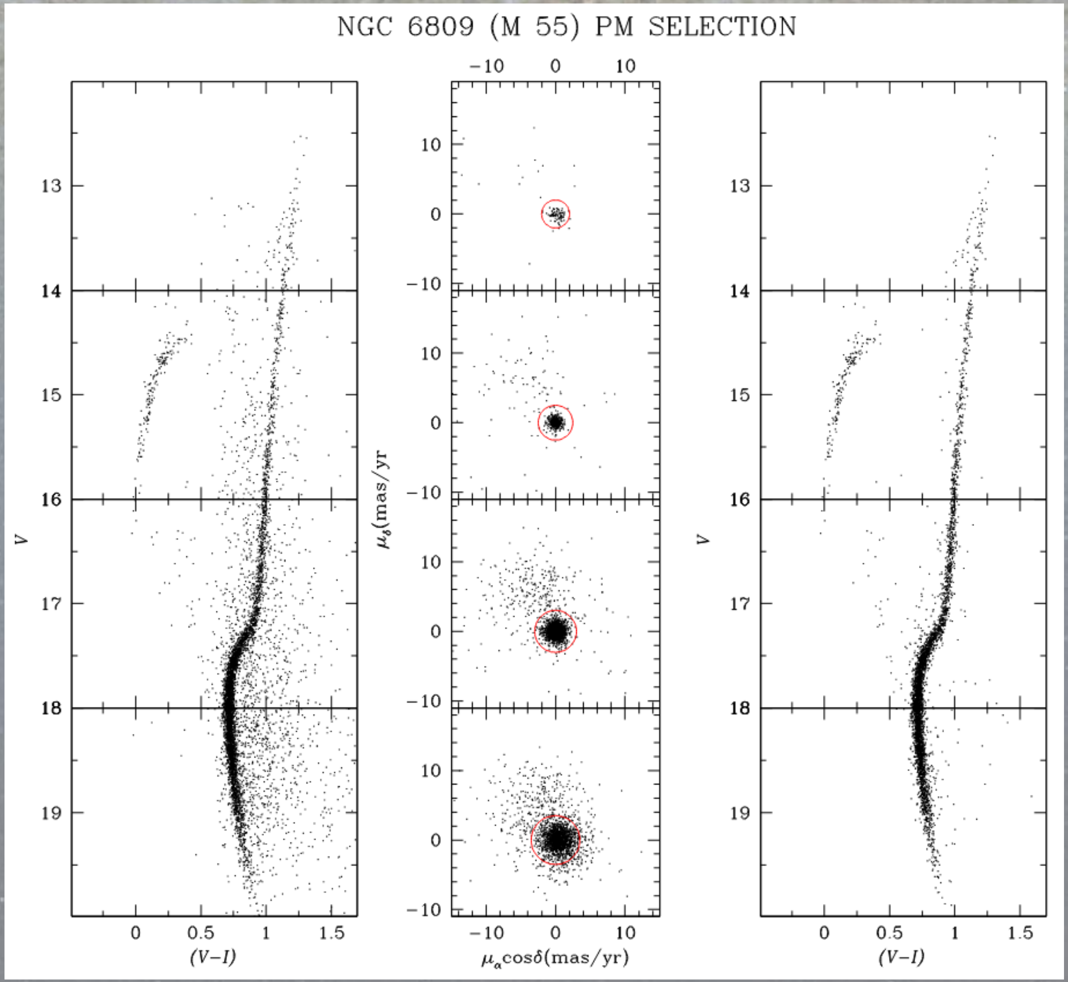
Steve Quirk,
Wikipedia Commons



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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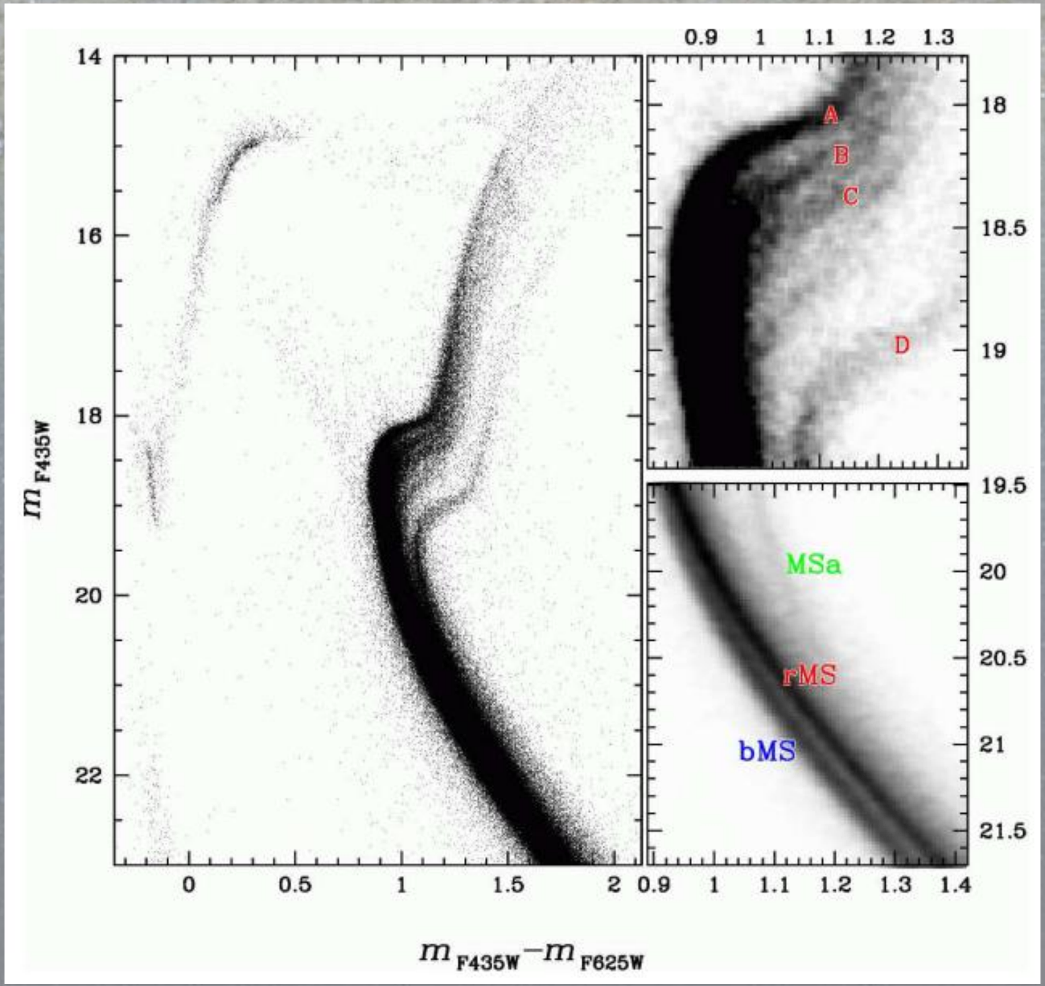

Bellini et al. 2010, 2017

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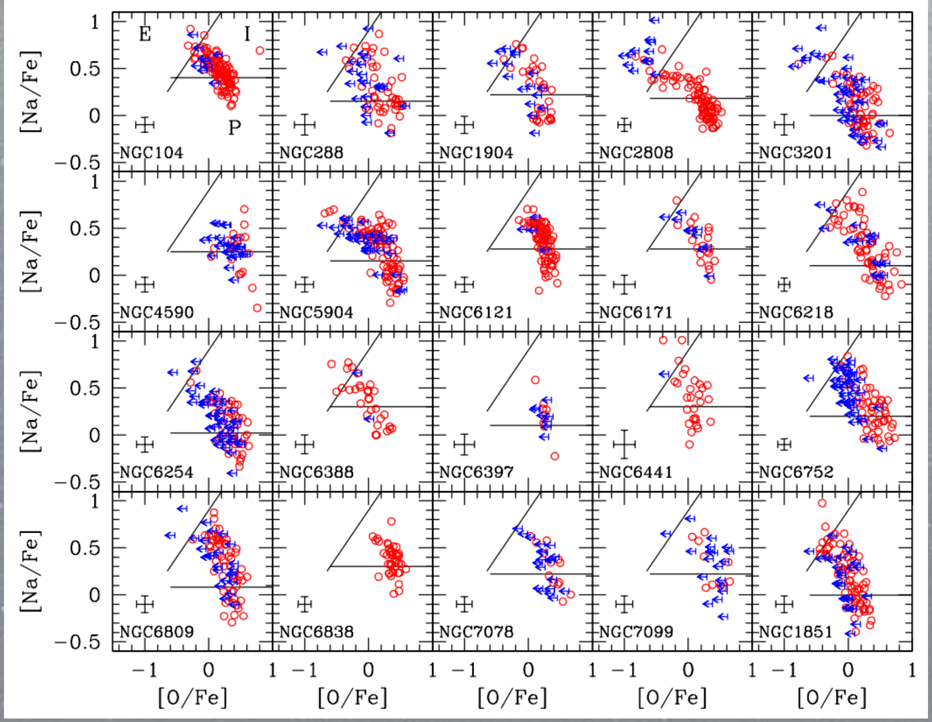


Carretta et al. 2009

★ Fe enrichment in only a limited cases: massive clusters

★ Light-element (proton capture) variations:

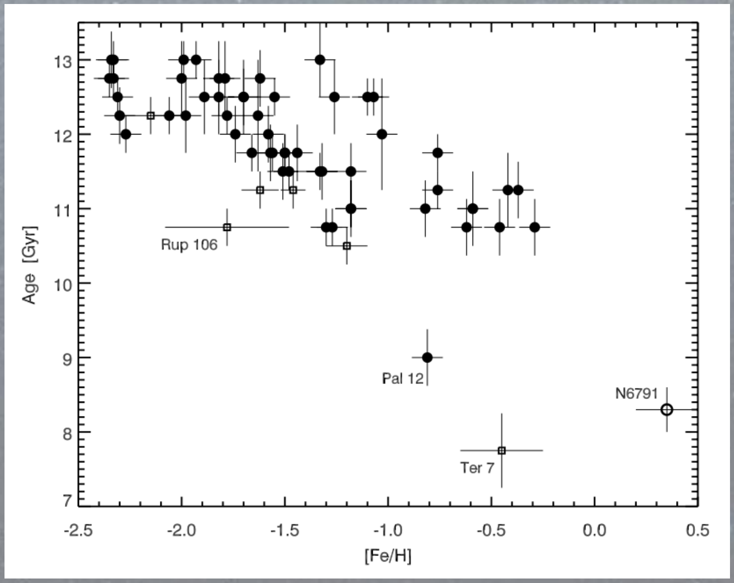
- ★ C, N, O, Na, Mg, Al, Si, … among others!

★ 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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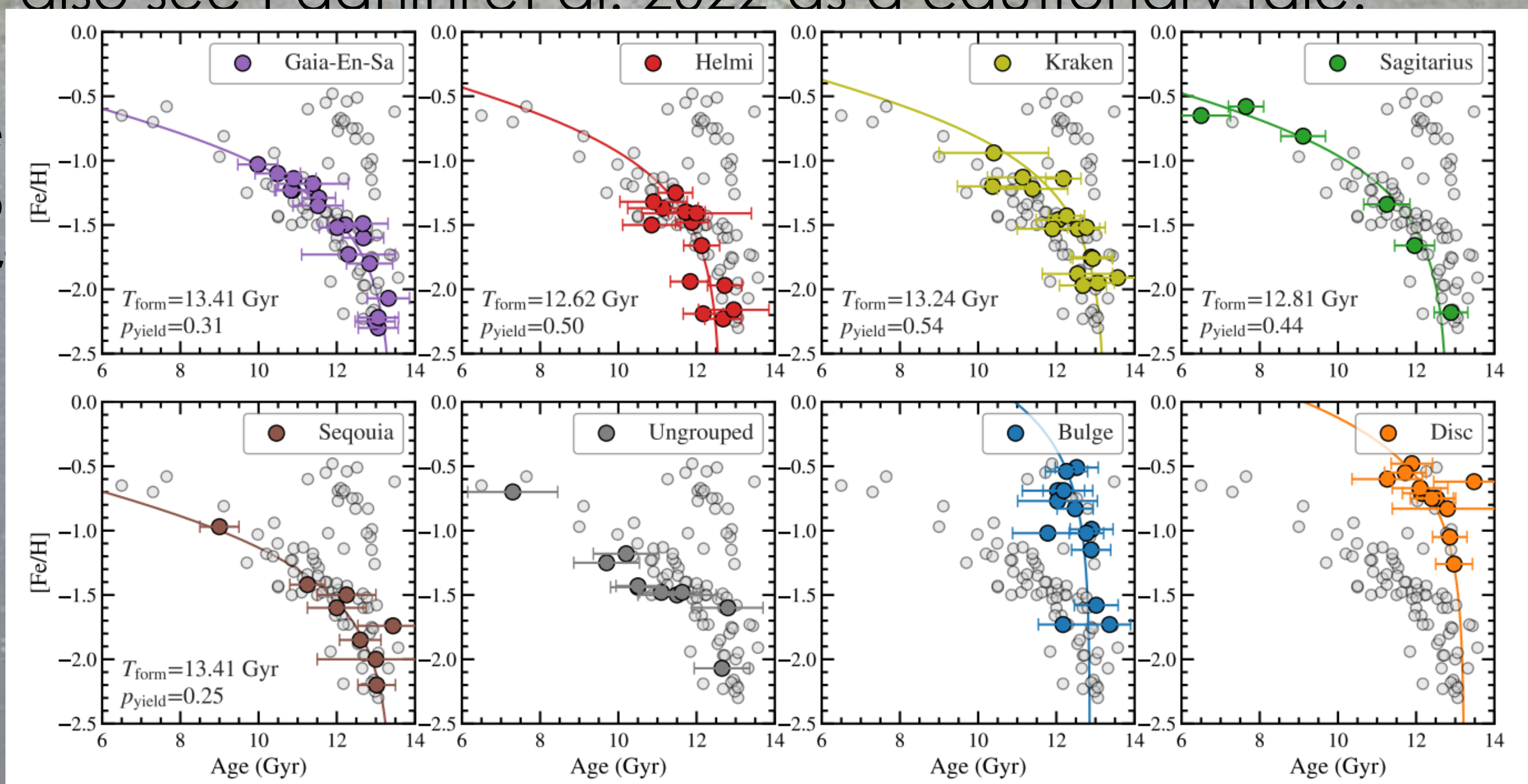
- ★ We … ry lab… **enr…**



Callingham et al. 2022

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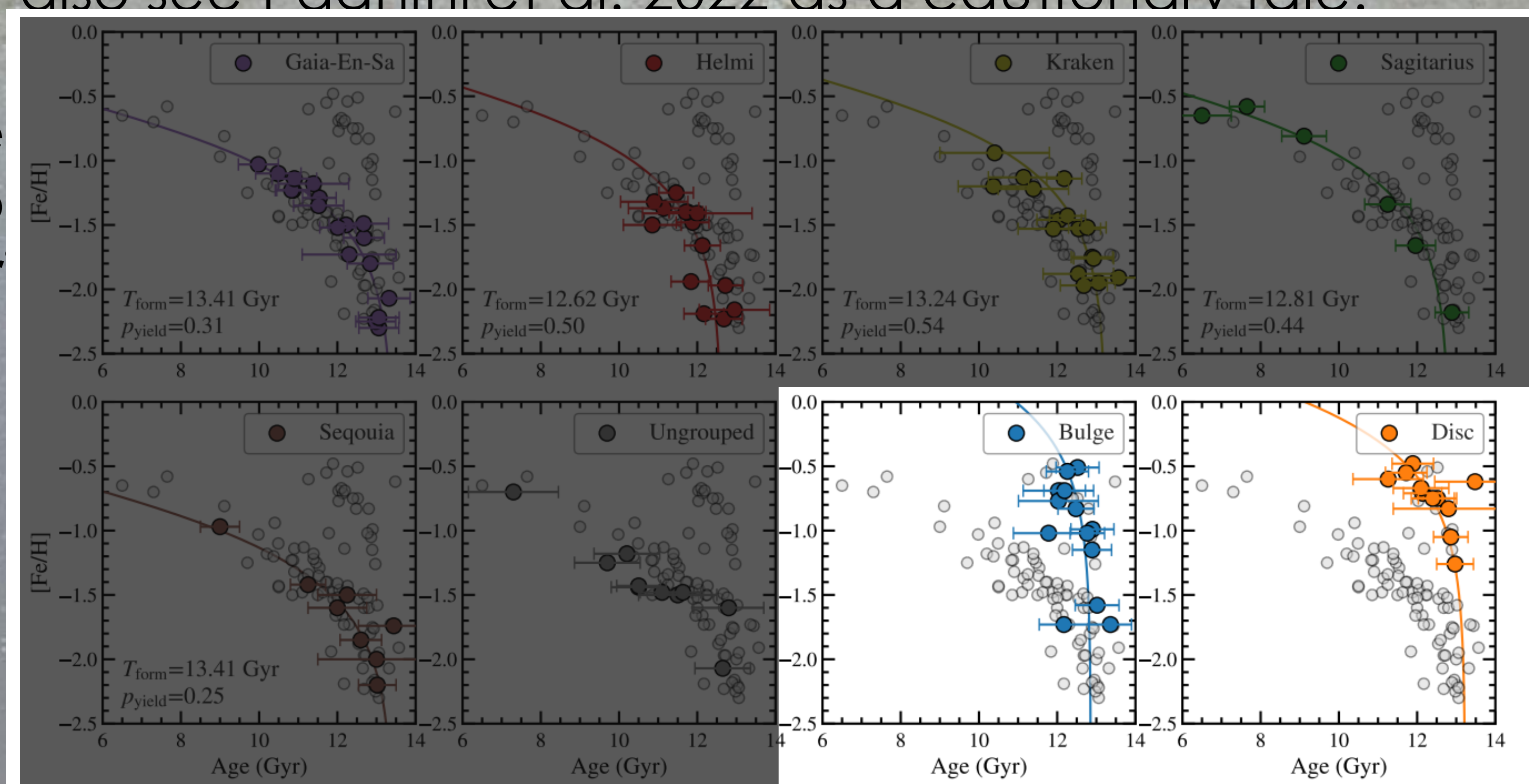


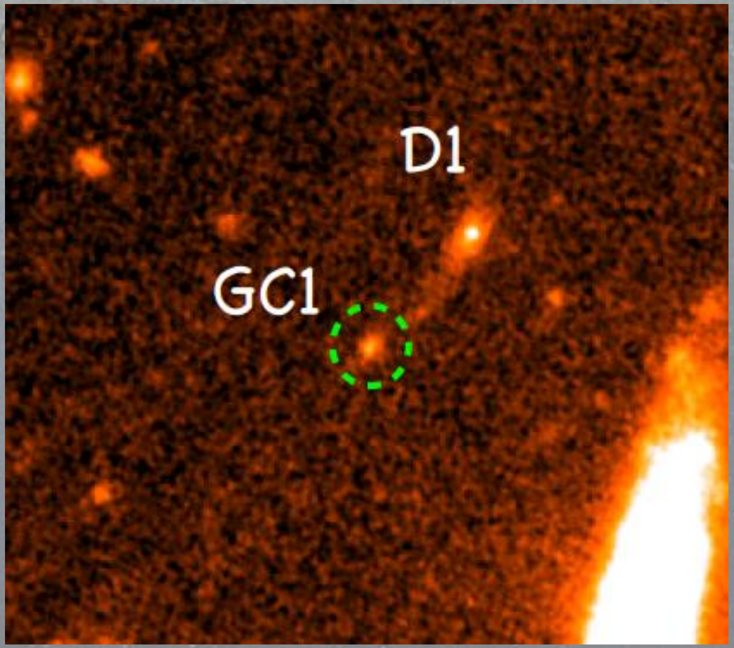
Callingham et al. 2022

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**.

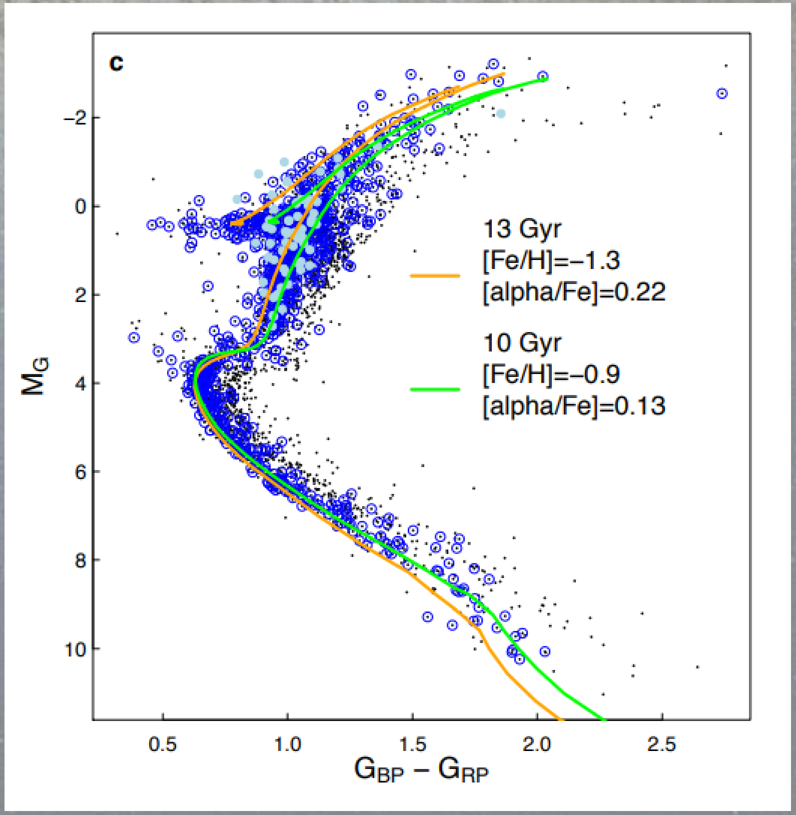


Vanzella et al. 2017

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

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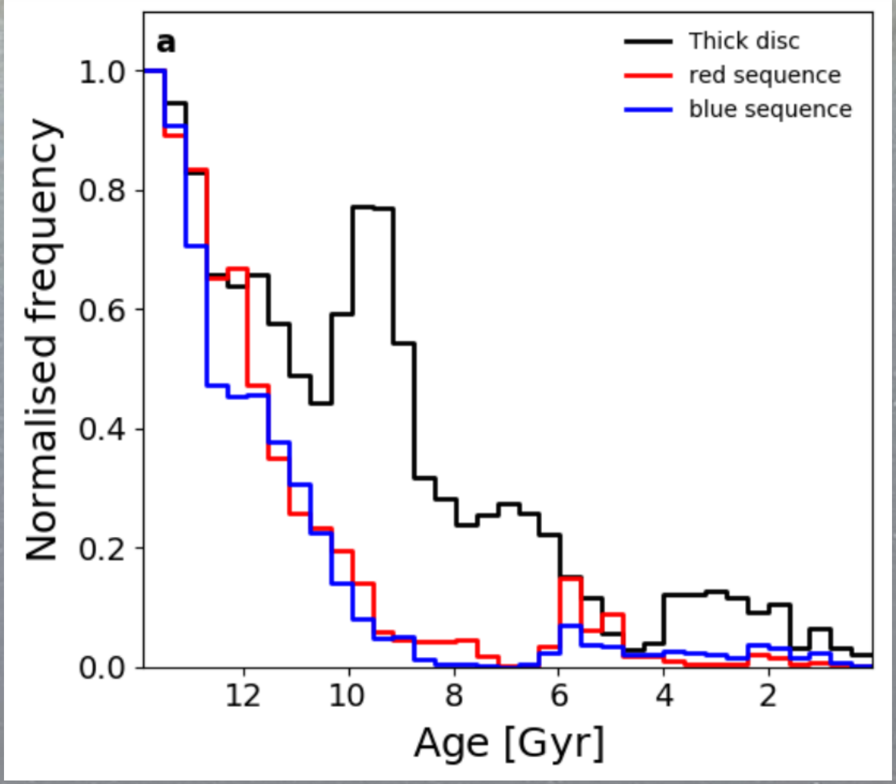

Gallart et al. 2019

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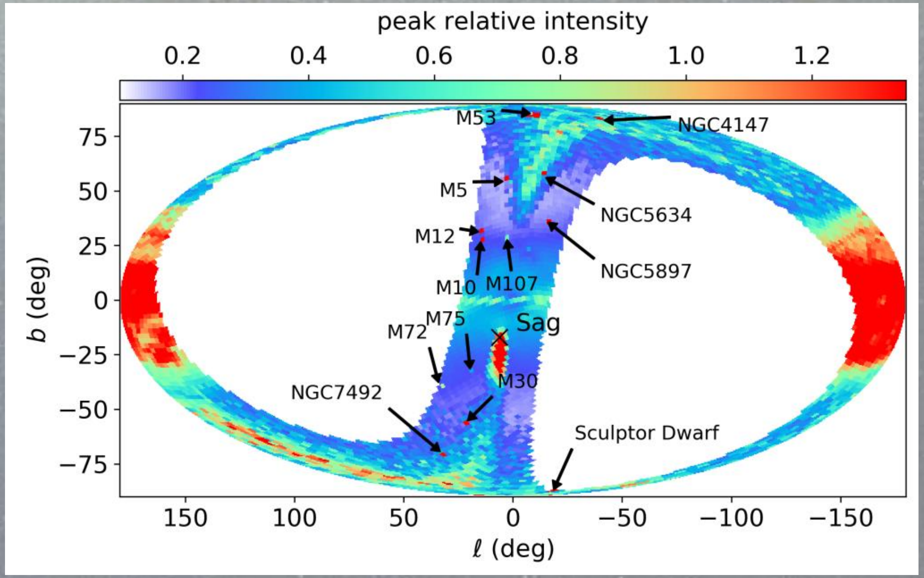

Antoja et al. 2020; Ramos et al. 2020

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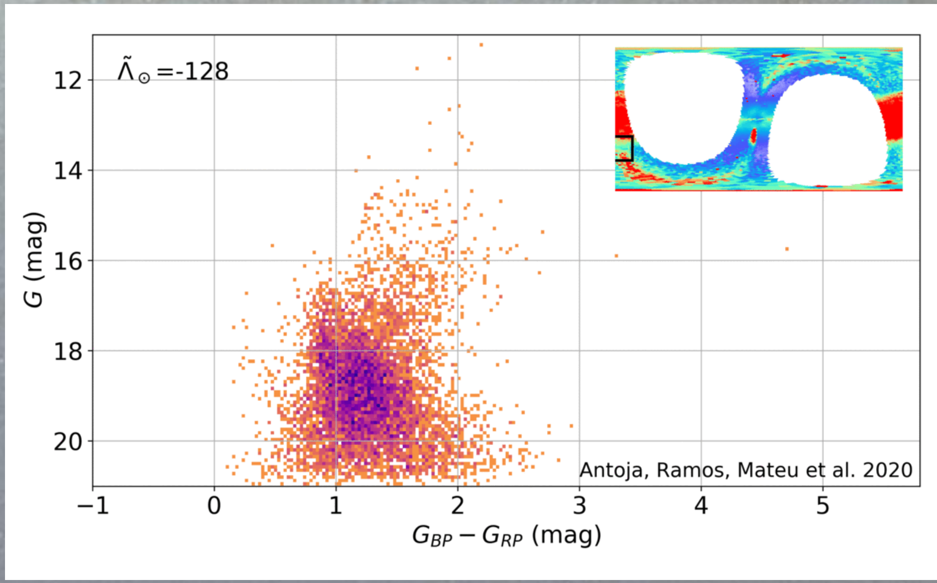

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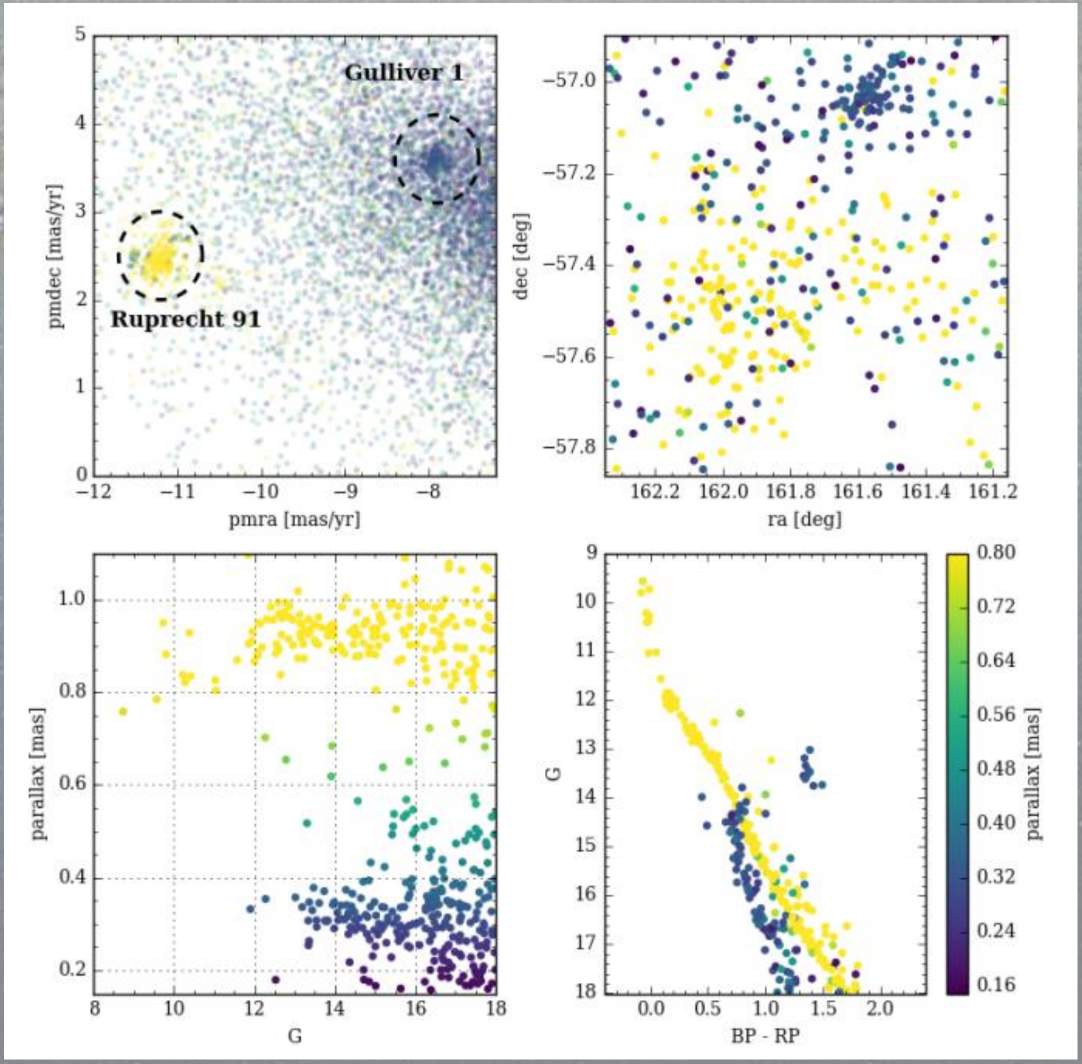
Key concept 1+2+3 = #6: proper motions to isolate different stellar populations

★ **CLUSTER SCIENCE!**



Cantat-Gaudin et al. 2018

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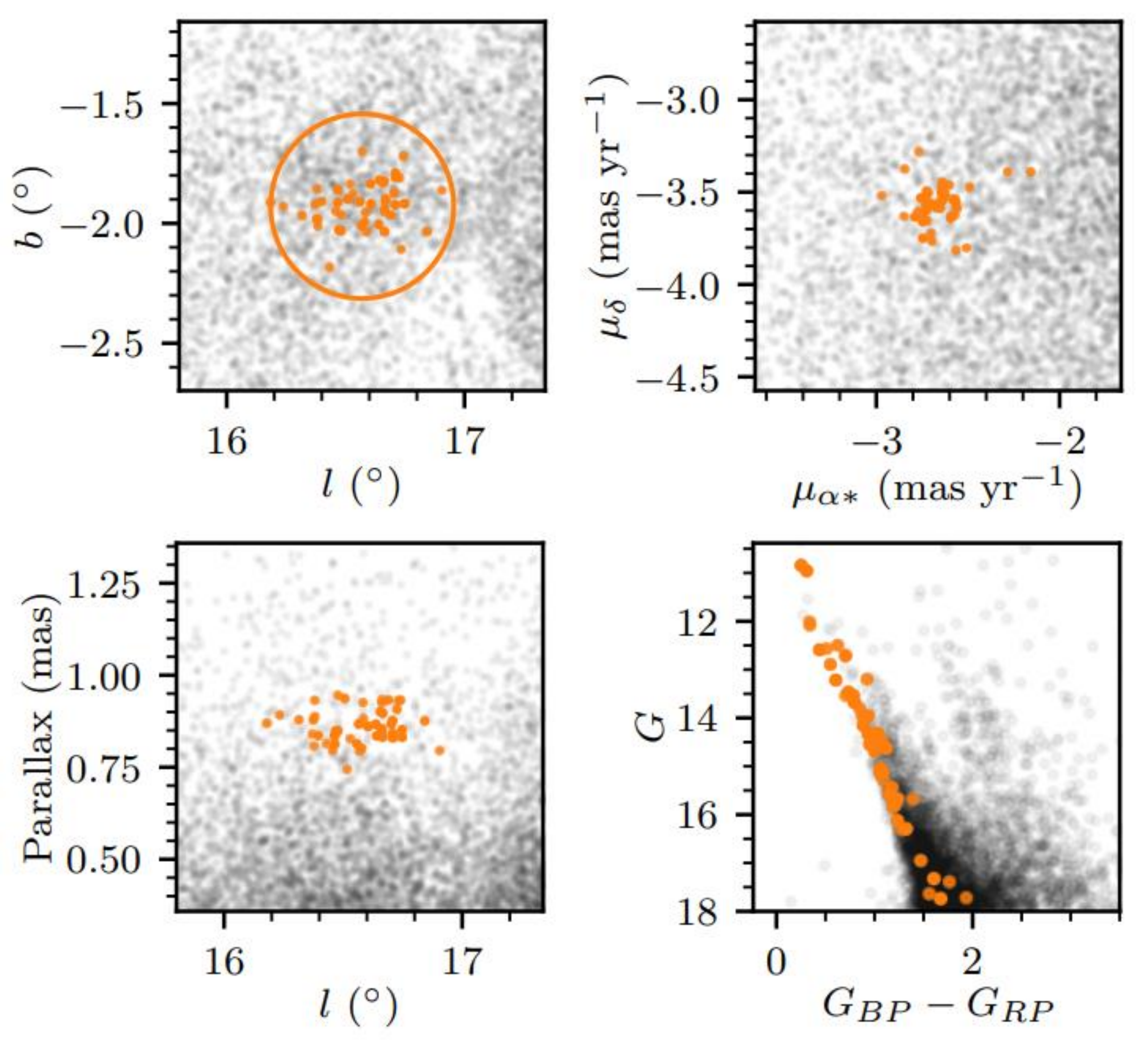
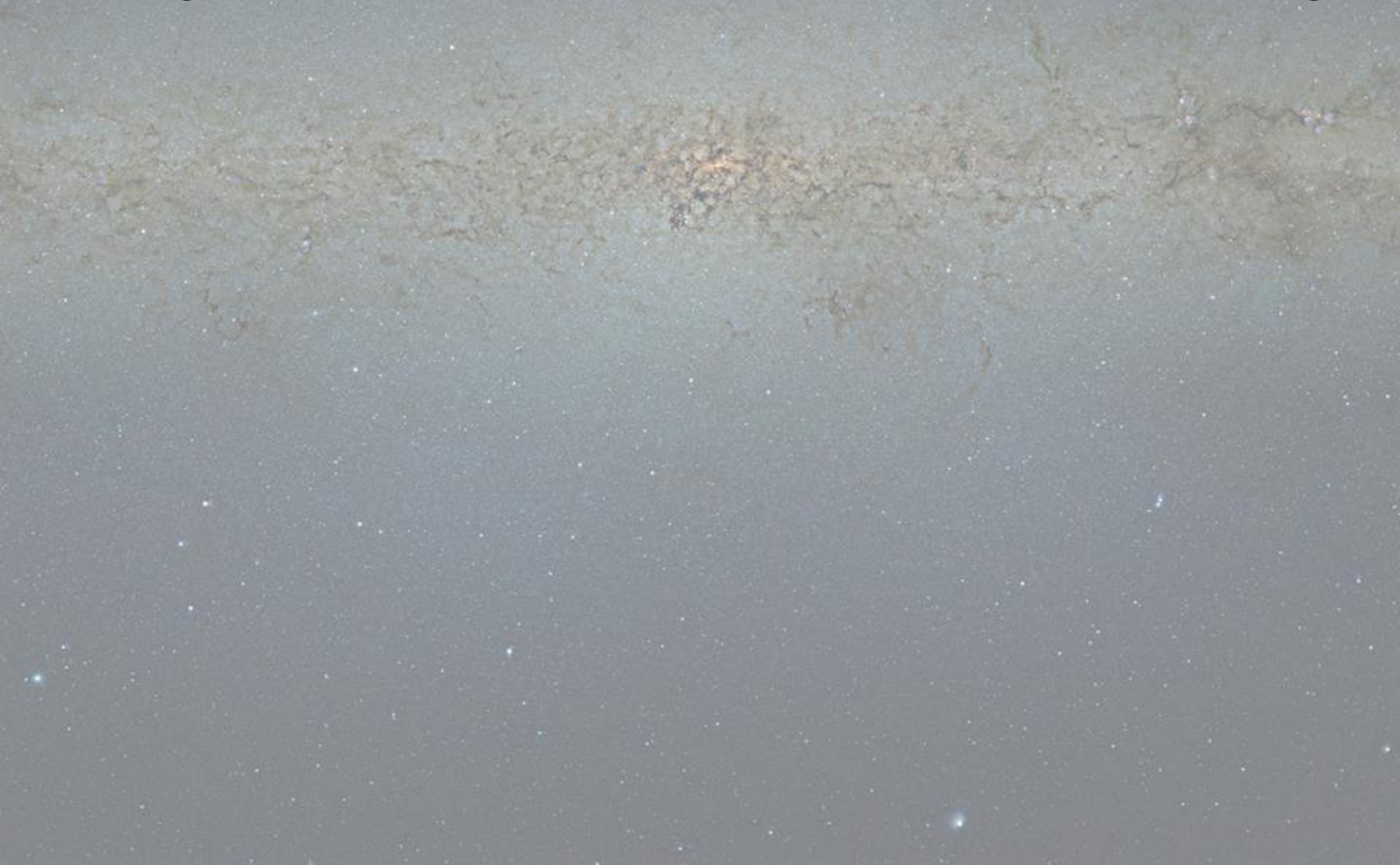


Hunt & Reffert 2021

Hidden in the haystack:

New globular clusters towards the Milky Way bulge



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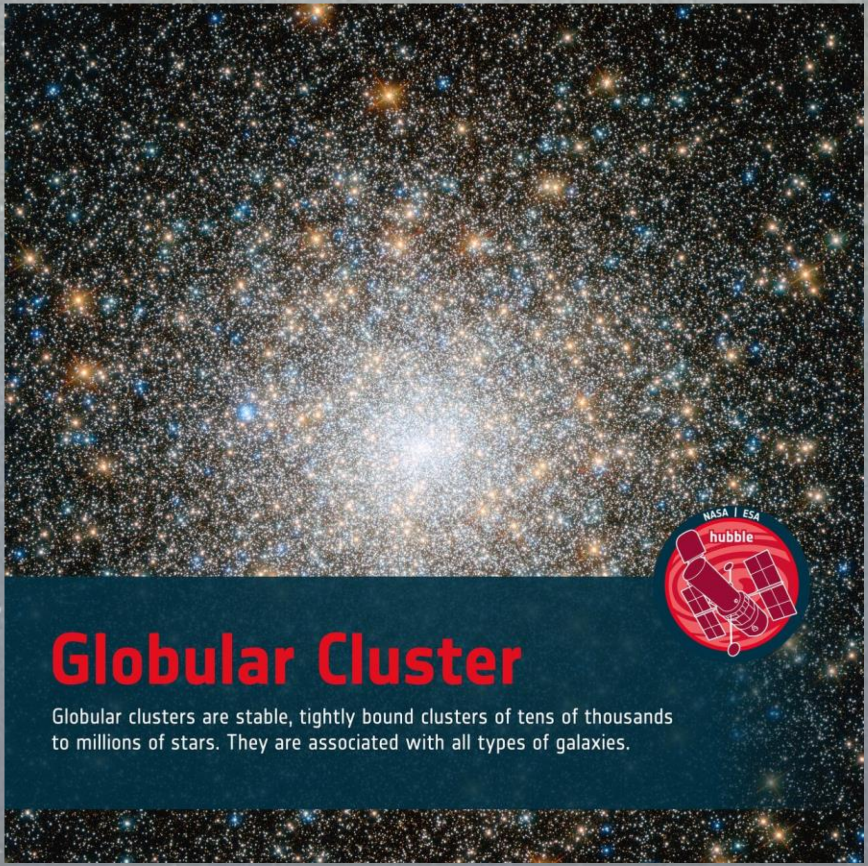

Credit: NASA & ESA

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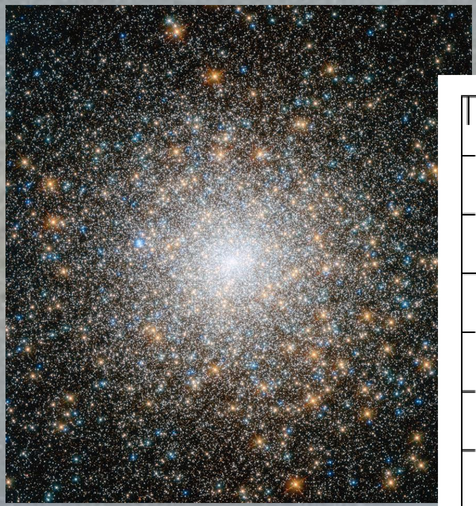
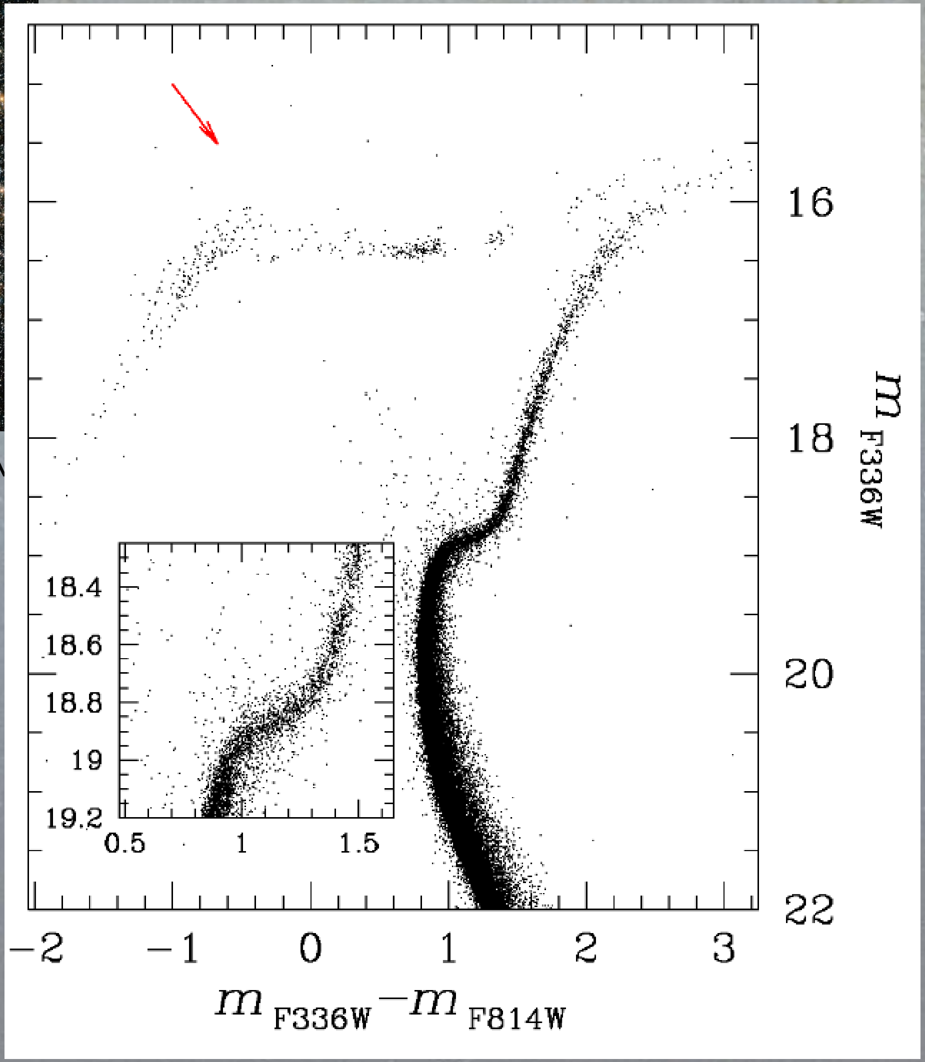


Credit: NASA & ESA



Nardiello et al. 2018

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

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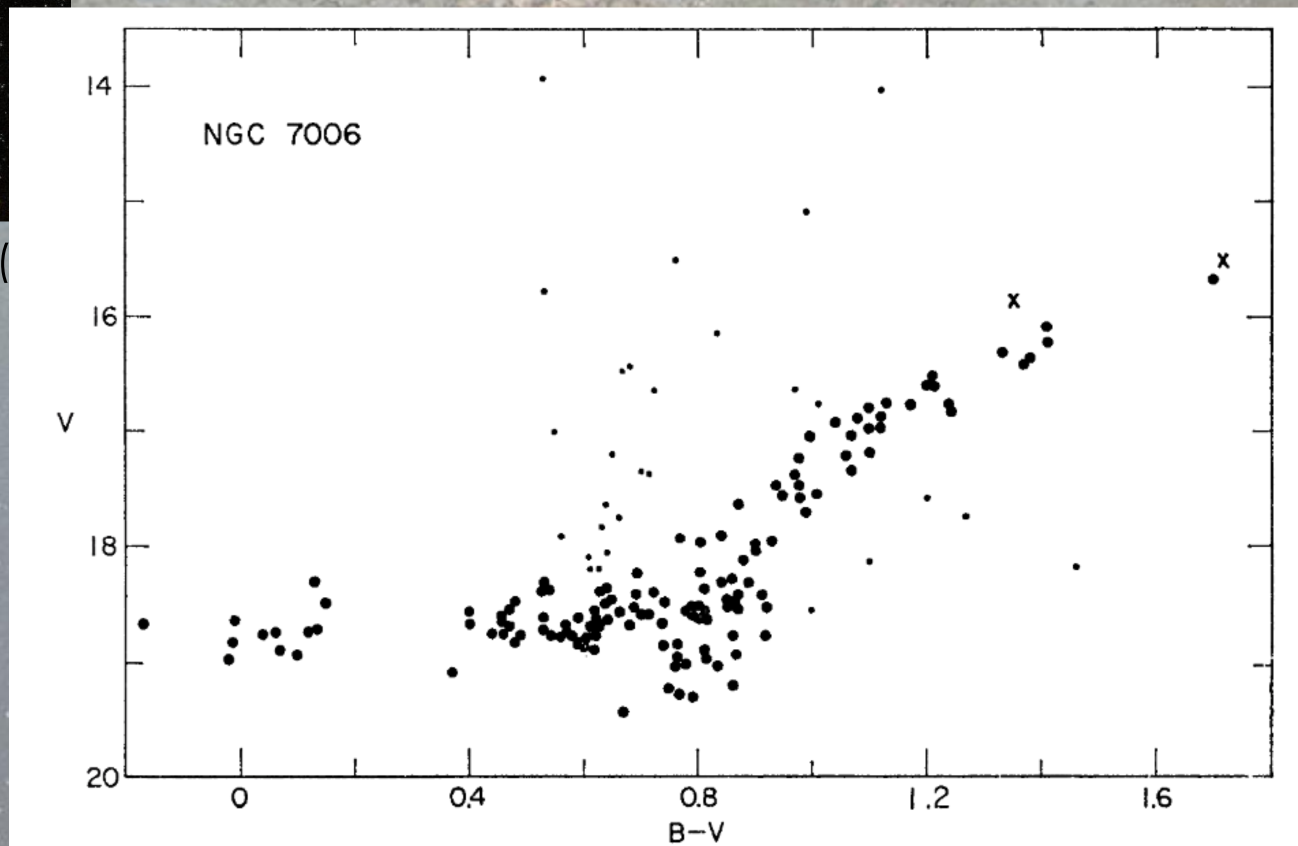

Sandage & Widley 1967

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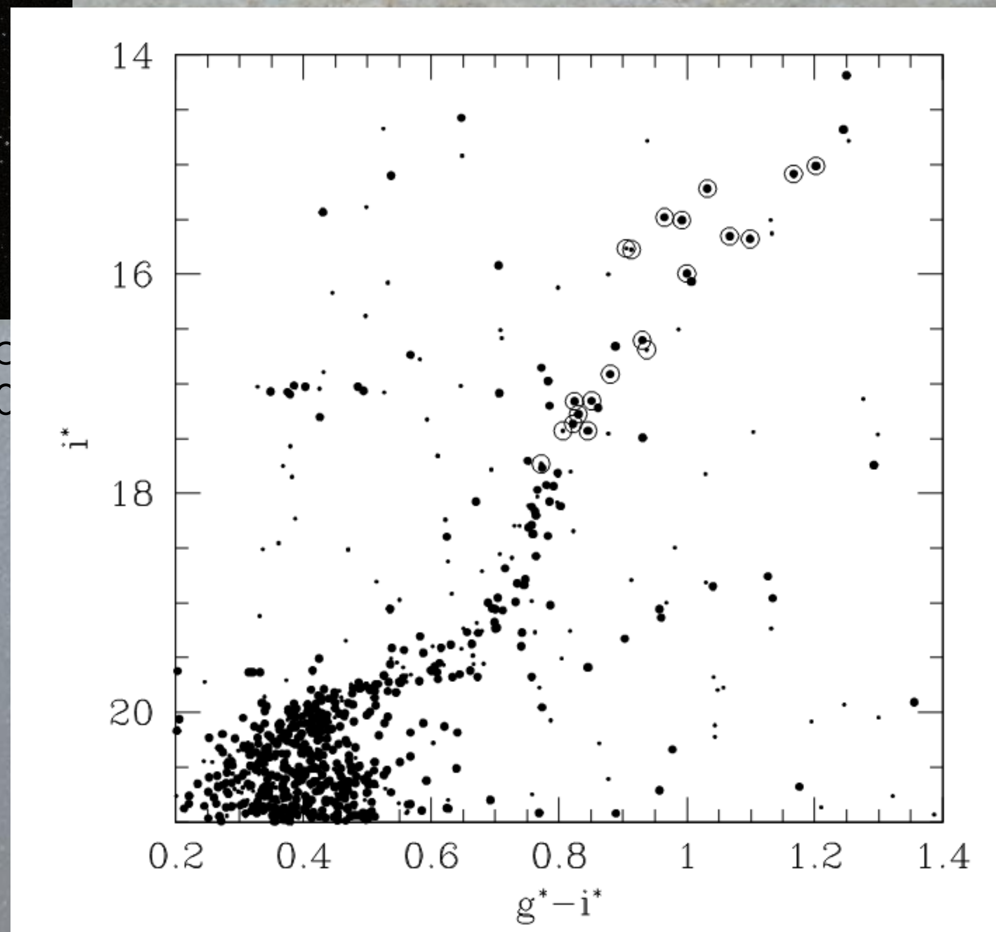

Odenkirchen et al. 2002

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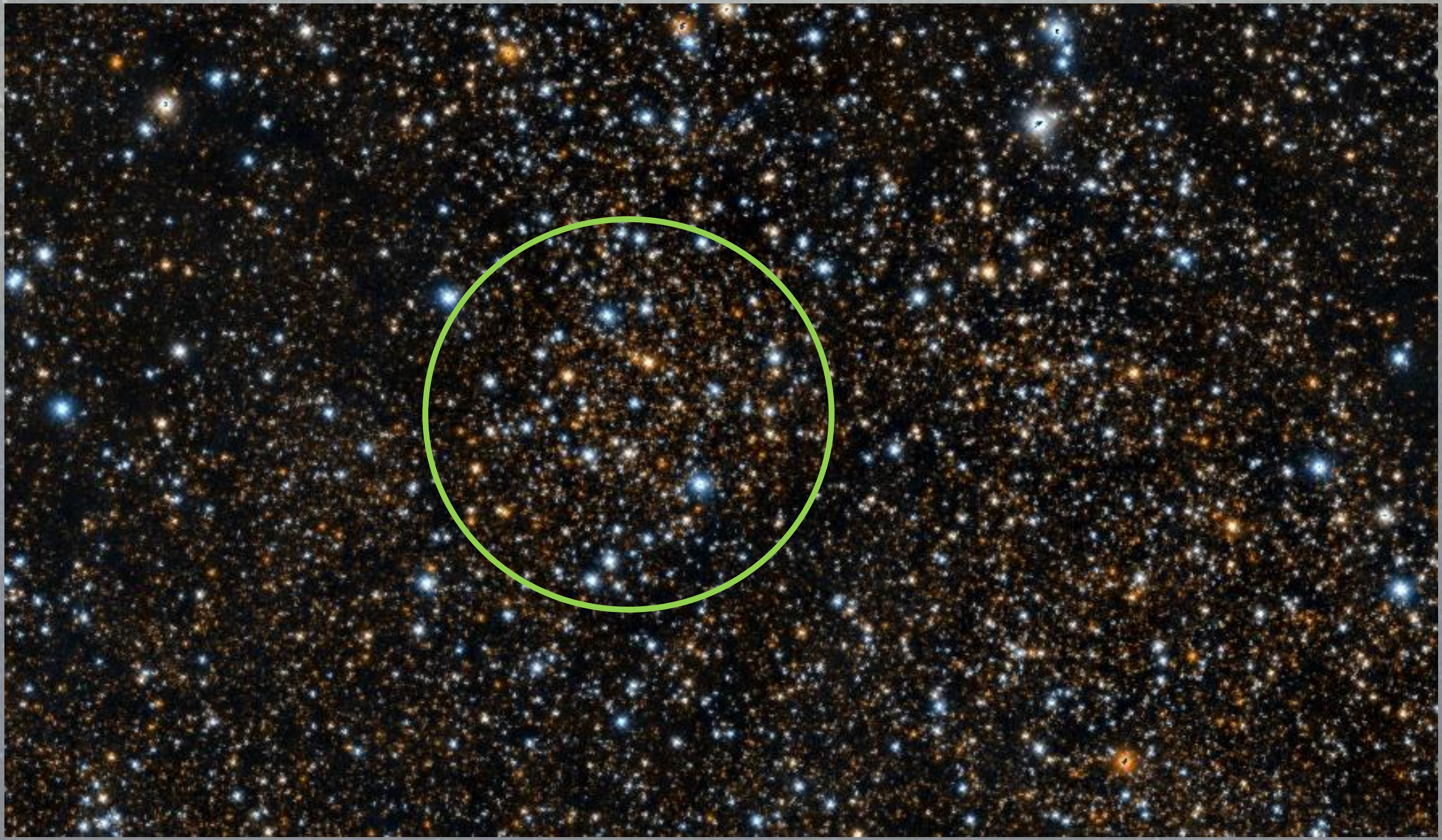

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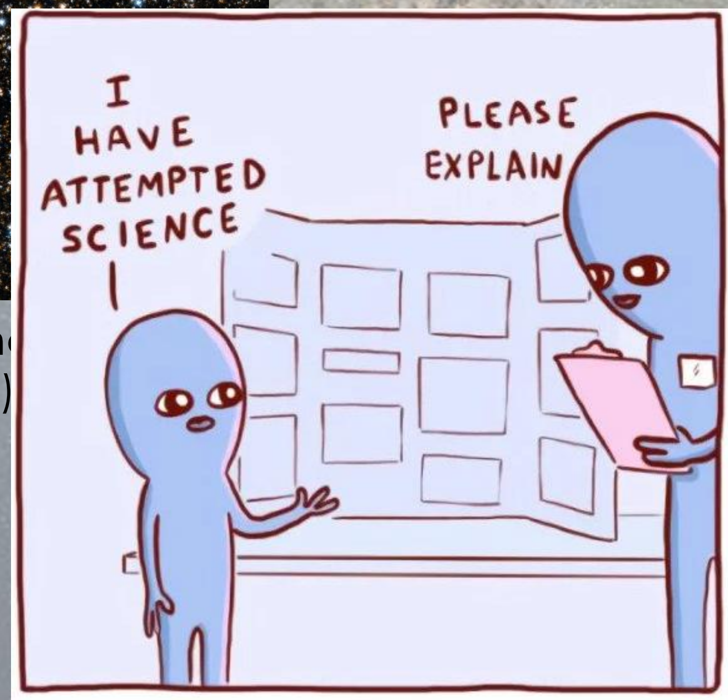

@nathanwpyle: STRANGE PLANET

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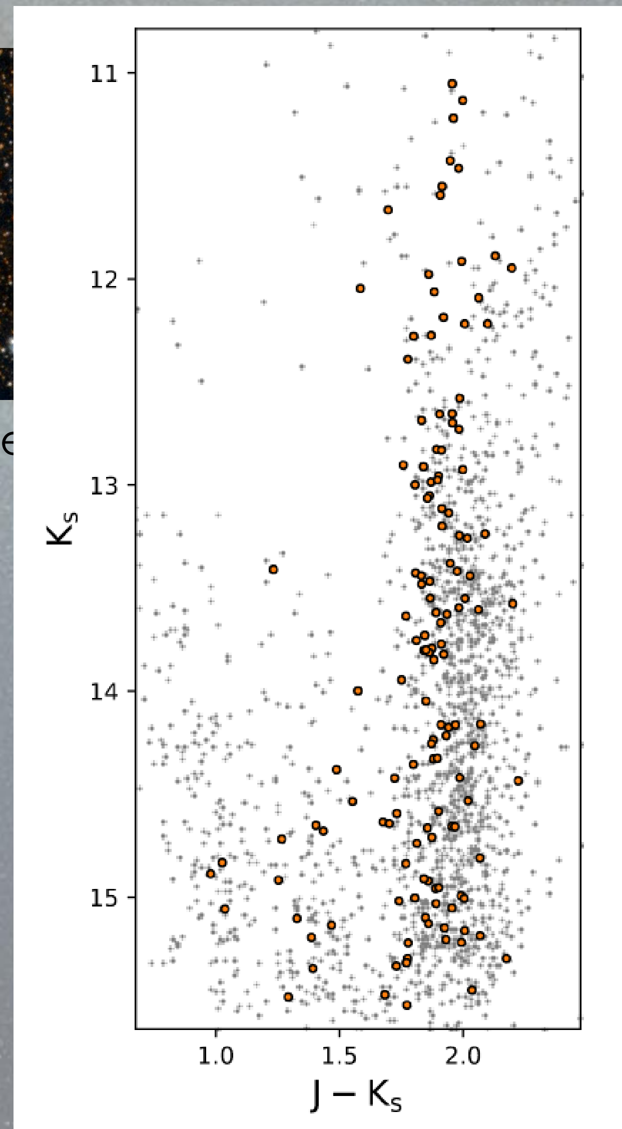

Gran et al. 2019

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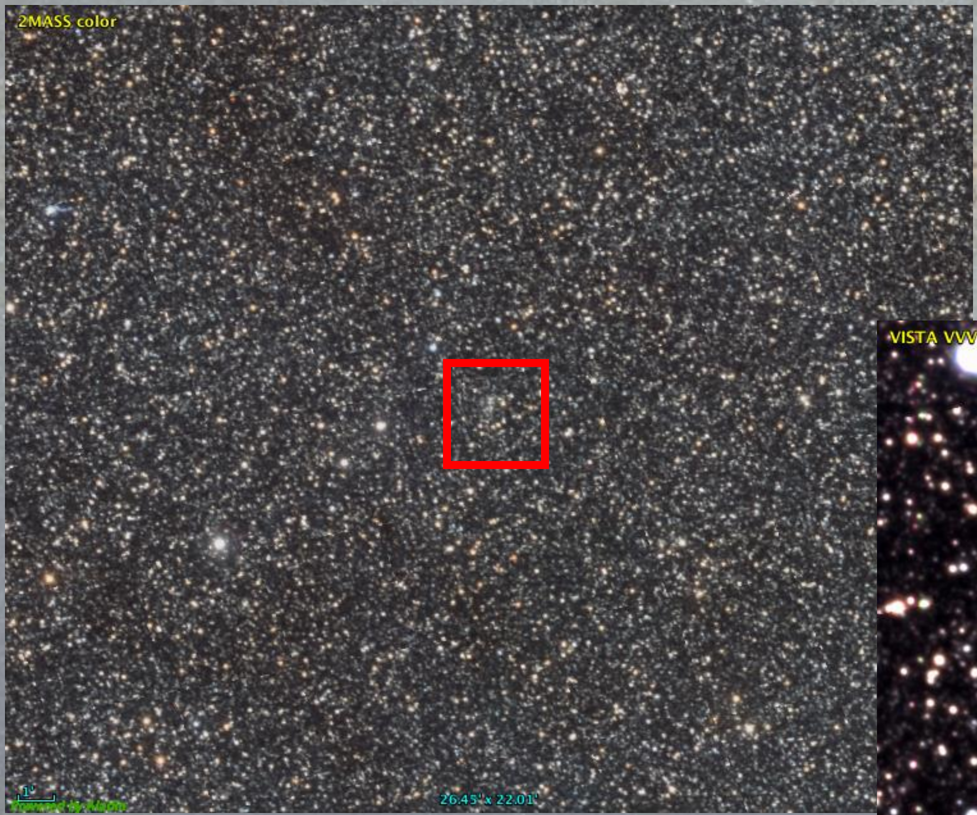

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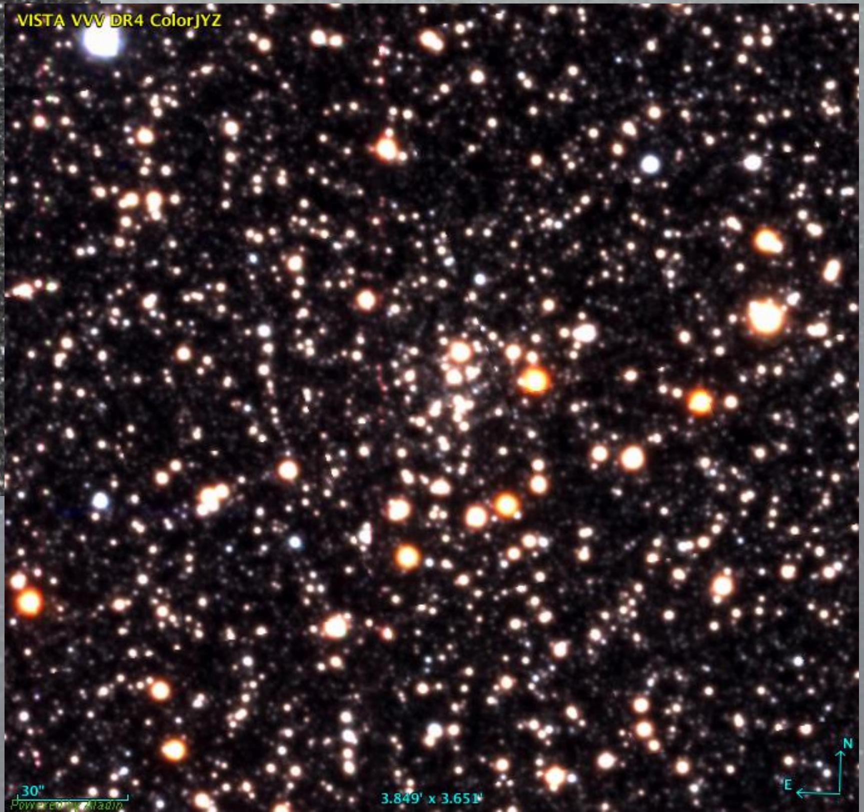

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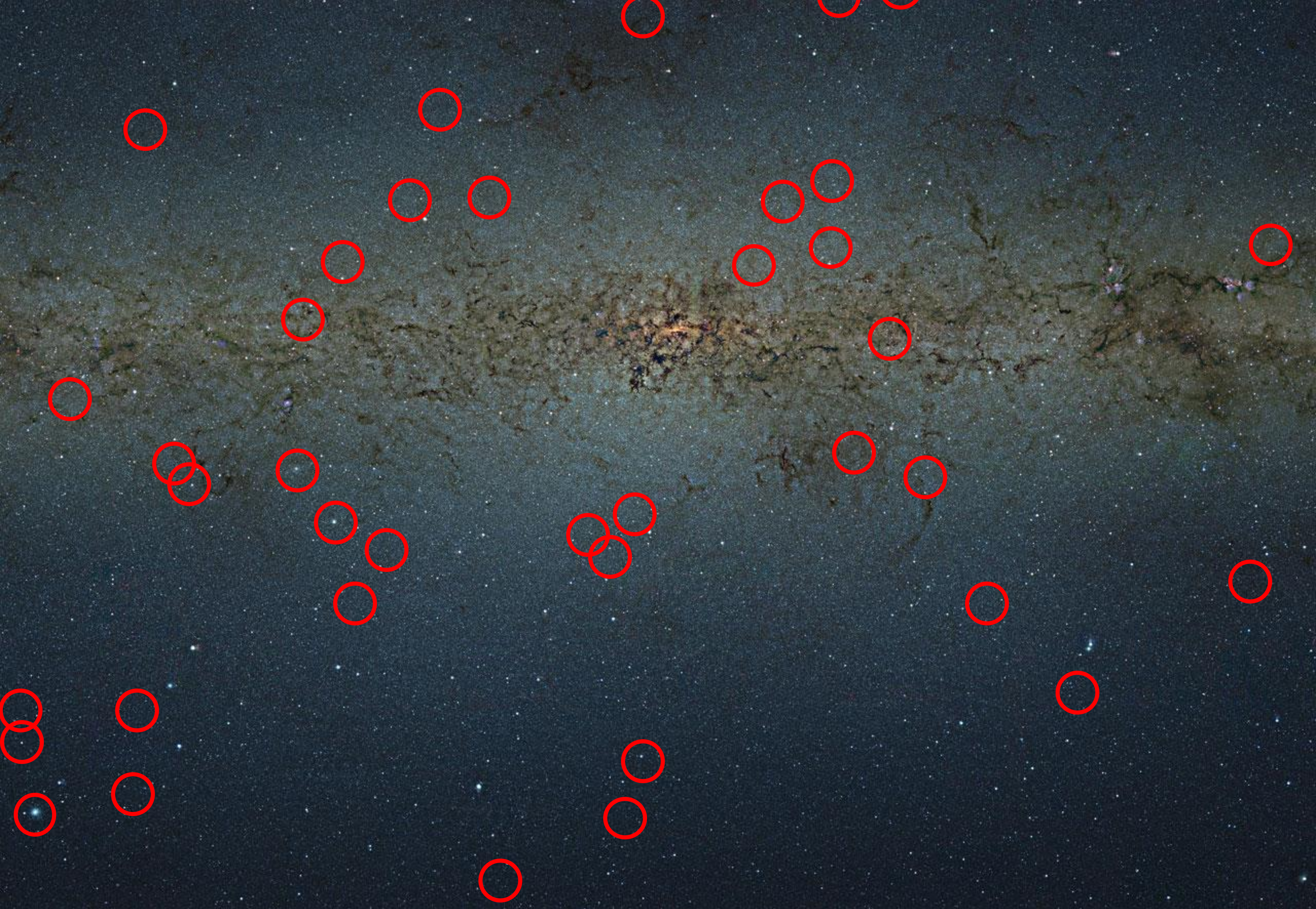
- ★ Valuable tracers of understand the Milky Way evolution
- ★ Galactic bulge GCs compose a major part of the ***in situ*** component (Myeong et al. 2018)
- ★ The total number of GCs in the Milky Way is still **unknown**



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

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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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. Bica[3] and B. Barbuy[4]†

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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

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

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

K… …AR CLUSTER IN THE CONSTELLATION OF CENTAURUS

Dongwon… …Mackey, Gary S. Da Costa, and Antonino P. Milone
Research School of Astr… …l University, Canberra, ACT 2611, Australia; dongwon.kim@anu.edu.au

Re… …February 12; published 2016 March 29

DISCOVERY OF A FAINT O… …CLUSTER IN THE SOUTHERN SKY

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dongw…

Received 2015 January 1; accepted 20…

A NEW DISTANT MILKY WAY GLOBULAR CLUST… …RVEY

Segue 3: the youngest globular cluster in th…

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THE DISCOVERY OF TWO EXTREMELY LO…

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N. W. Evans,[2] G…

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Research School of Astro… …ongwon.kim@anu.edu.au

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…RY OF A FAINT O… …N THE SOUTHERN SKY

…nd Gary S. Da Costa
…tter Road, Weston, ACT 2611, Australia;

STAR CLUSTER IN THE CONSTELLATION OF URSA MINOR[*]

…A. Santana[2], P. Stetson[3], J. D. Simon[4], and S. G. Djorgovski[5,6]
…University, New Haven, CT 06520, USA
…Observatorio 1515, Las Condes, Santiago, Chile; rmunoz@das.uchile.cl
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…3 Santa Barbara Street, Pasadena, CA 91101, USA
…hnology, Pasadena, CA 91125, USA

…; published 2012 June 15

…KY WAY GLOB… …RVEY

…Rix,[1] …

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

V. Belokurov,[2] D. B. Zucker,[2] N. W. Evans,[2] J. T. Kleyna,[3] S. Koposov,[4] S. T. Hodgkin,[2] M. J. Irwin,[2] G. Gilmore,[2] M. I. Wilkinson,[2] M. Fellhauer,[2] D. M. Bramich,[2] P. C. Hewett,[2] S. Vidrih,[2] J. T. A. De Jong,[4] J. A. Smith,[5,6] H.-W. Rix,[4] E. F. Bell,[4] R. F. G. Wyse,[7] H. J. Newberg,[8] P. A. Mayeur,[8,9] B. Yanny,[10] C. M. Rockosi,[11] O. Y. Gnedin,[12] D. P. Schneider,[13] T. C. Beers,[14] J. C. Barentine,[15] H. Brewington,[15] J. Brinkmann,[15] M. Harvanek,[15] S. J. Kleinman,[16] J. Krzesinski,[15,17] D. Long,[15] A. Nitta,[18] and S. A. Snedden[15]

Received 2006 August 20; accepted 2006 September 20

THE DISC…

R. R. Muñoz[1,2], M…
2 Departamento de A…
3 Herzbe…
4 Observatorie…
5 Astr…

Re…

…bica[3] and B. Barbuy
…e Astronomia Galileo Galilei, Università di Padova, Vicolo dell'Osservatorio 2,
…o Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padua, Italy
…Federal do Rio Grande do Sul, Departamento de Astronomia, CP 15051, Porto Alegre 91501-970, Brazil
4 U…idade de São Paulo, IAG, Rua do Matão 1226, Cidade Universitária, São Paulo 05508-900, Brazil

Gaia 1 and 2. A pair of new Gala... ...ters

S... Koposov,[1,2★] V. Beloku...

...rsity of Cambridge, Cambri...

...s Center for Cosmo...

...5213, USA

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]

...[6] M. dal Ponte,[1,2] A. Fausti Neto,[2]

...[8] F. B. Abdalla,[9,10] S. Allam,[4]

...tin,[12,13] D. Brooks,[9] A. Carnero

...ce,[17] C. Davis,[18] P. Doel,[9] T.

...s,[22,23] D. Gruen,[18,24] R.

...[27] K. Kuehn,[28]

... Sanchez,[31]

...res-Santos,[4]

...NOR[*]

...VSKI[5,6]

...US

Dongwo...

Research School of Astr...

...au

...Weston, ACT 2611, Australia;

...RY OF A FAIN...

CATS AND D...

V. Bel...

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)

THE DISC...

R. R. Mu...

Deep SO... companions

E. Luque,[1,2★] B. San...

A. Drlica-Wagner,[4] A. ...

L. N. da Costa,[2,7] M. A. G...

J. Annis,[4] K. Bechtol,[11] A. Be...

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. Nicho...

...V. Scarpine,[4] R. Schindler,[24] I. Sevilla-Noarbe,

...Sobreira,[2,33] E. Suchyta,[34] G. Tarle[23] and D. Th...

...Y GLOB... ...RVEY

...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]

...tine,[15] H. Brewington,[15] J. Brinkmann,[15]

...ong,[15] A. Nitta,[18] and S. A. Snedden[15]

...006 September 20

... Padova, Vicolo dell'Osservatorio ...,

...orio 5, I-35122 Padua, Italy

... Federal d... ...e Astronomia, CP 15051, Porto Alegre 91501-970, Brazil

[4]U... ...idade de São Paulo, ...de Universitária, São Paulo 05508-900, Brazil

Photometric searches of GCs

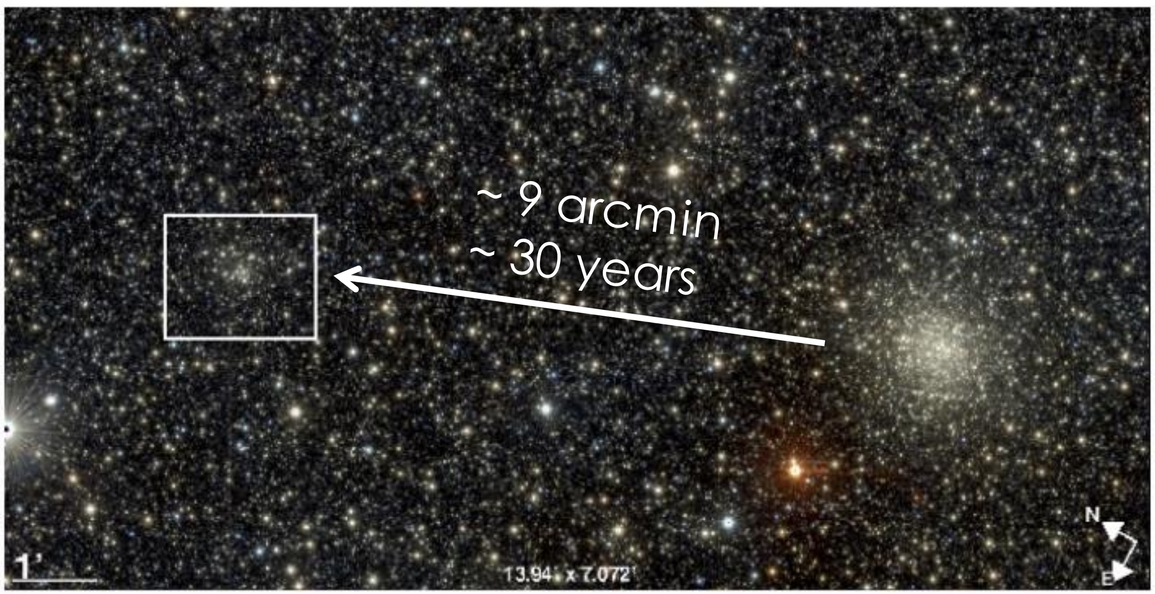
Thanks to the recent **near-IR photometric surveys**, the number of star cluster candidates has risen exponentially in the last few years in the **bulge region**.

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**

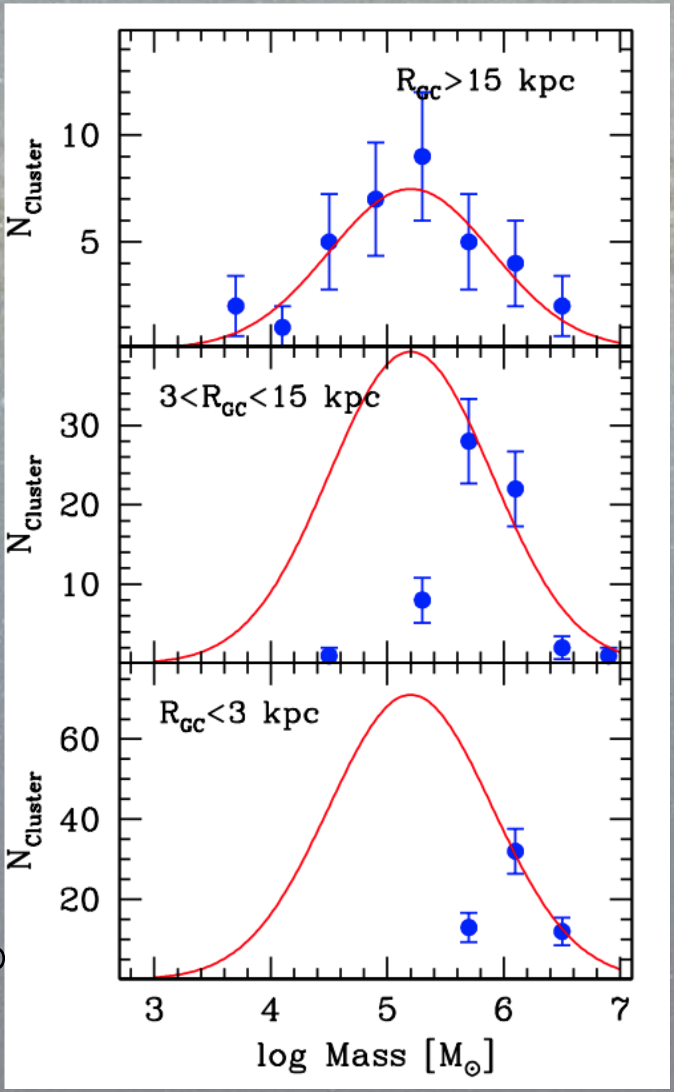
Photometric searches of GCs

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



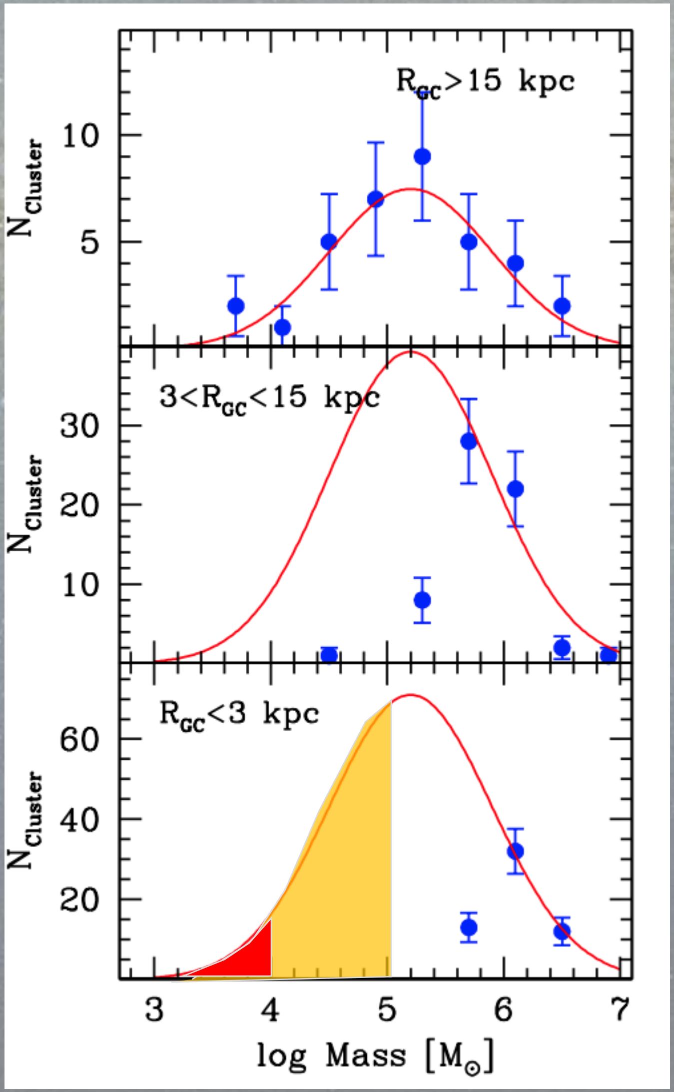
Baumgardt et al. 2018

~Halo GCs

~Disk GCs

~Bulge GCs

Initial mass distribution of GCs in the MW



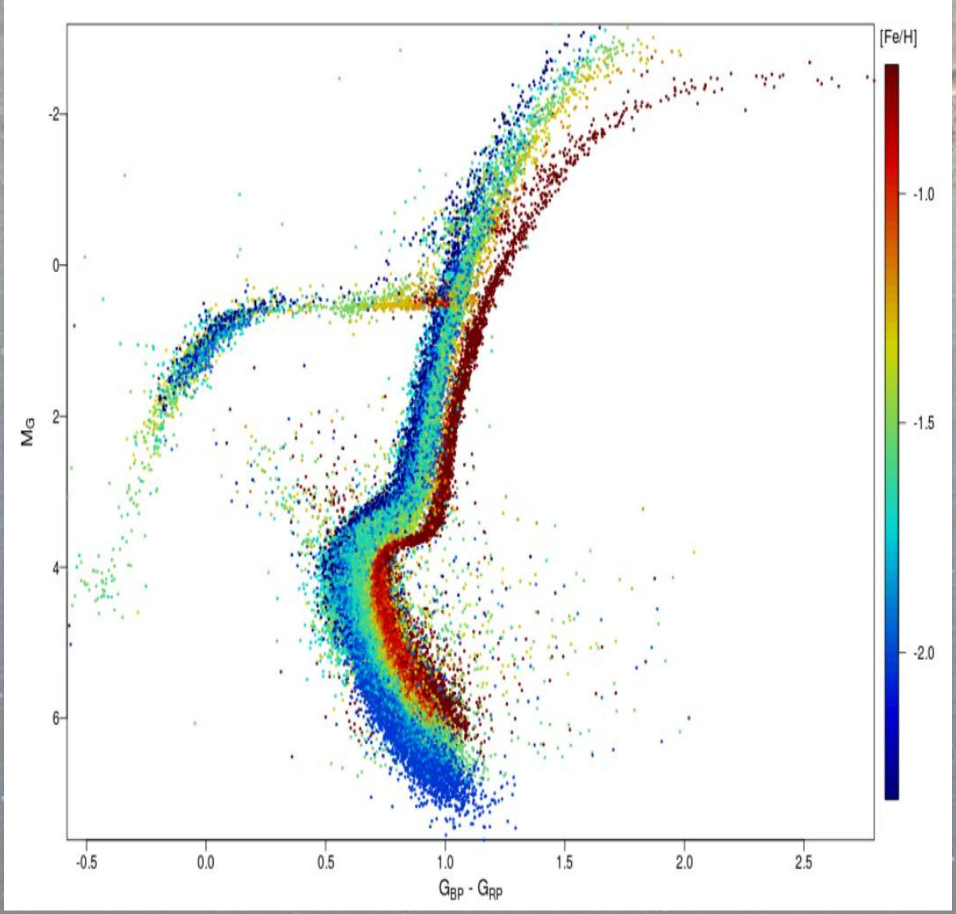
Baumgardt et al. 2018

~Halo GCs

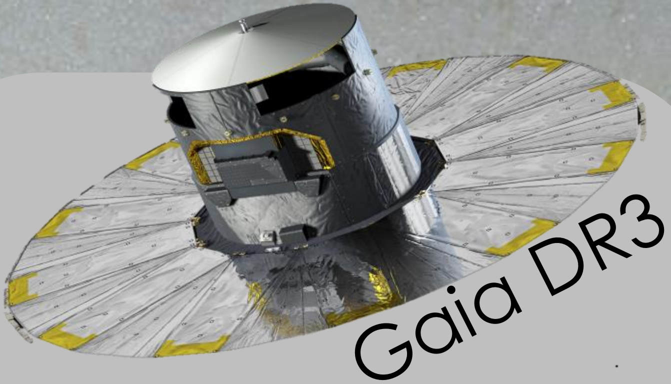
~Disk GCs

~Bulge GCs

Gaia DR3 proper motion catalogue



Gaia Collaboration et al. 2018



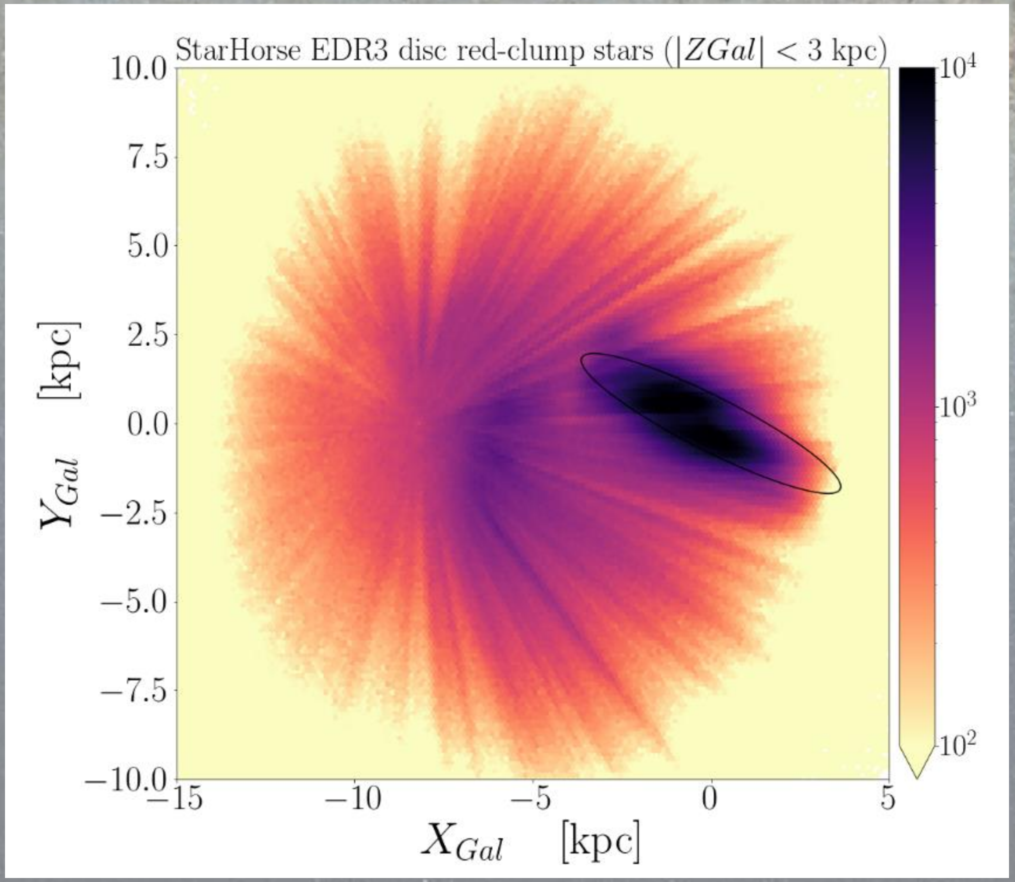
Optical survey
(G,G_{BP},G_{RP},
G_{RVS}, XP spectra)

Valid for $|b| \geq 2°$

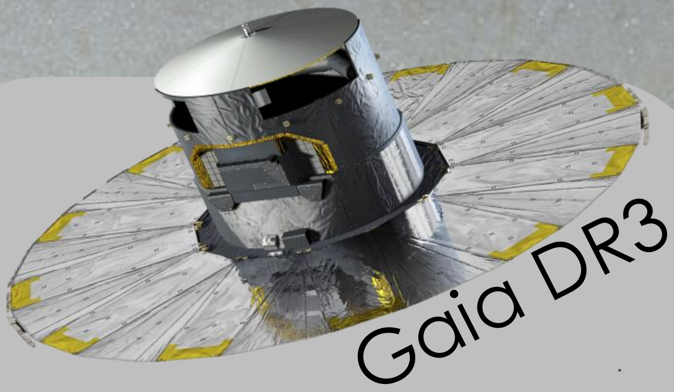
Absolute proper motions:
$\mu_{\alpha} \cos(\delta)$, μ_{δ}

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

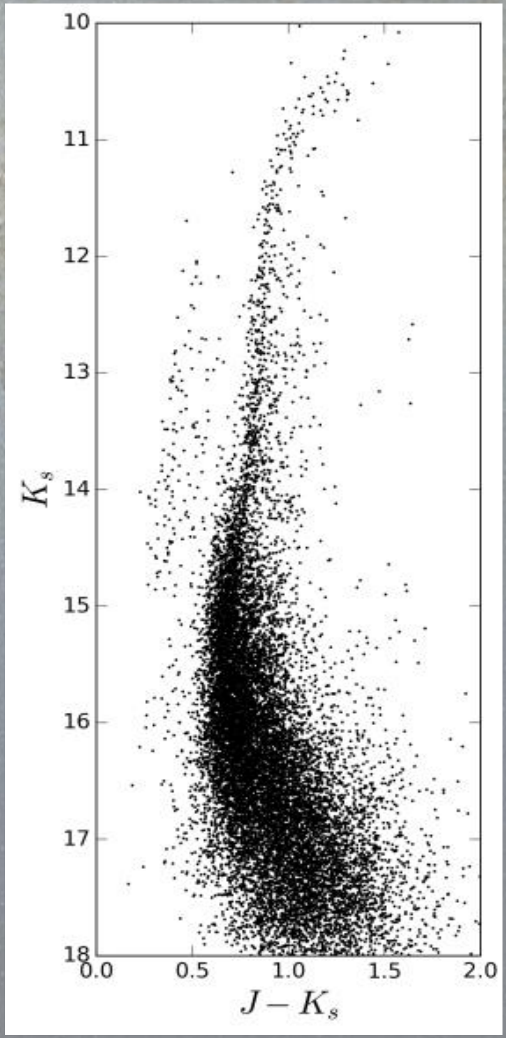
VVV survey catalogue

VVV X 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, $J-K_s$

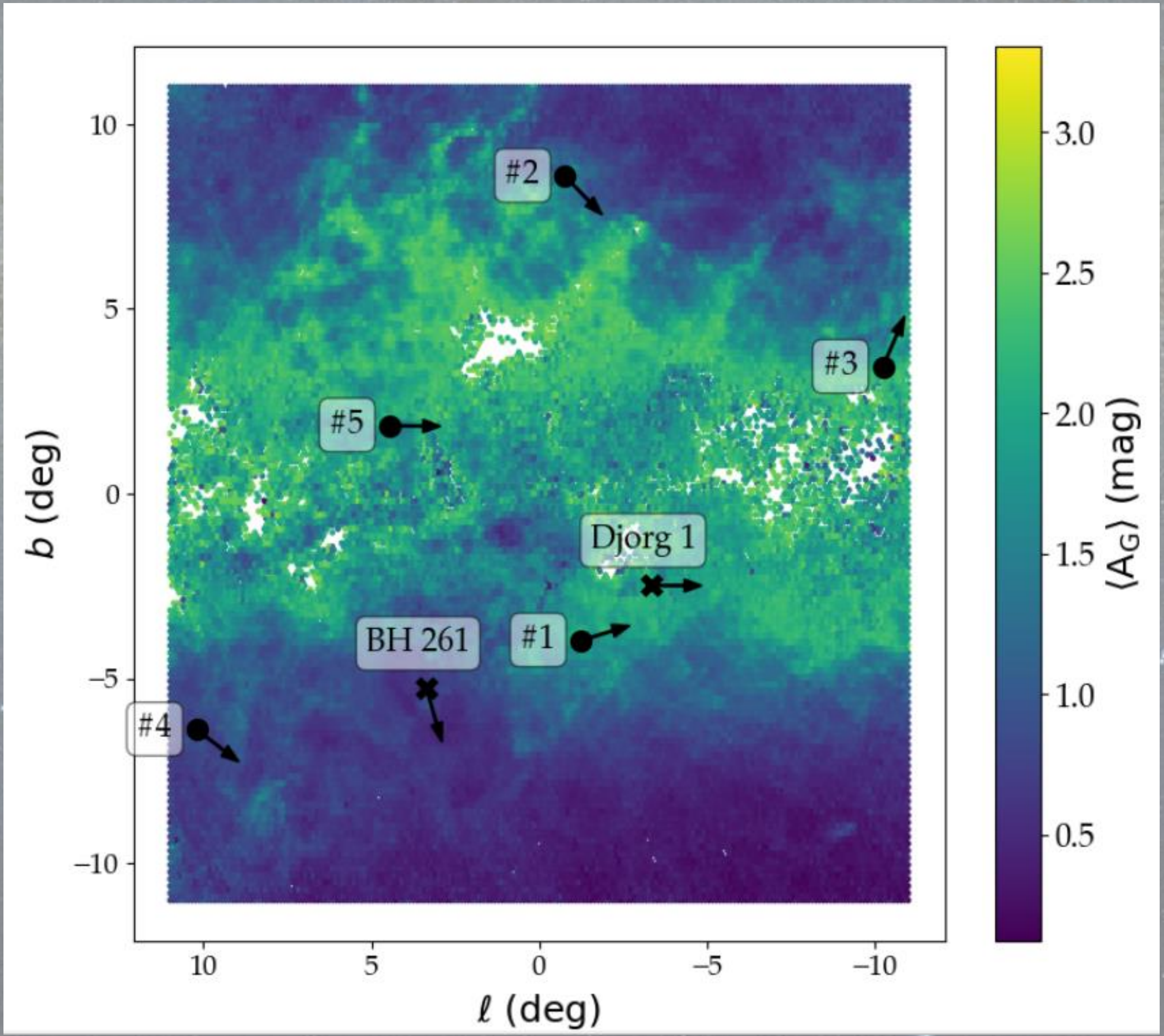
+

scikit learn: KDTree
and DBScan

Pedragosa et al 2011

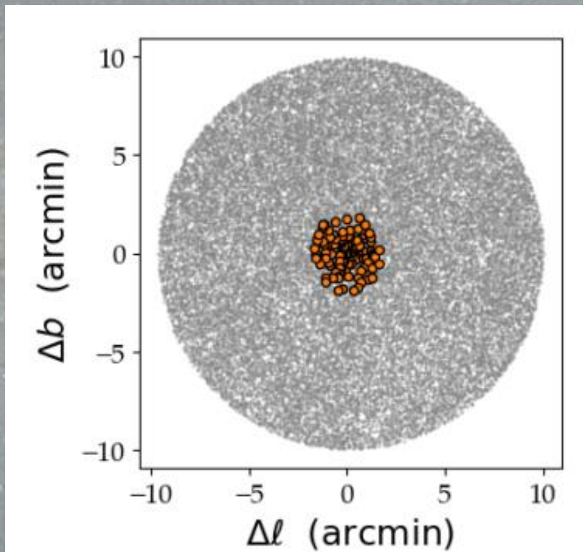
¡Candidate clusters in the 5-D phase space!

Map of the new GCs



Gran et al. 2022

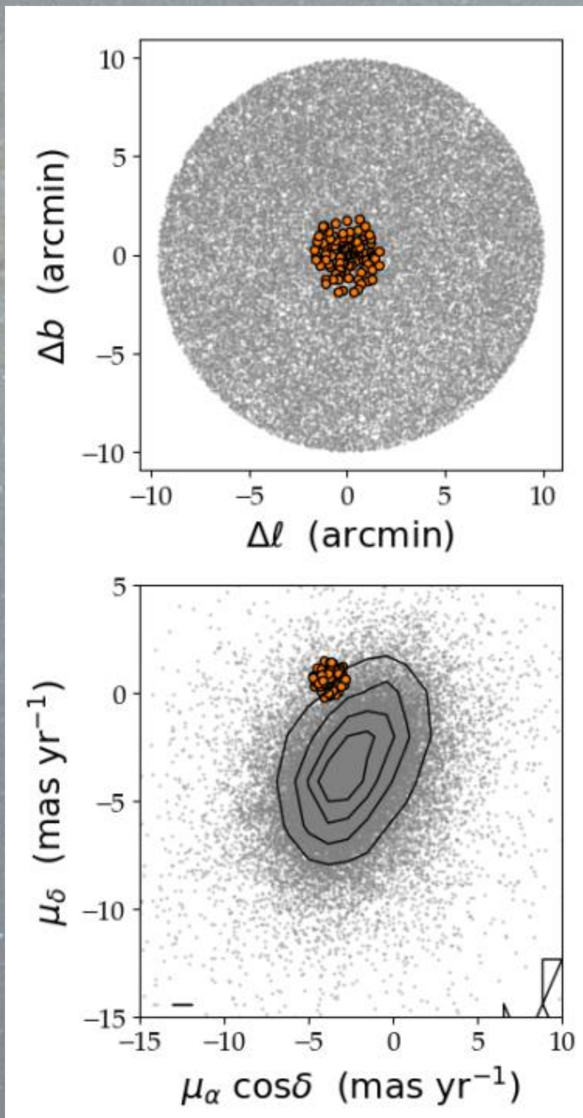
New GCs: the case of Gran 3



Clustering requirements:

- Grouped in space (ℓ,b)

New GCs: the case of Gran 3

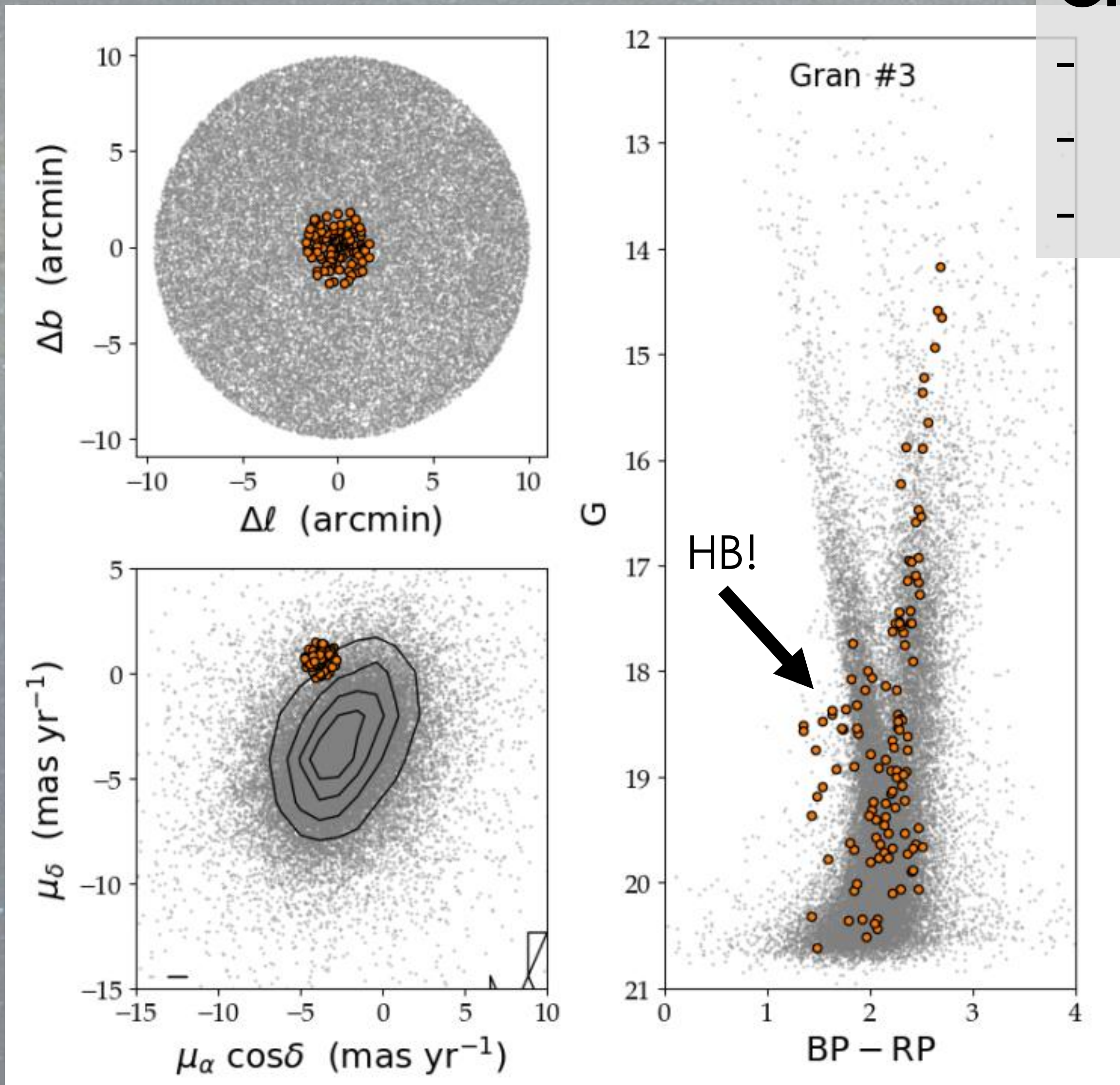


Clustering requirements:

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

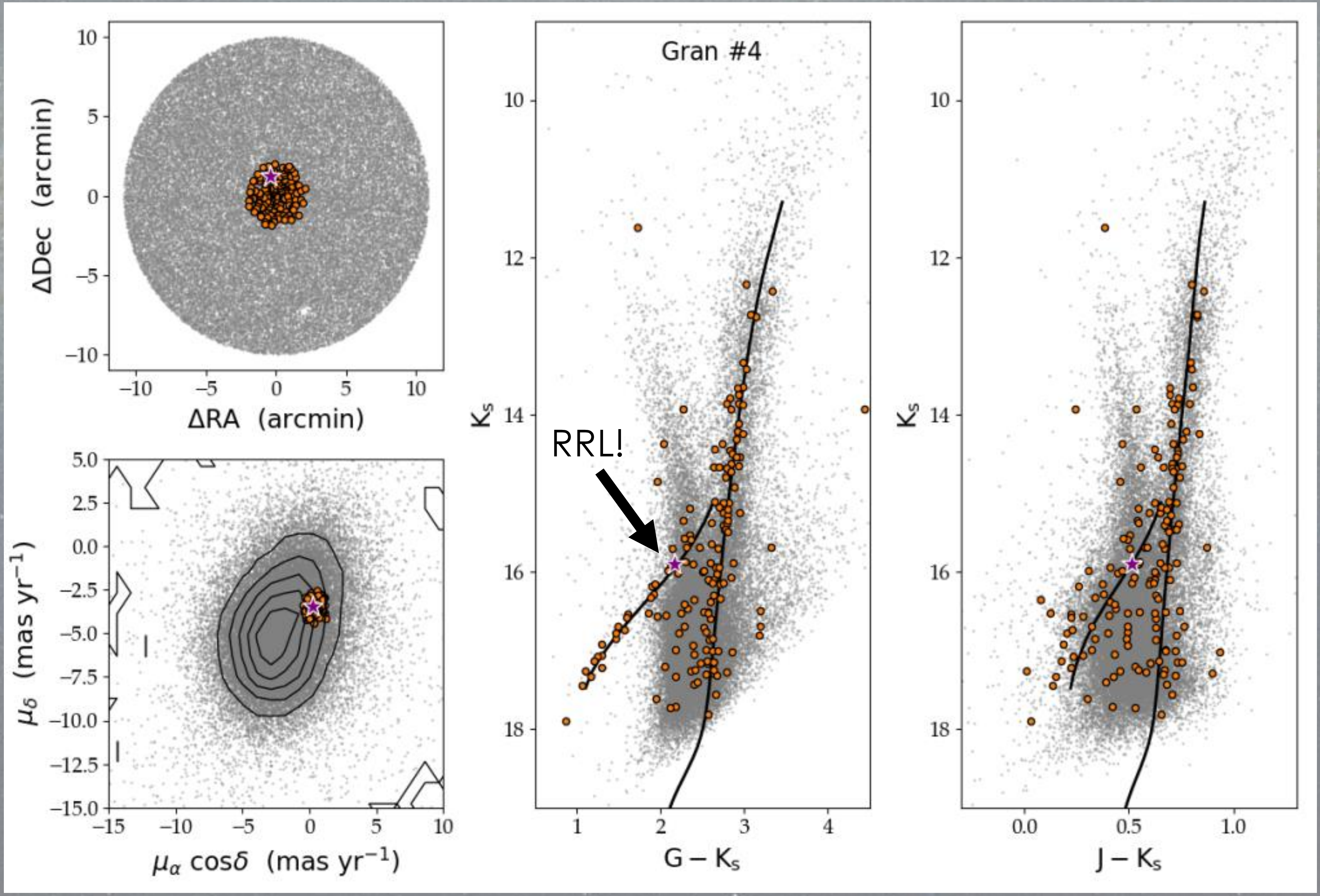
New GCs: the case of Gran 3

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



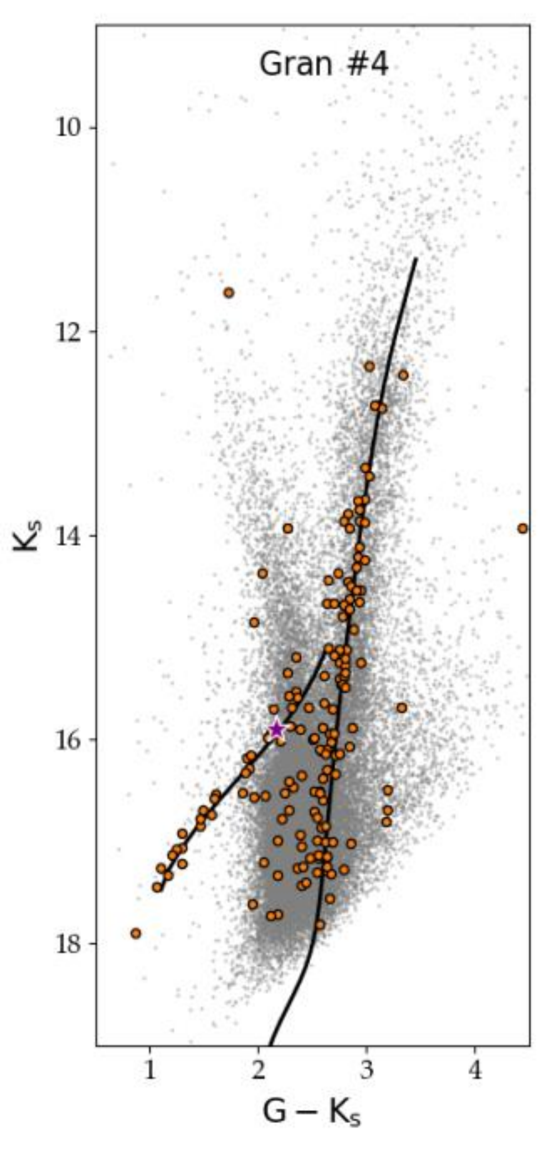
Gran et al. 2022

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})	$N_{\rm members}$ (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

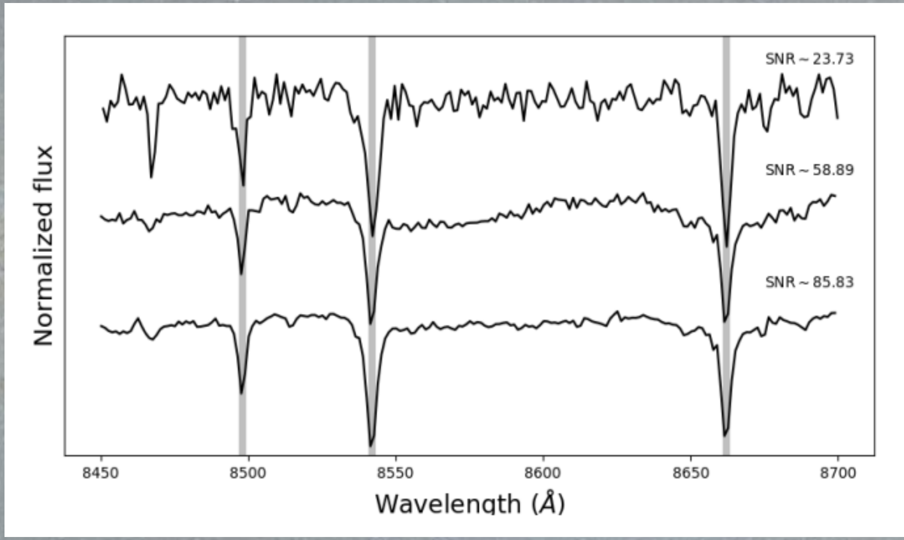
Gran et al. 2022

New GCs: MUSE observations

ESO P103-105
PI: F. Gran

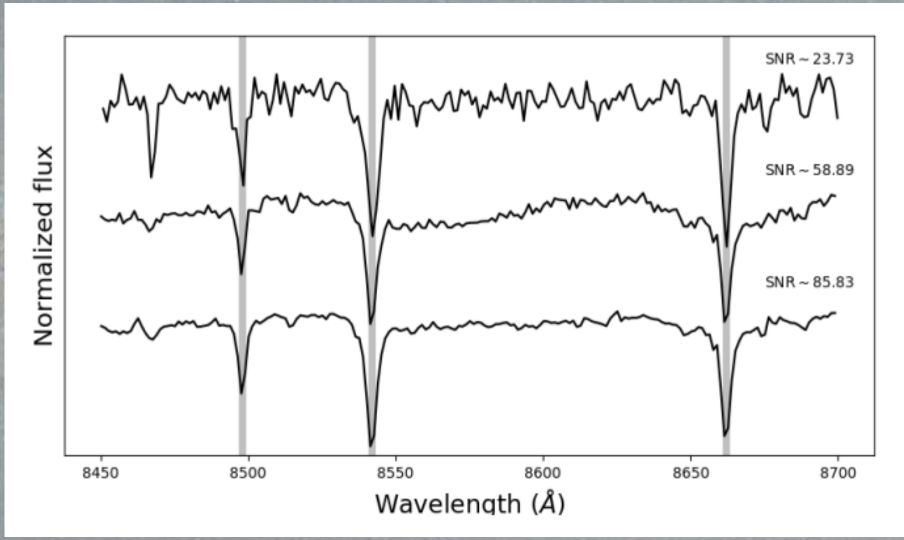
14 hours
WFM ~ 1 arcmin^2
4650 < λ (Å) < 9300
R @ 8800 Å ~ 4000

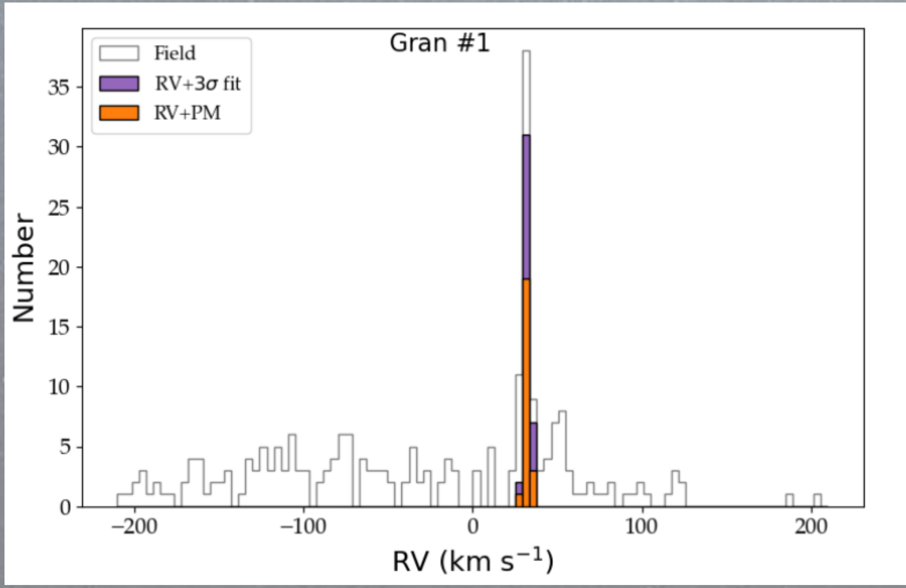
New GCs: MUSE observations



Gran et al. 2022

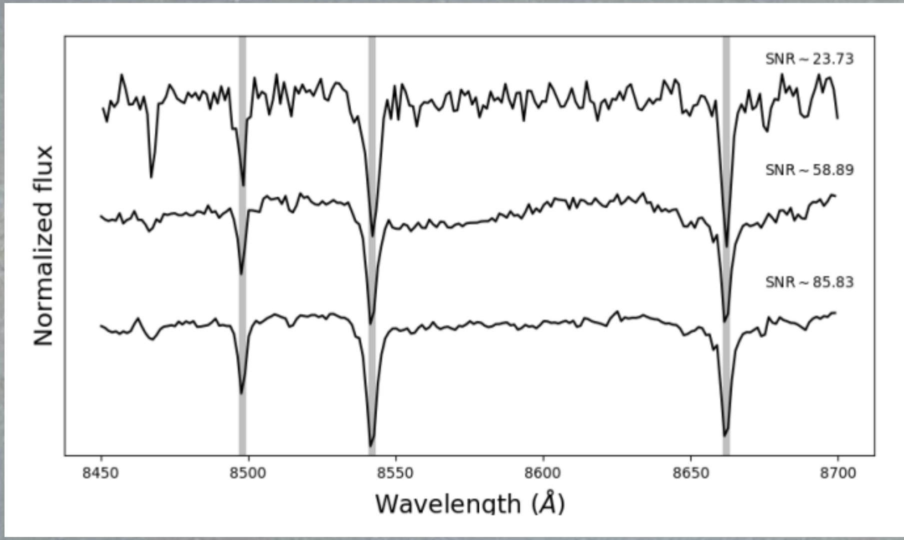
New GCs: MUSE observations

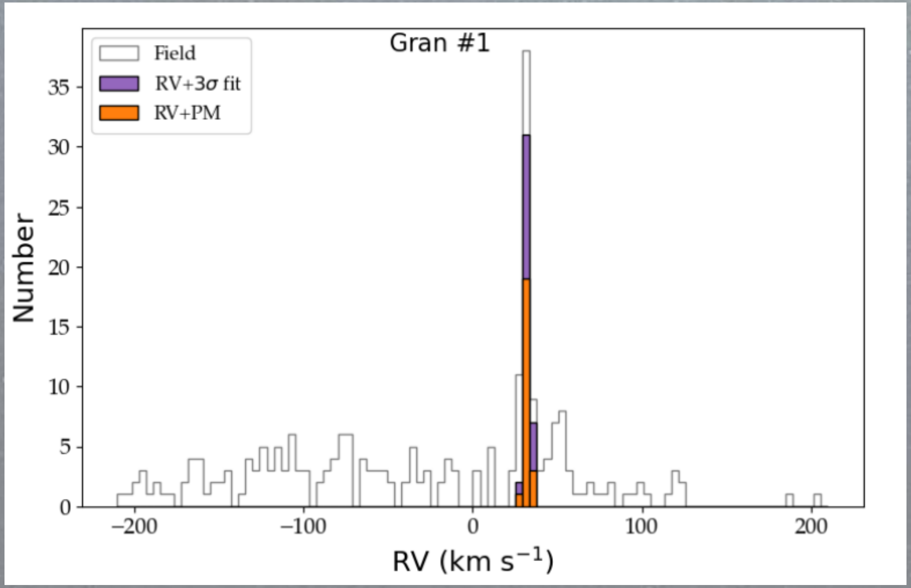


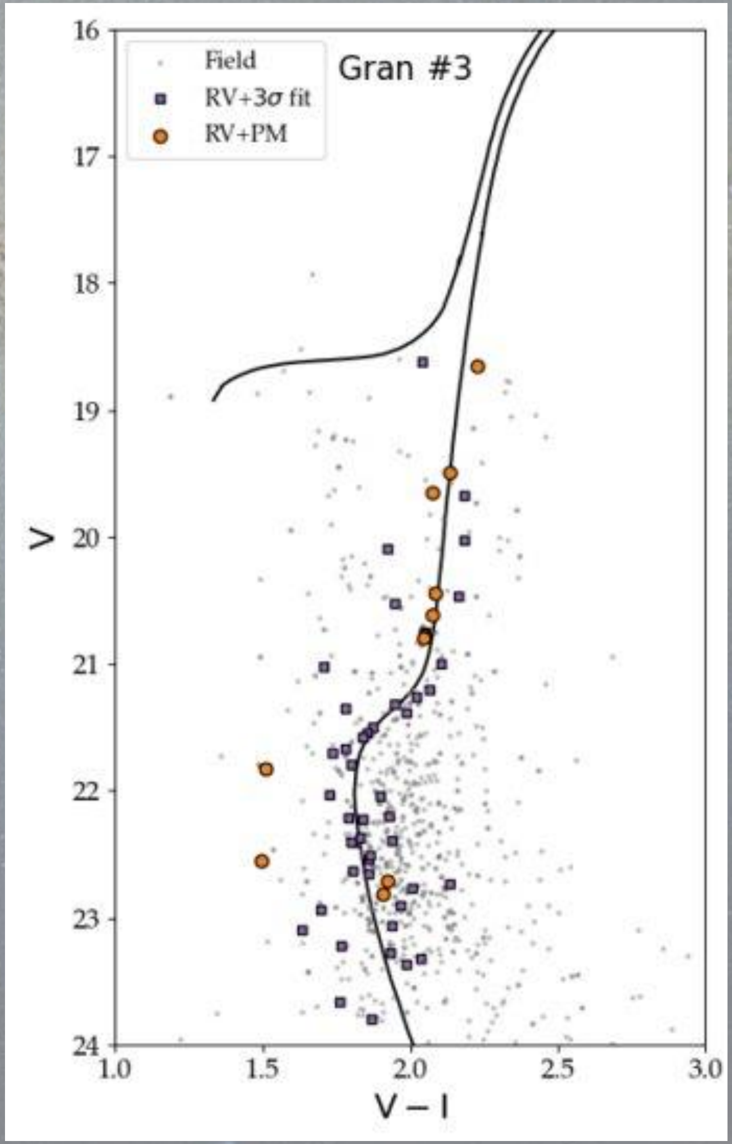


Gran et al. 2022

New GCs: MUSE observations

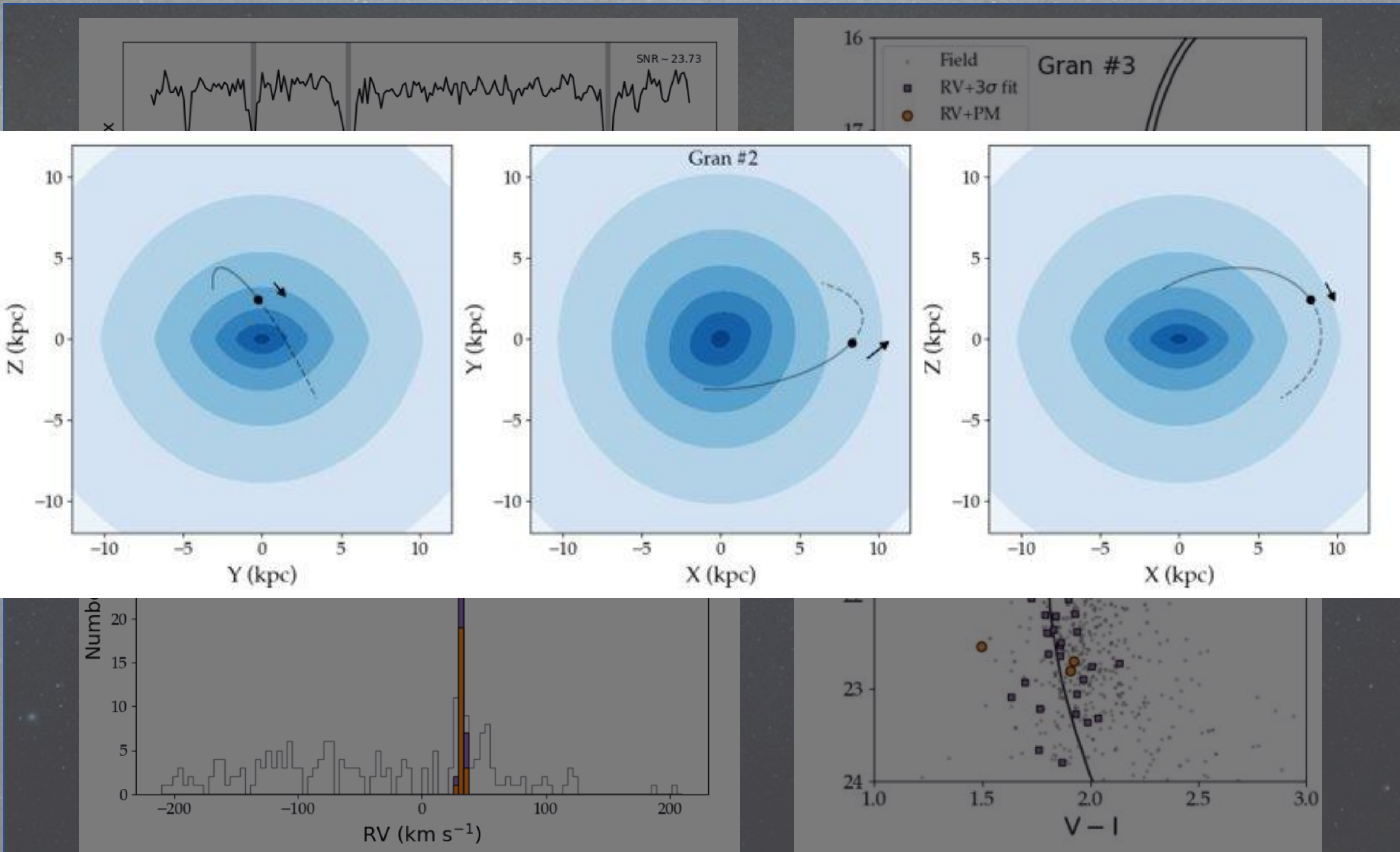






Gran et al. 2022

New GCs: MUSE observations



Gran et al. 2022

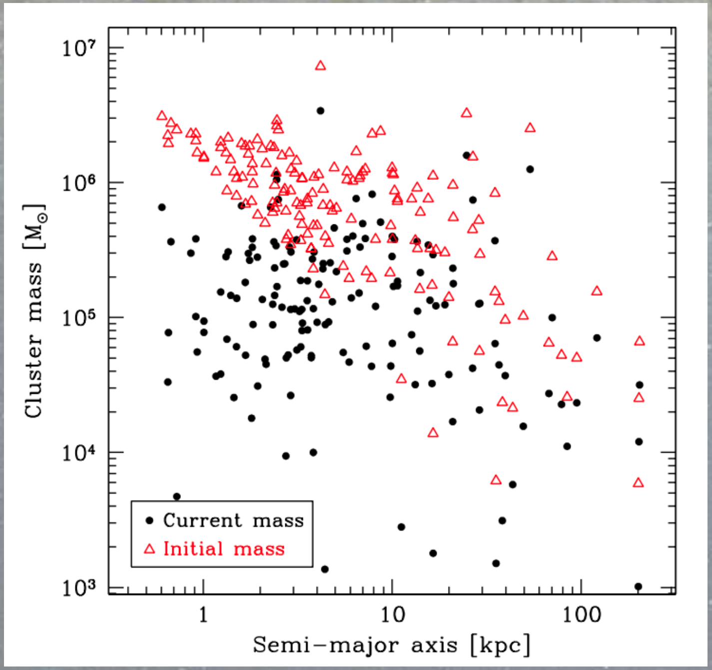
New GCs: MUSE observations

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

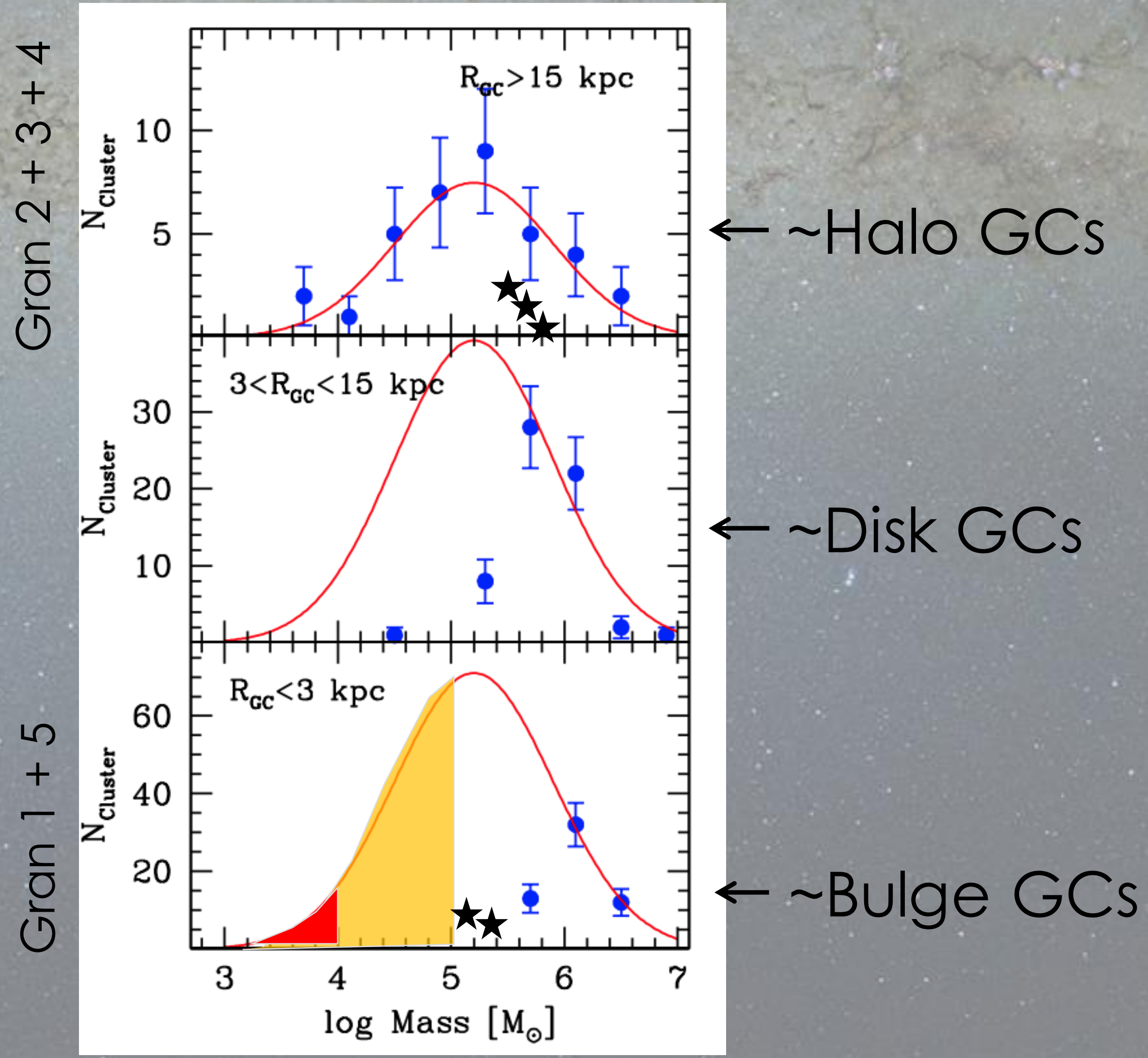
GC	RV (km s^{-1})	[Fe/H] (dex)	V_{HB} (mag)	e	z_{max} (kpc)	r_{peri} (kpc)	r_{apo} (kpc)	L_z (kpc^2 Myr^{-1})	E_{tot} (kpc^2 Myr^{-2})
Gran 1	32.30 ± 1.87	-1.19 ± 0.19	19.08	0.76	0.38	0.31	2.22	0.03	-0.21
Gran 2	53.22 ± 1.67	-2.07 ± 0.17	18.59	0.34	5.44	4.59	9.24	0.79	-0.16
Gran 3	74.32 ± 2.70	-2.37 ± 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

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**.

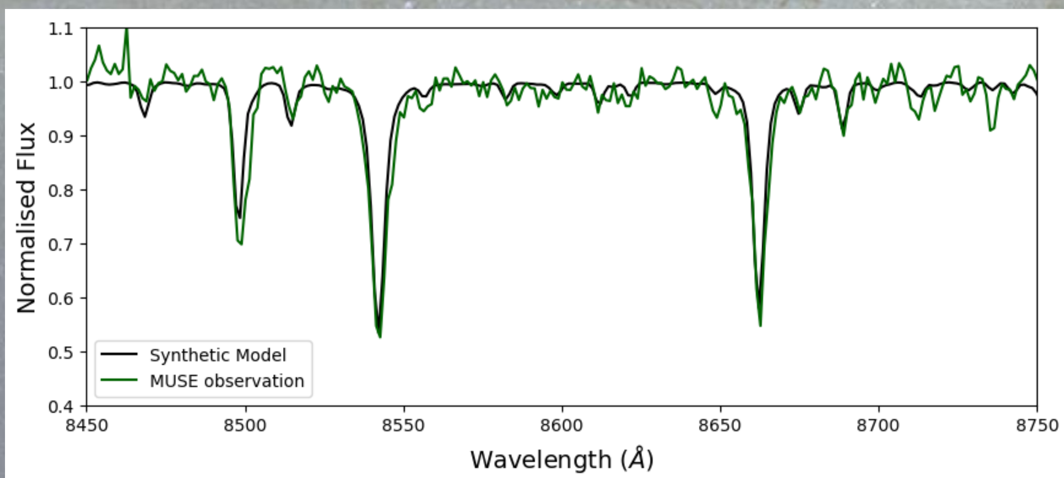
★ Using a clustering algorithm, we were able to discover **5 new** clusters with old stellar sequences.

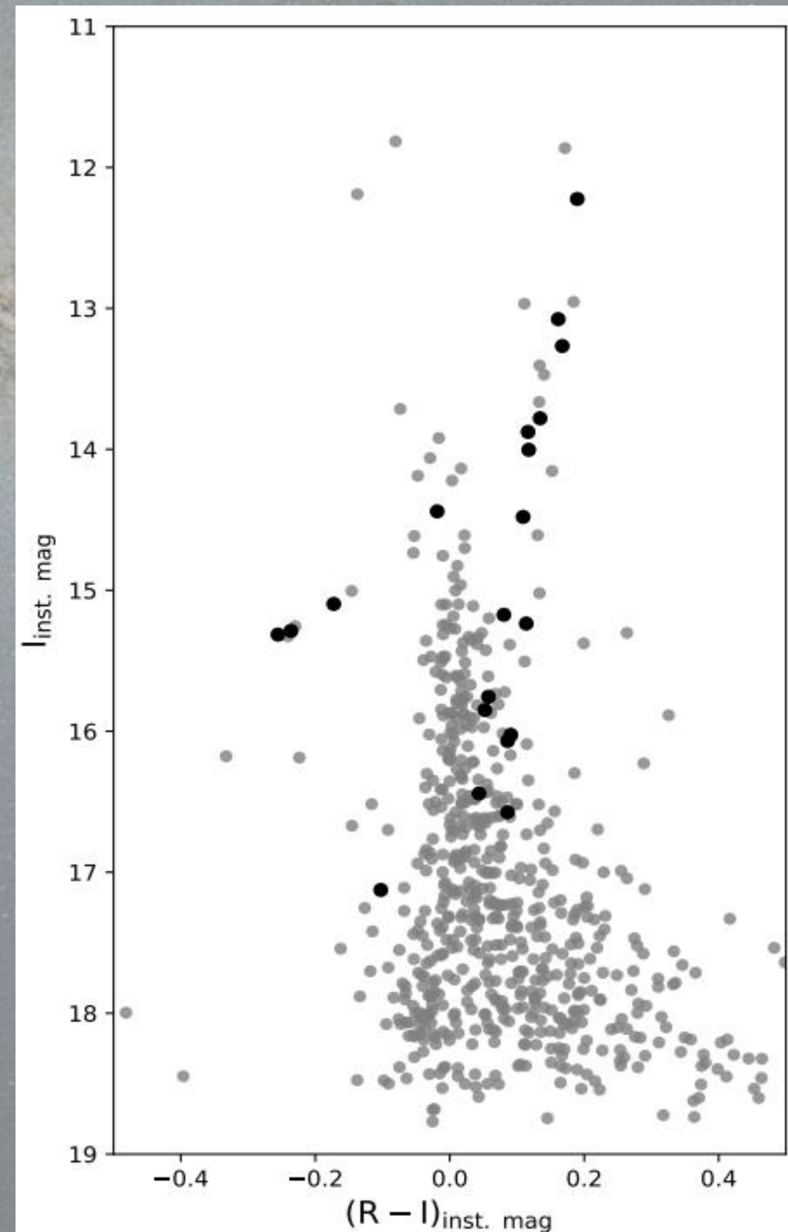
★ Orbital parameters and metallicities from the analysis of 5 **MUSE** cubes.

★ Key observable: **proper motions!**

Future work

★ Derive clusters metallicity via synthetic models



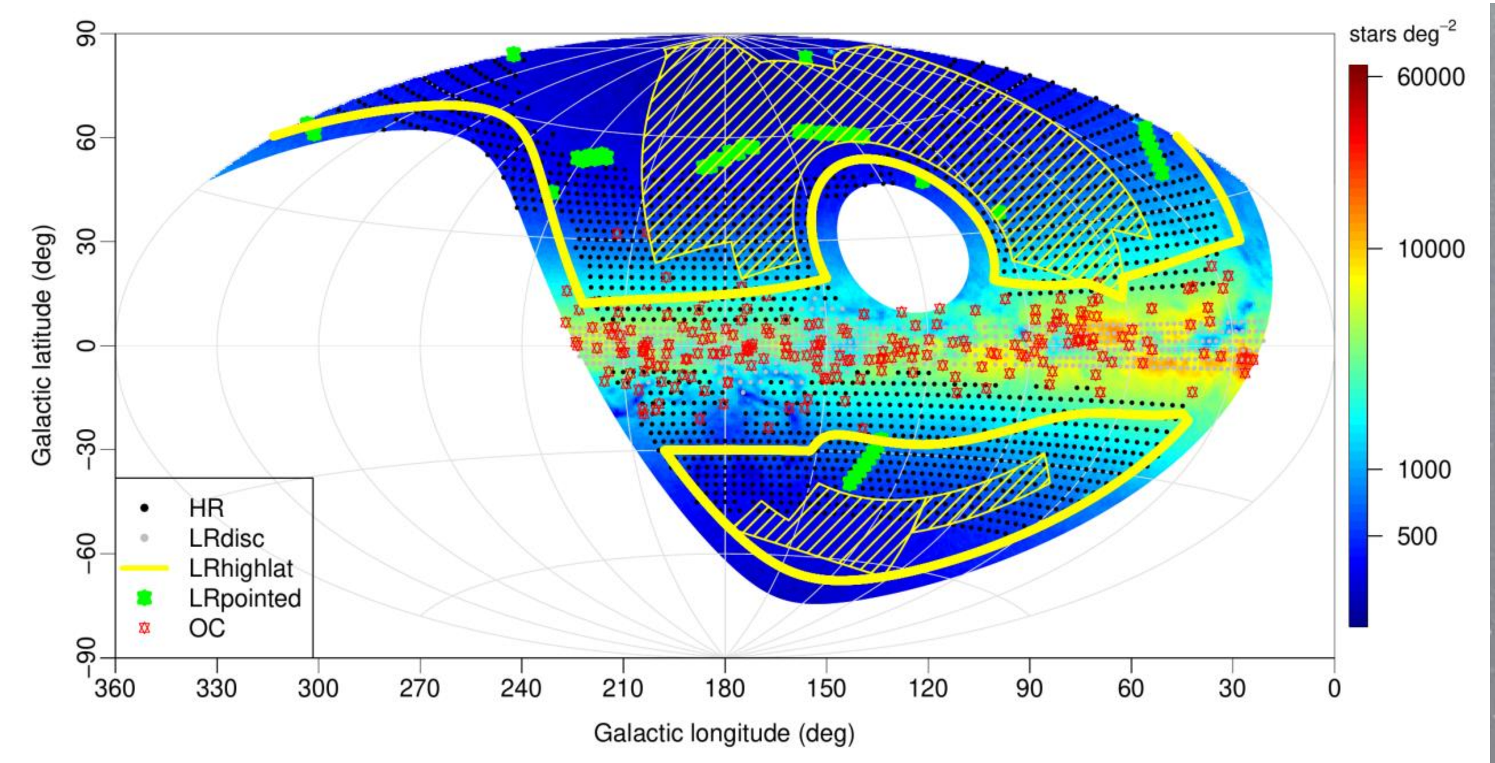


Future work

★ WEAVE survey: homogenisation of contributed catalogues for scientific exploration of the GA survey

[Submitted on 7 Dec 2022]

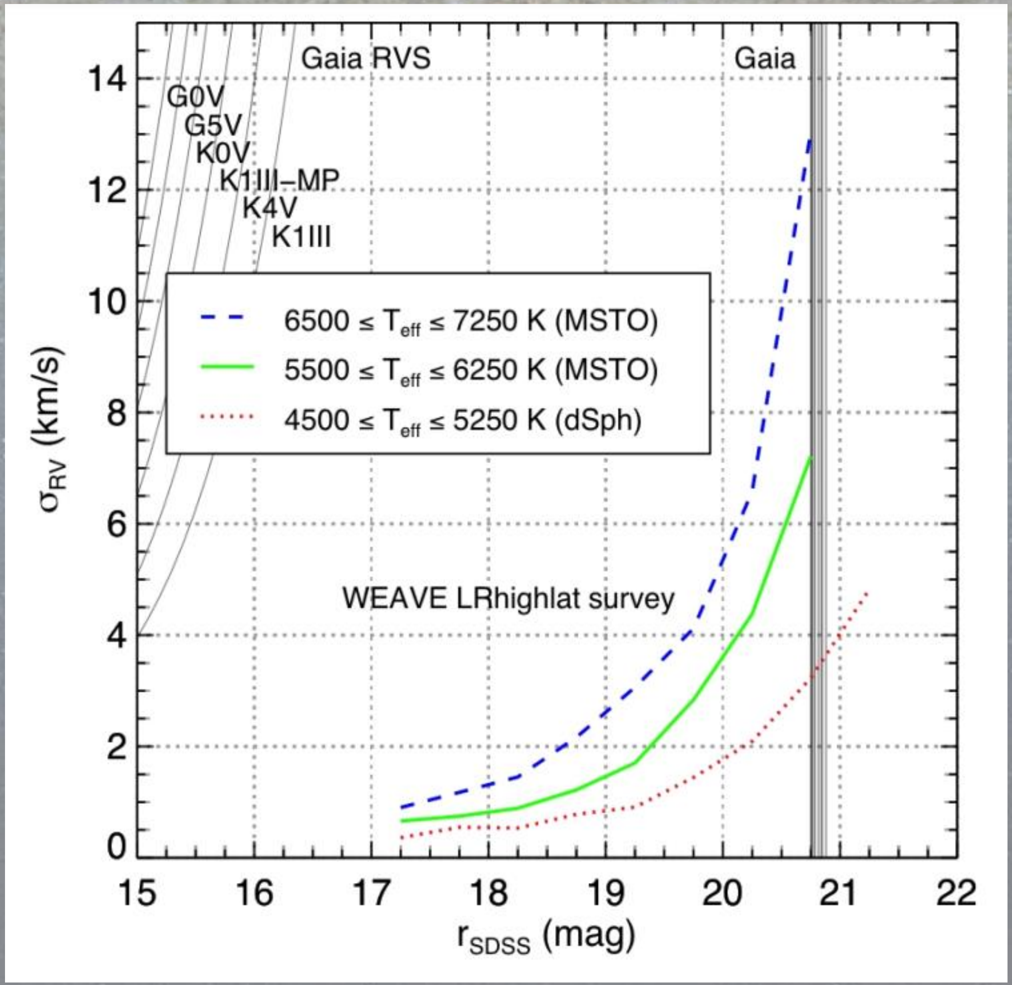
The wide-field, multiplexed, spectroscopic facility WEAVE: Survey design, overview, and simulated implementation



Jin et al. 2022

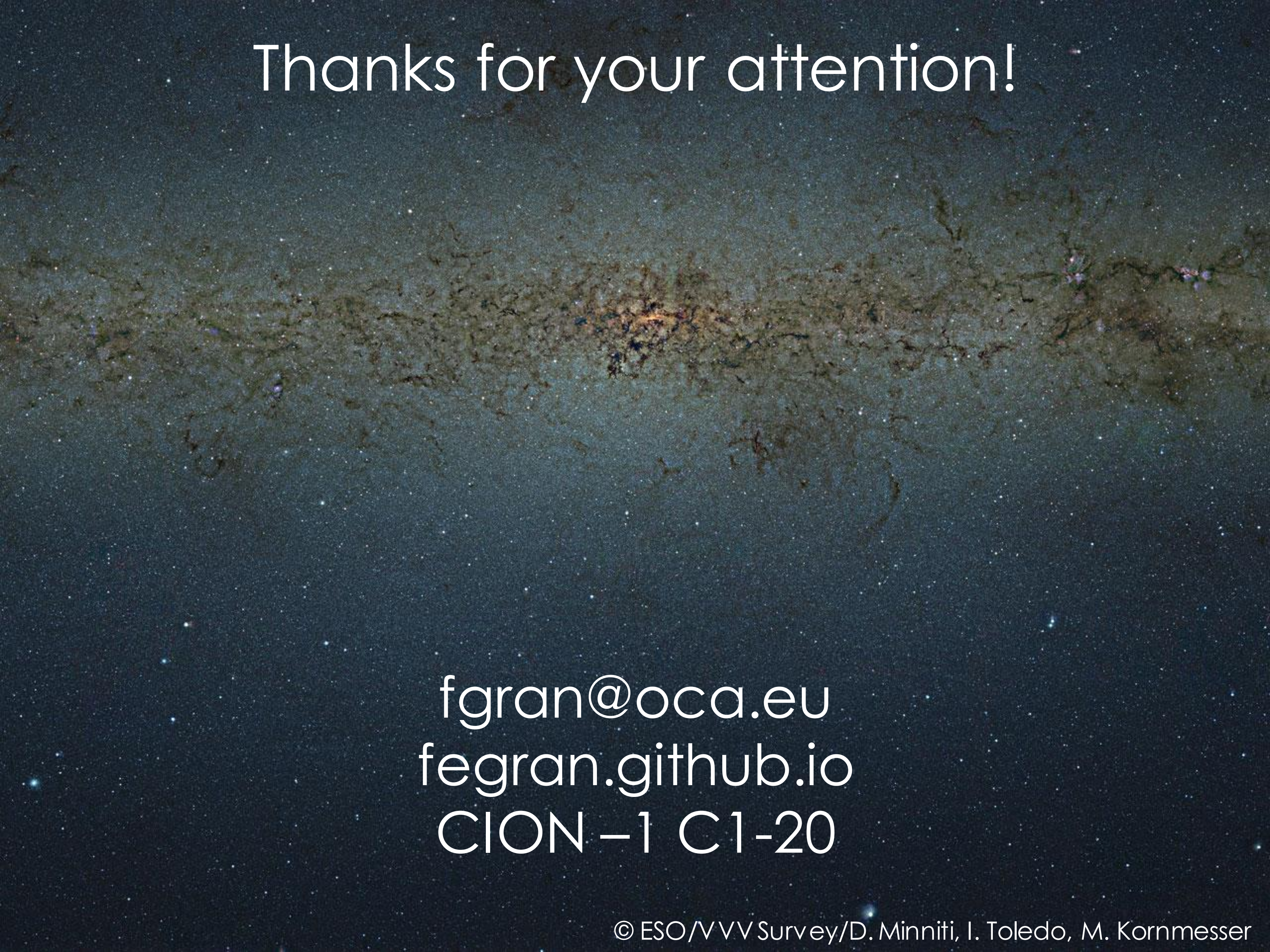
Future work

★ WEAVE survey: homogenisation of contributed catalogues for scientific exploration of the GA survey



Jin et al. 2022

Thanks for your attention!



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fegran.github.io
CION –1 C1-20