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

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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

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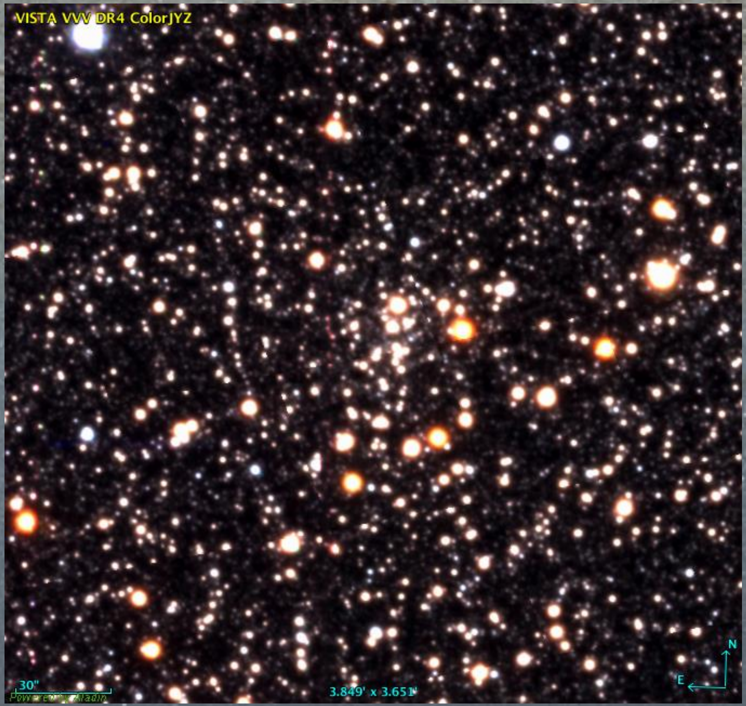


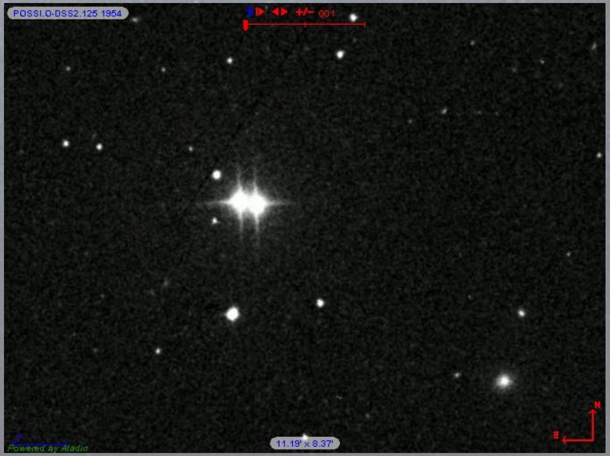
Gran et al. 2019

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

Key concept #1: stellar proper motions

POSS1, POSS2, DSS

Steve Quirk,
Wikipedia Commons

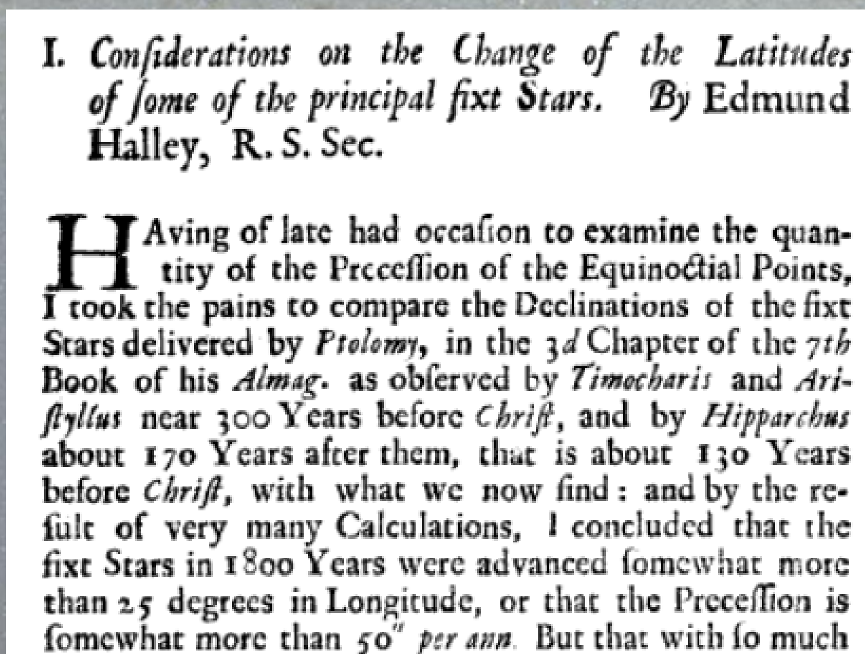


DSS/STScI

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

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POSS1, POSS2, DSS

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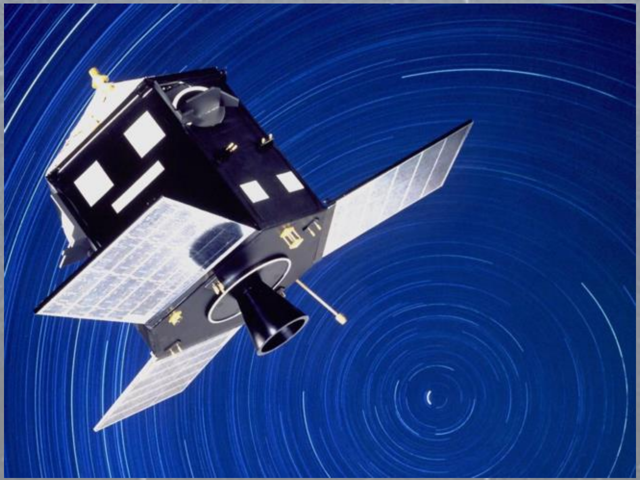
POSS1, POSS2, DSS



ESA, Hipparcos

Steve Quirk,
Wikipedia Commons

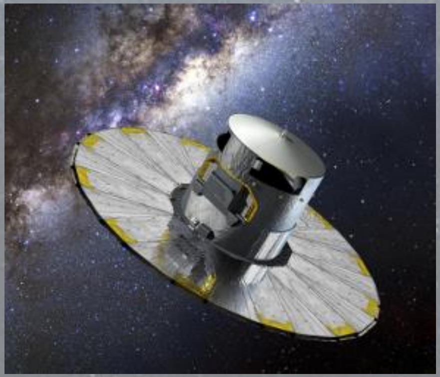
Key concept #1: stellar proper motions

★ 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

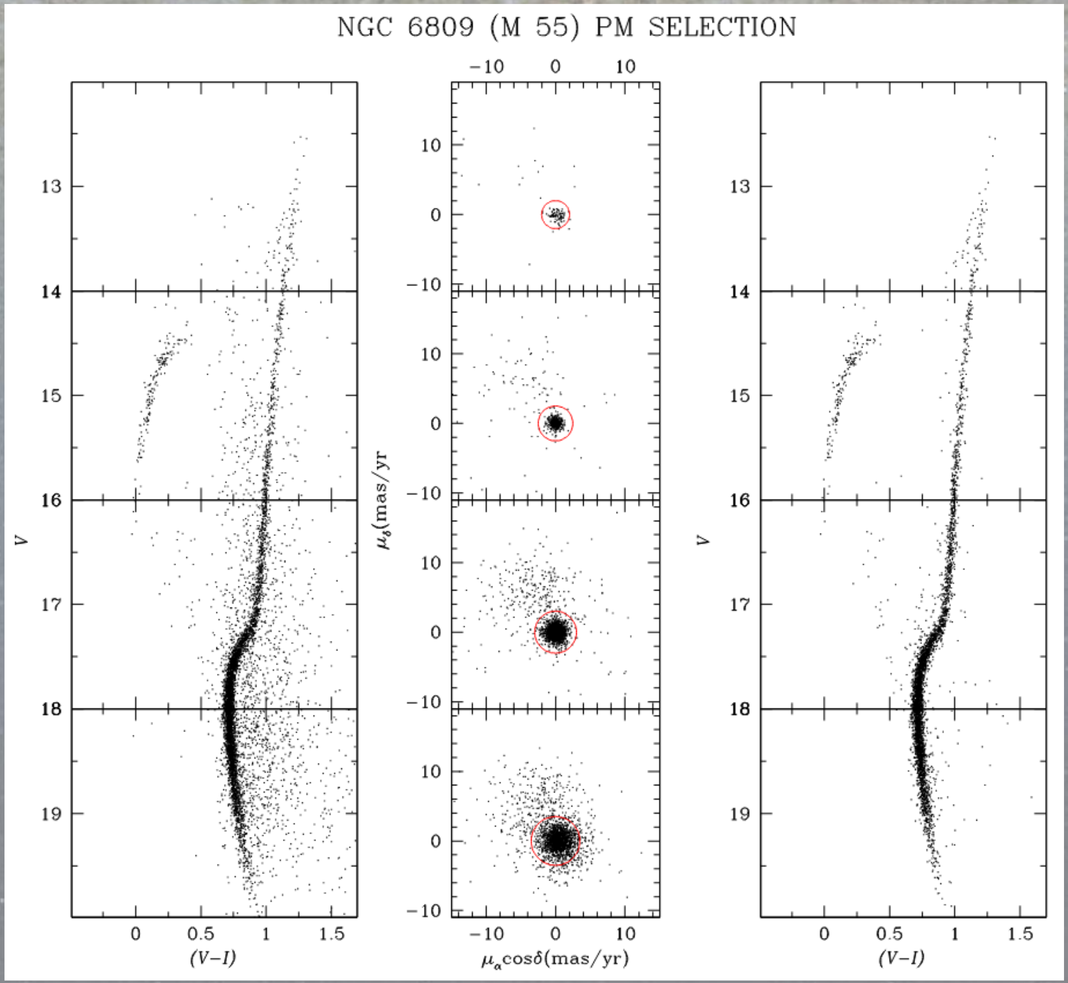
Steve Quirk,
Wikipedia Commons



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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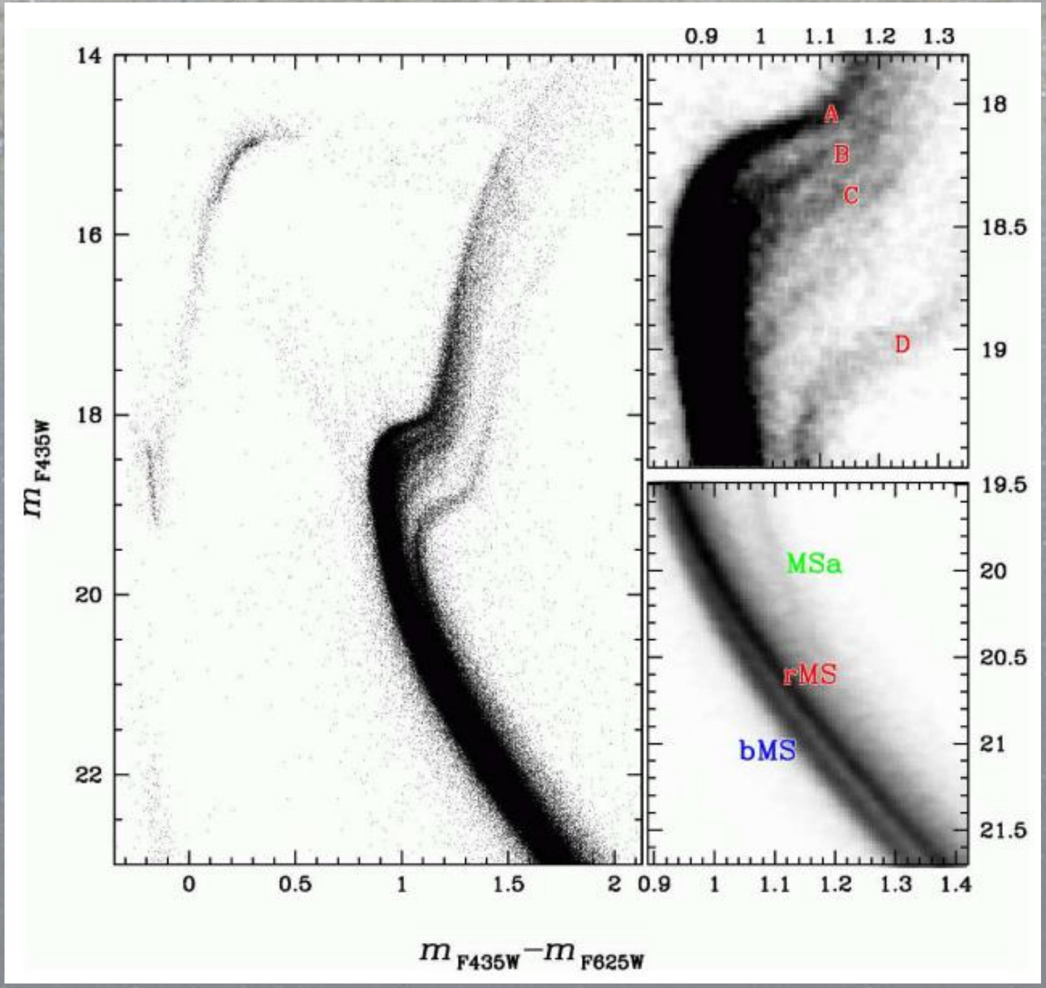

Bellini et al. 2010, 2017

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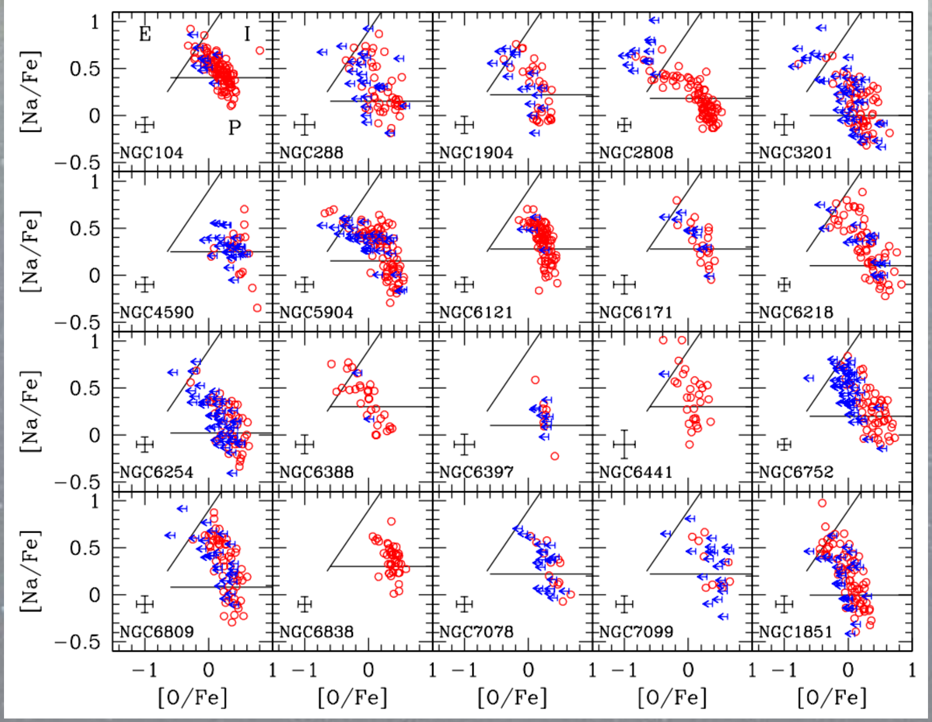


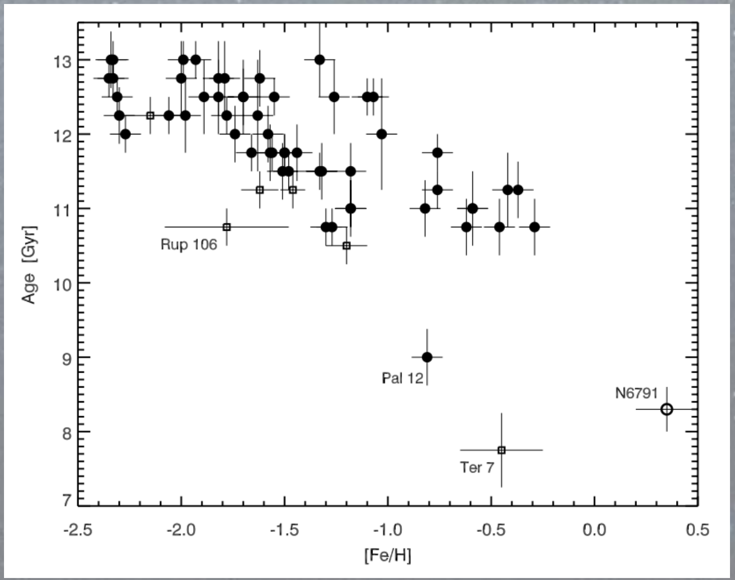
Carretta et al. 2009

- ★ 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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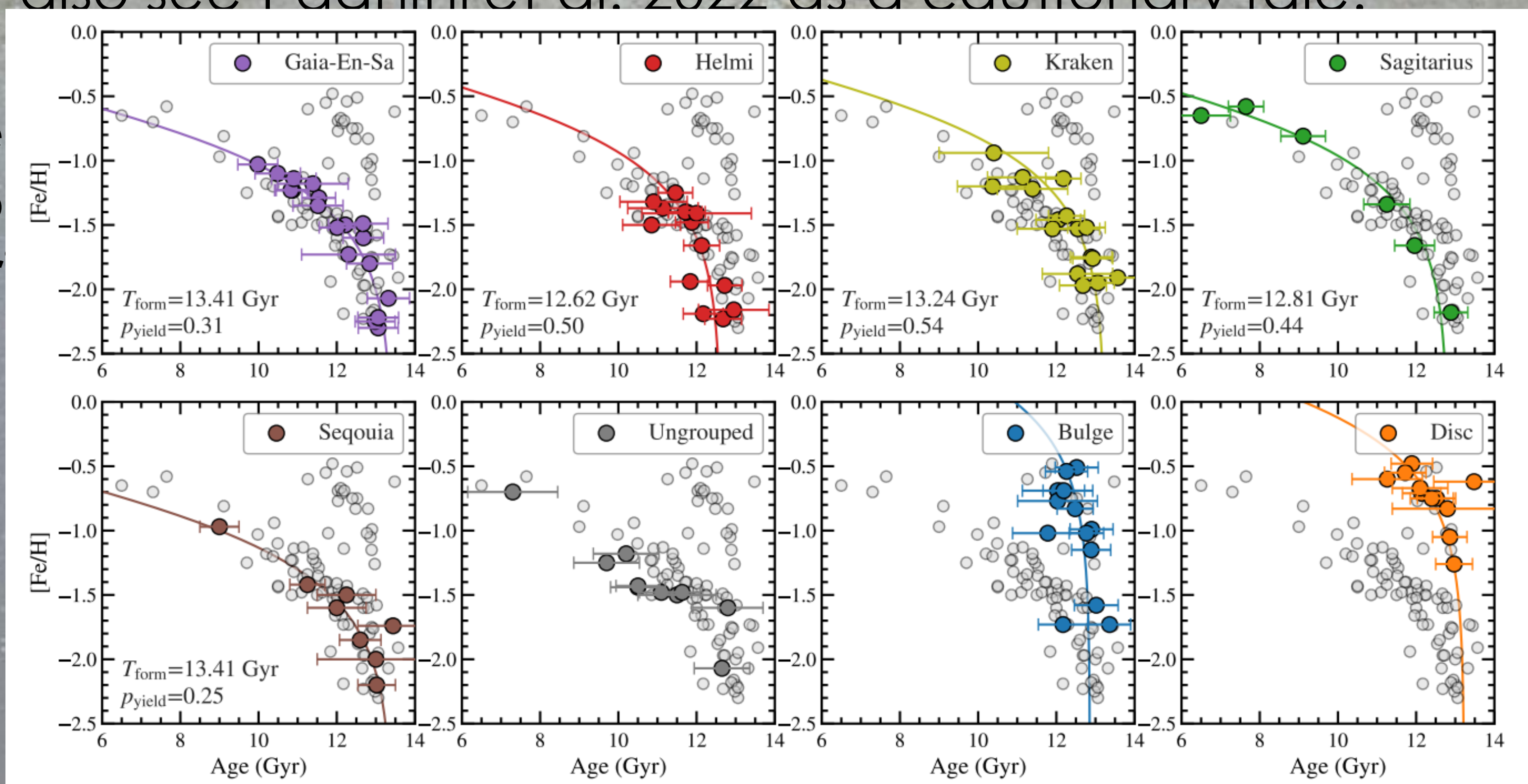
★ We ... ry
lab
enr



Callingham et al. 2022

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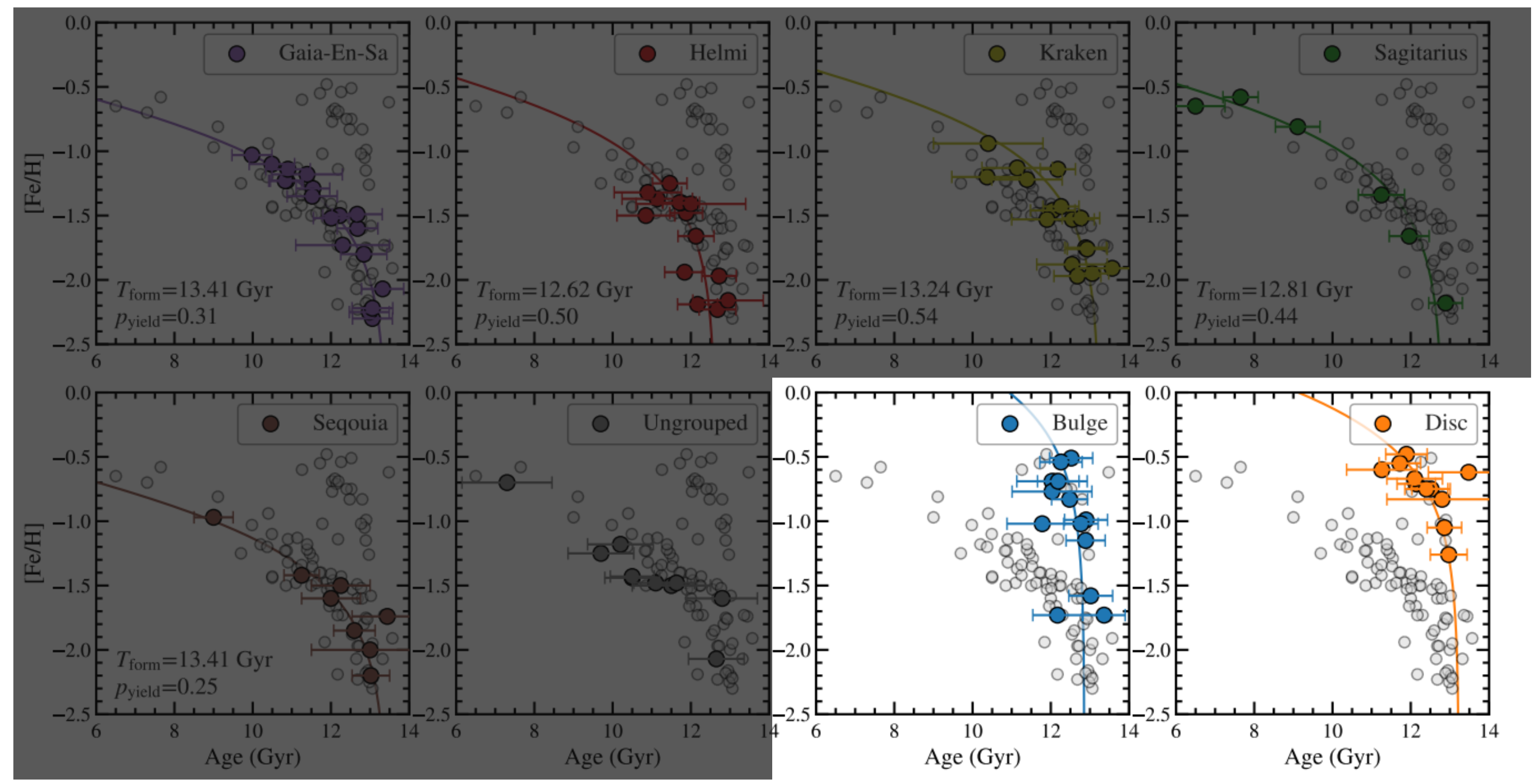

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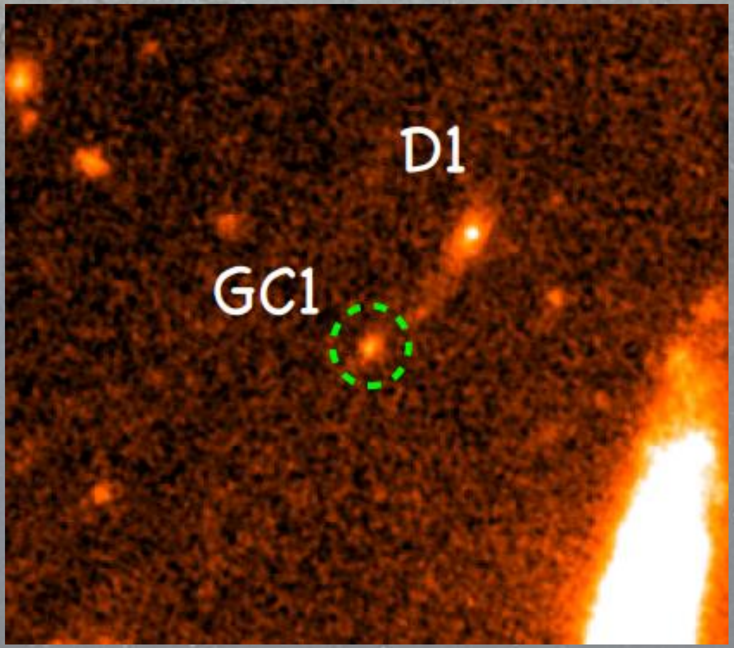
Key concept #3: the Galaxy evolution told by its globular clusters

★ **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**.

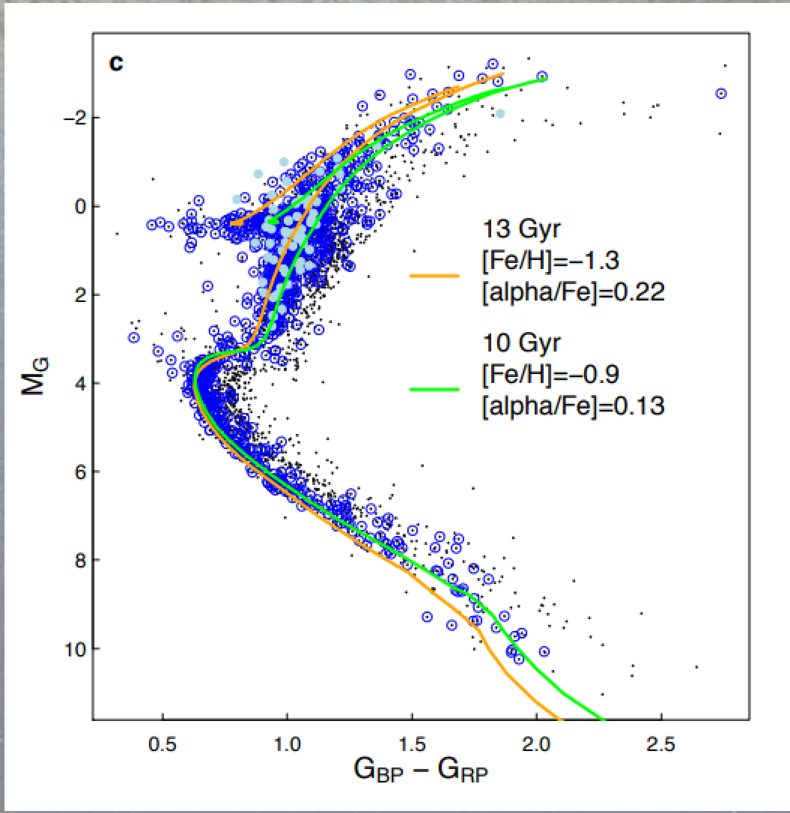


Vanzella et al. 2017

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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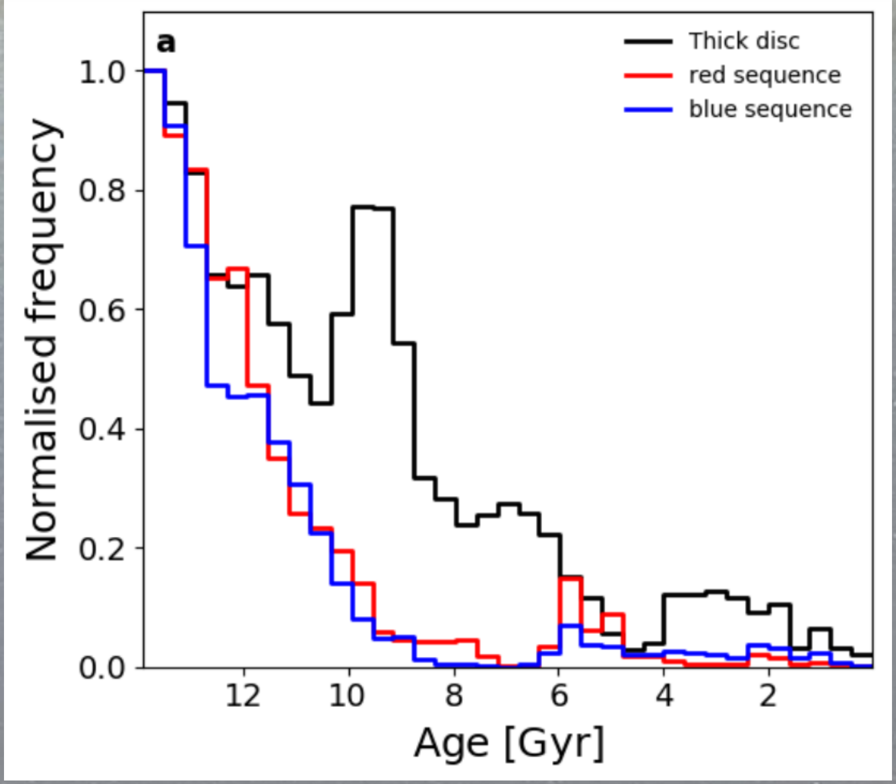

Gallart et al. 2019

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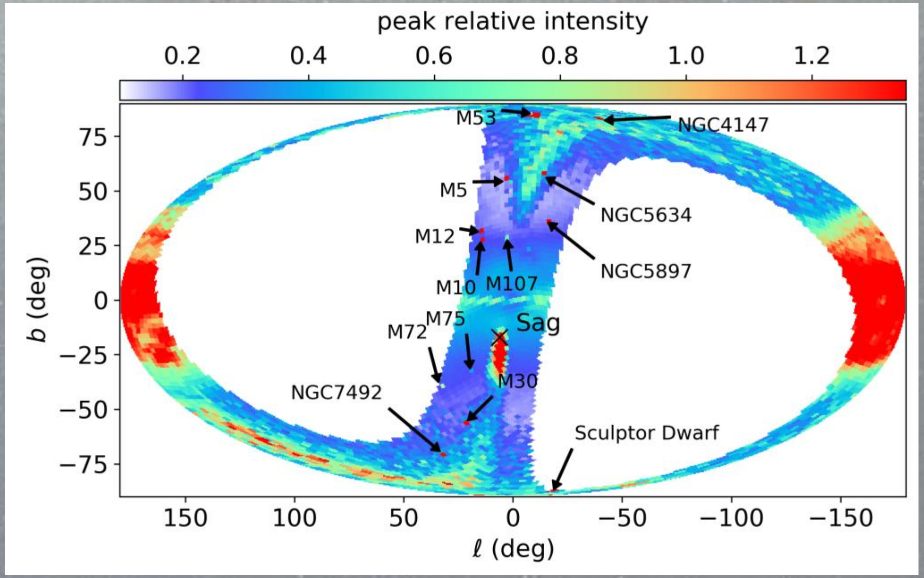

Antoja et al. 2020; Ramos et al. 2020

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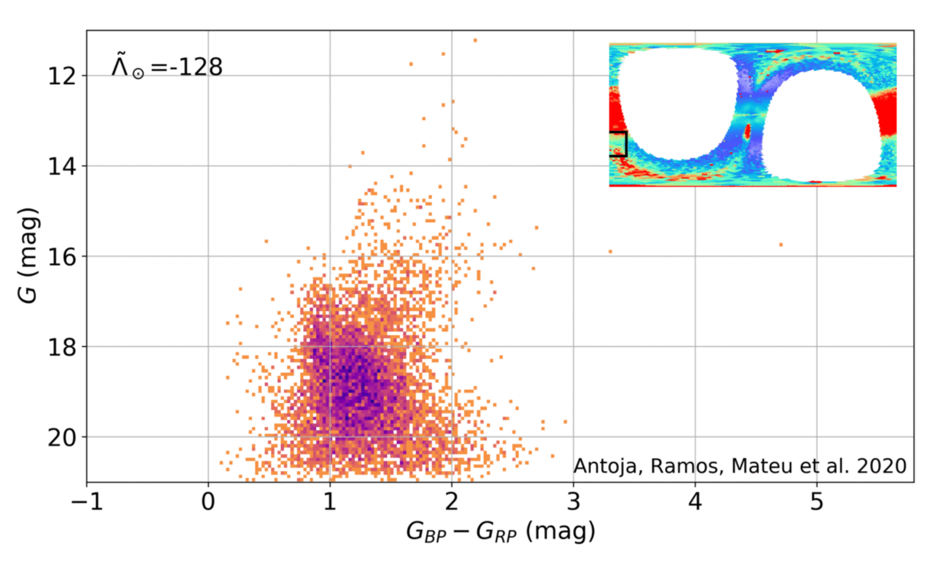
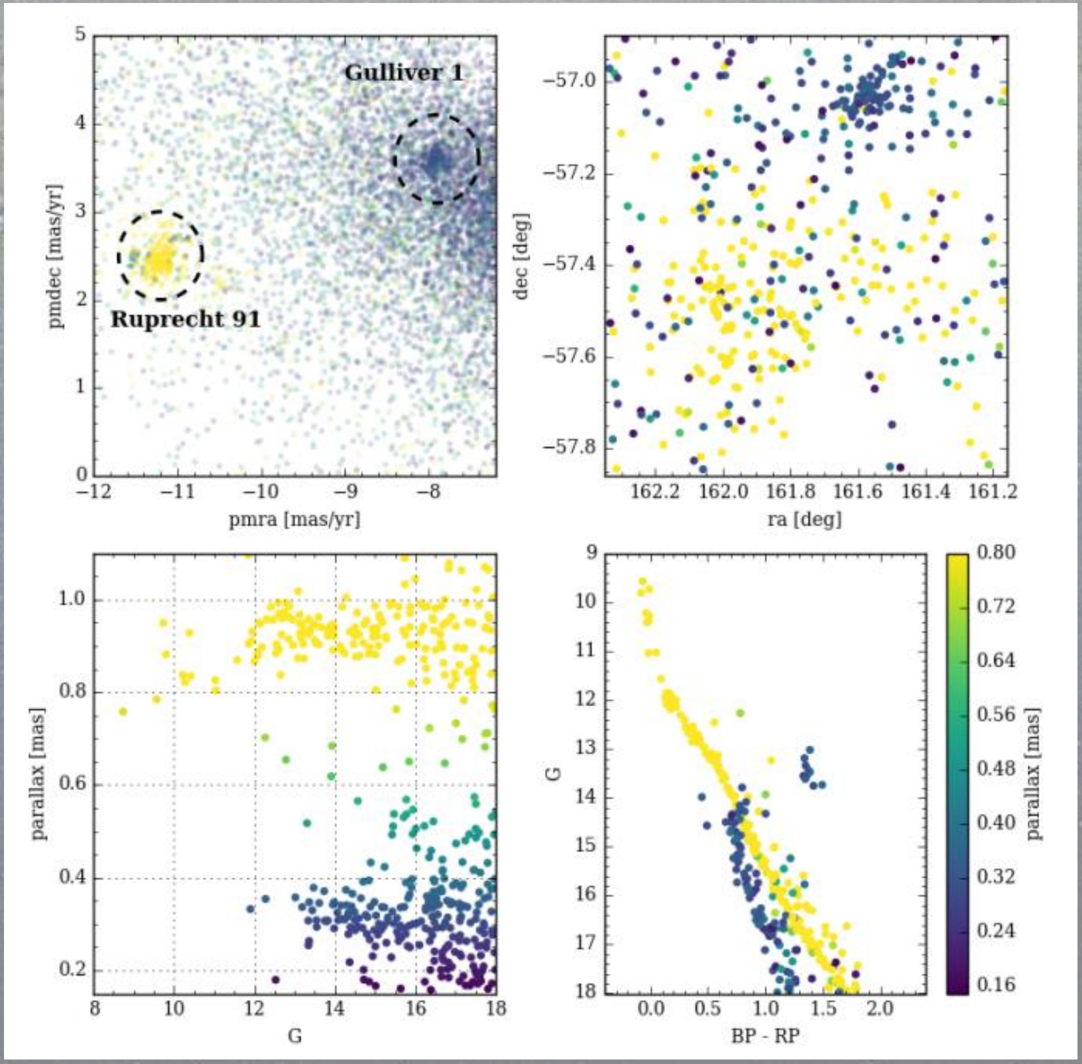


Antoja et al. 2020;
Ramos et al. 2020

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

★ **CLUSTER SCIENCE!**



Cantat-Gaudin et al. 2018

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

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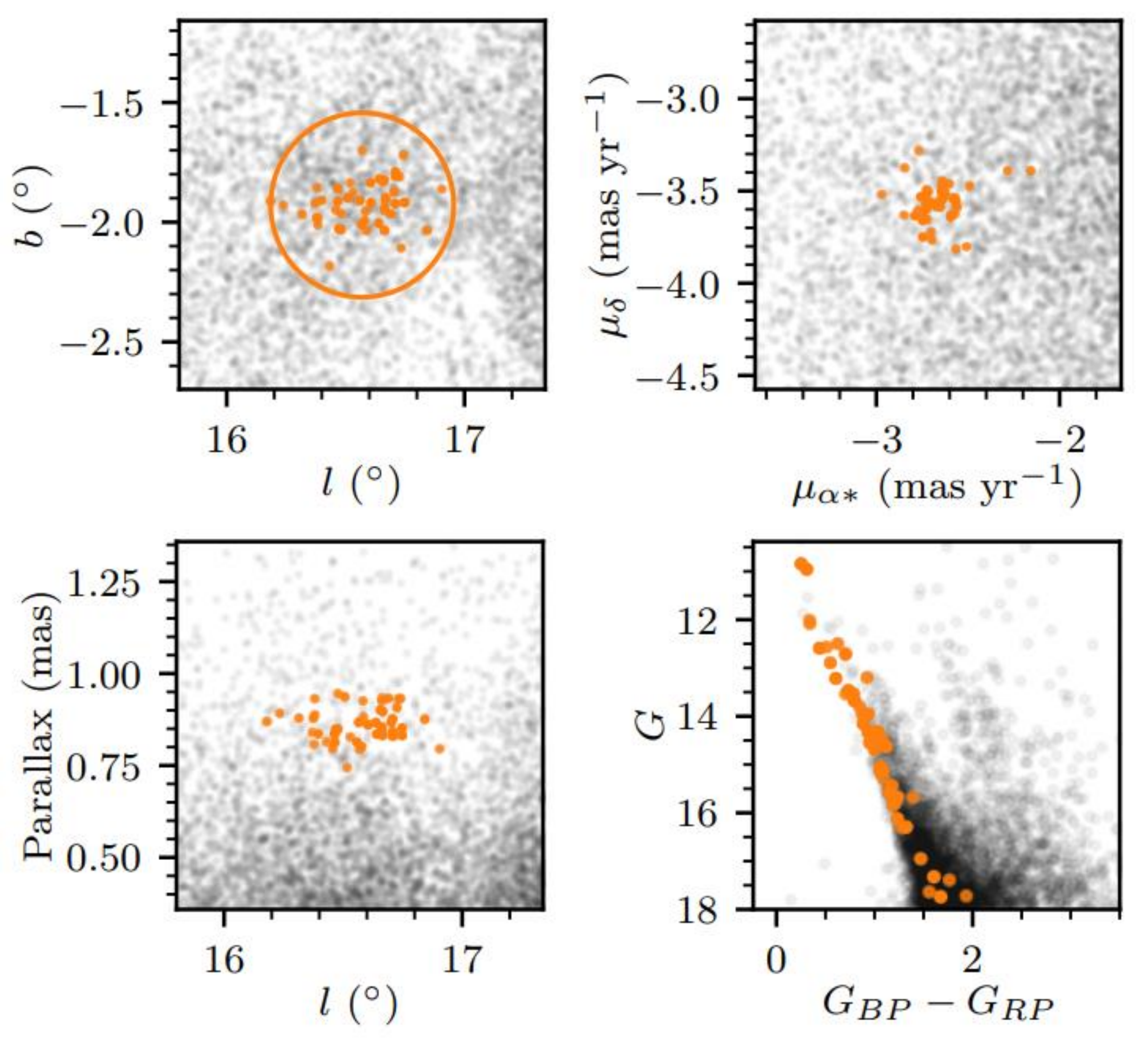
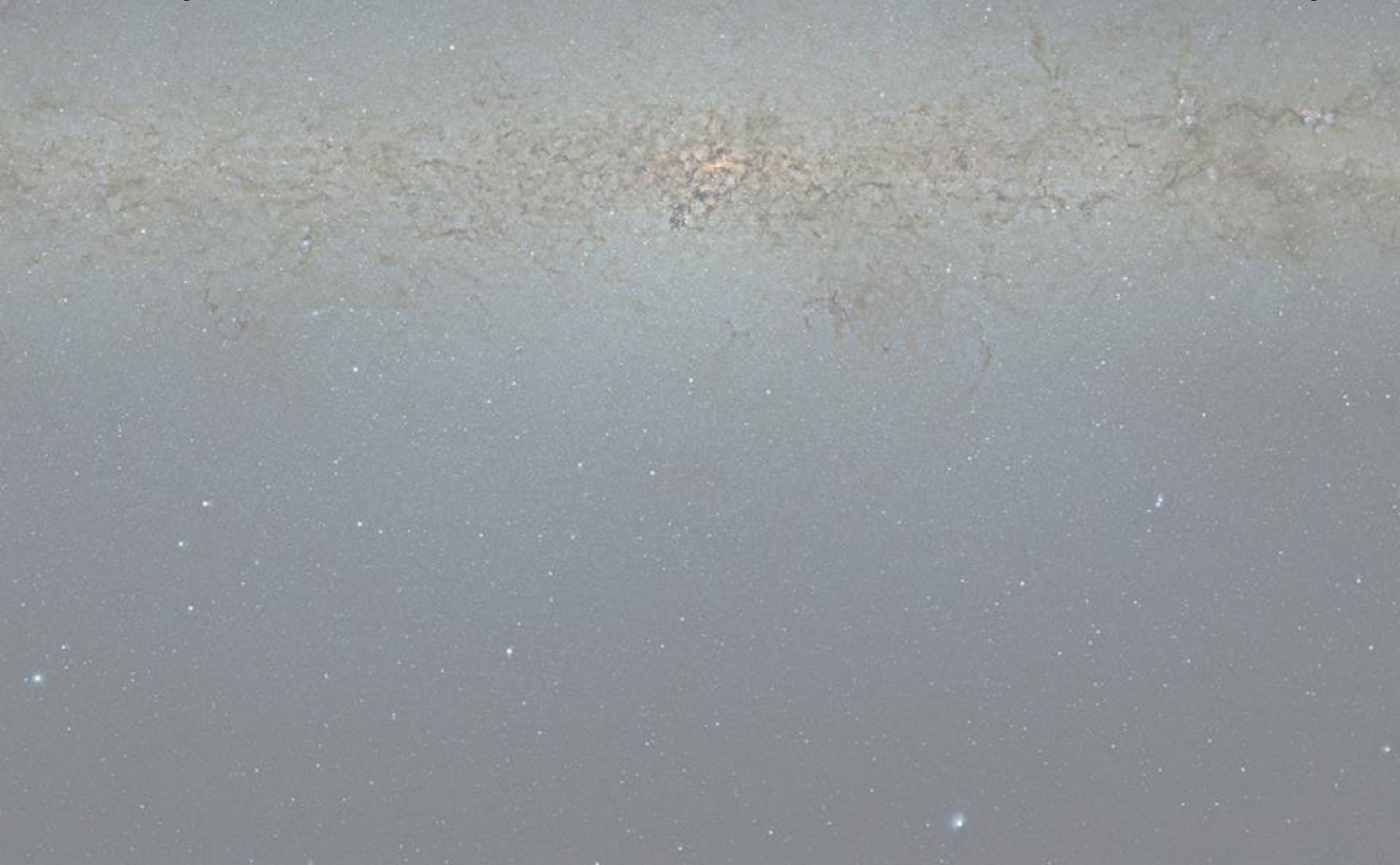


Hunt & Reffert 2021

Hidden in the haystack:

New globular clusters towards the Milky Way bulge



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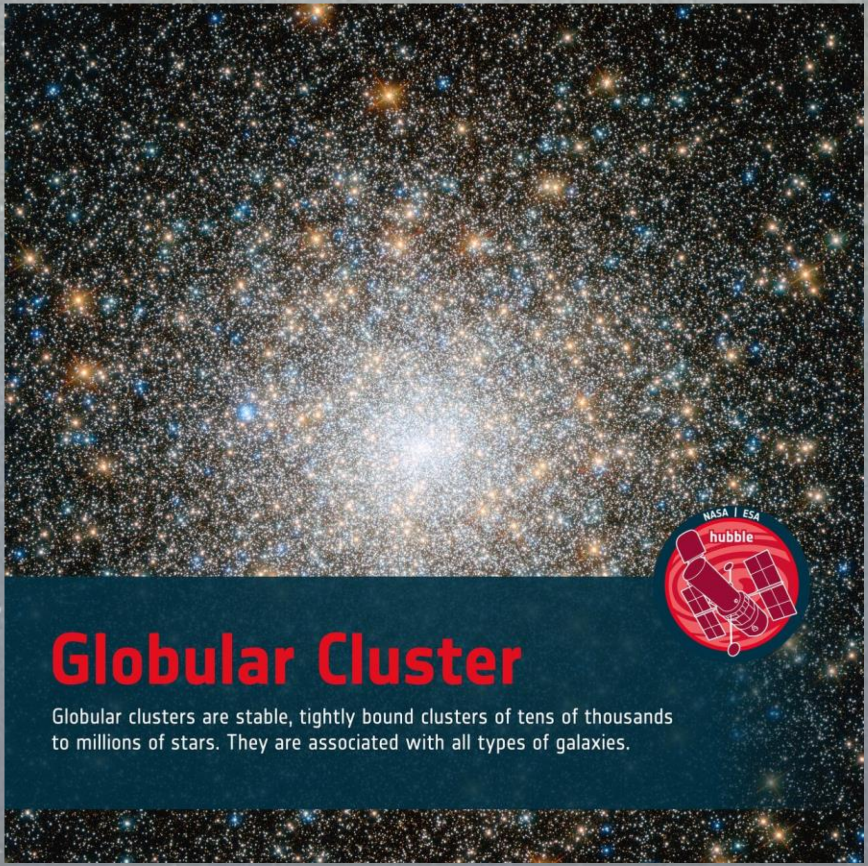

Credit: NASA & ESA

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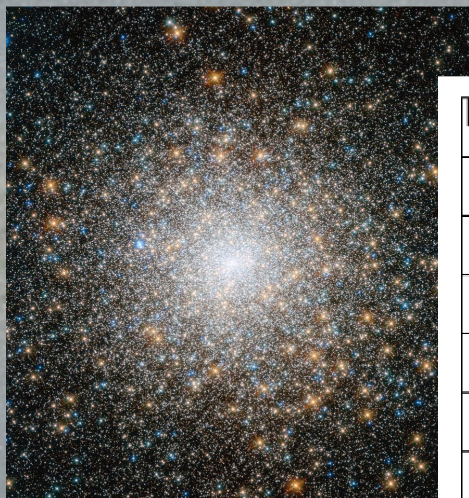

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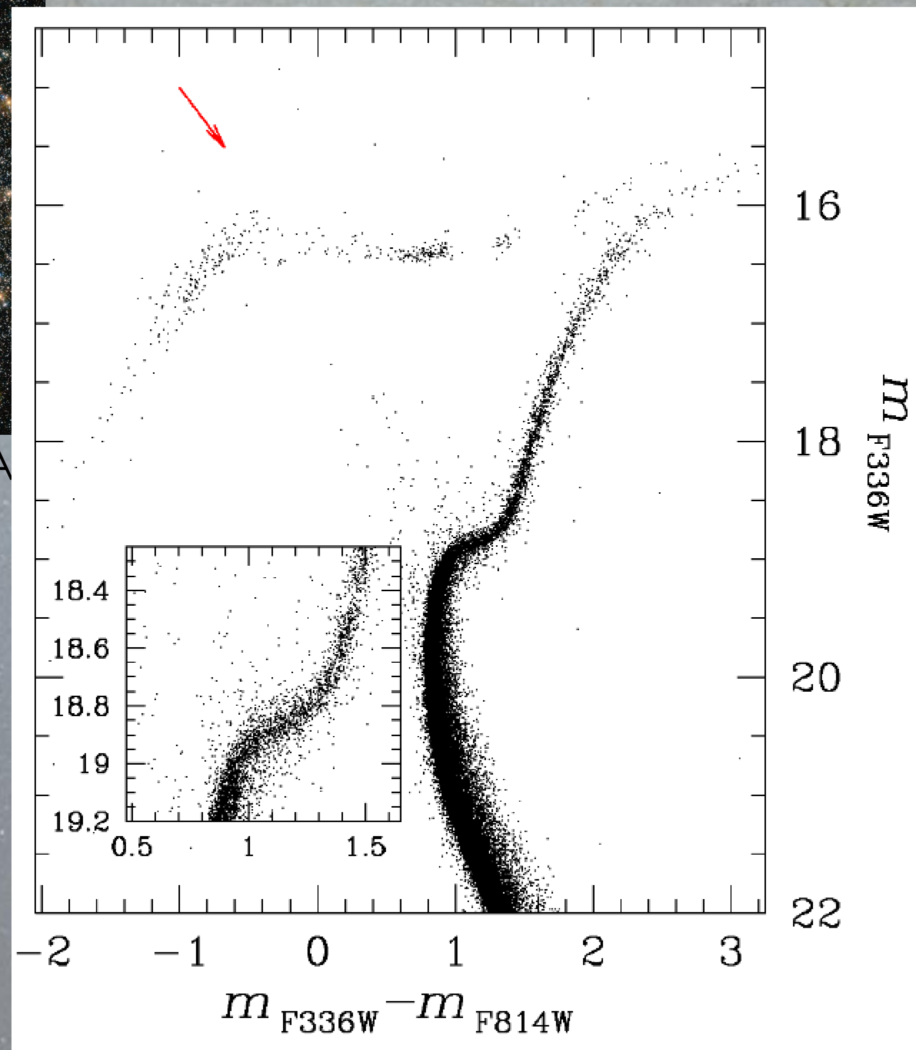

Nardiello et al. 2018

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Aladin Sky Atlas (Bonnarel et al. 2000,
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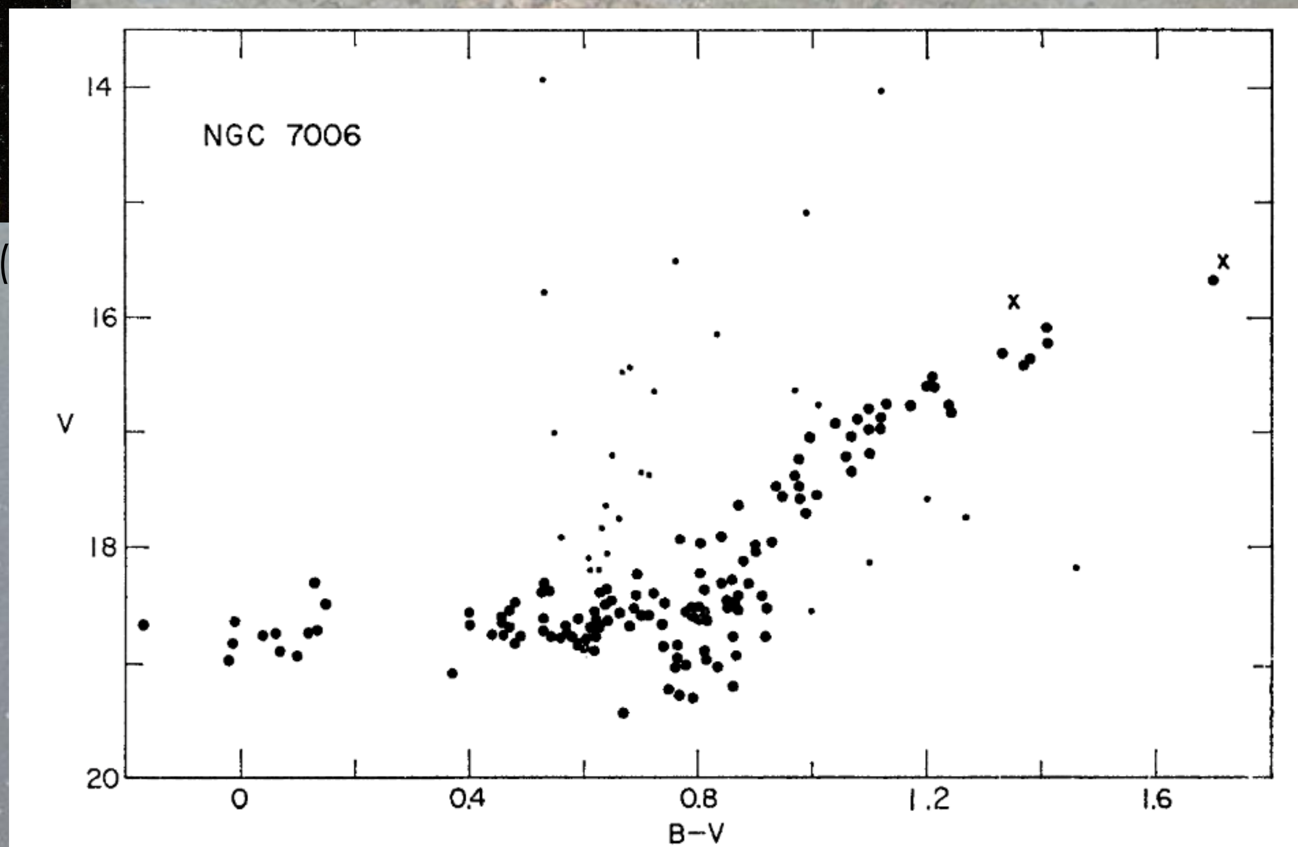

Sandage & Widley 1967

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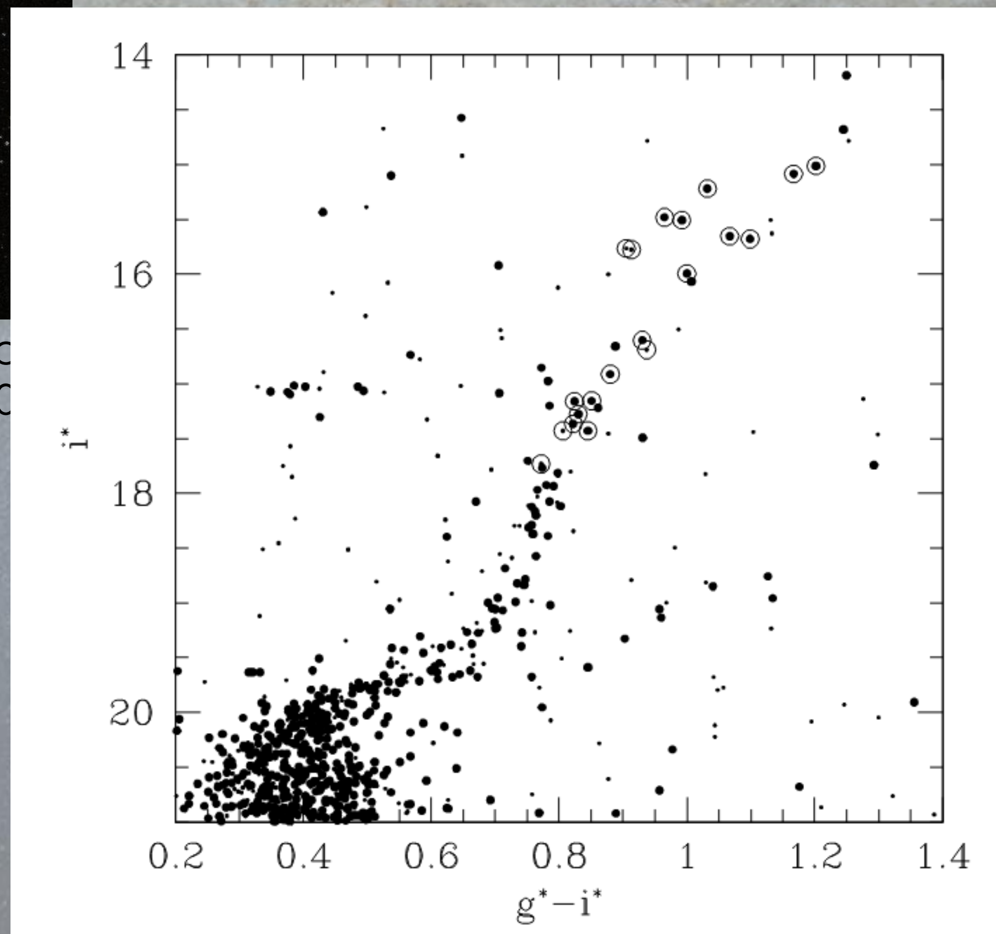

Odenkirchen et al. 2002

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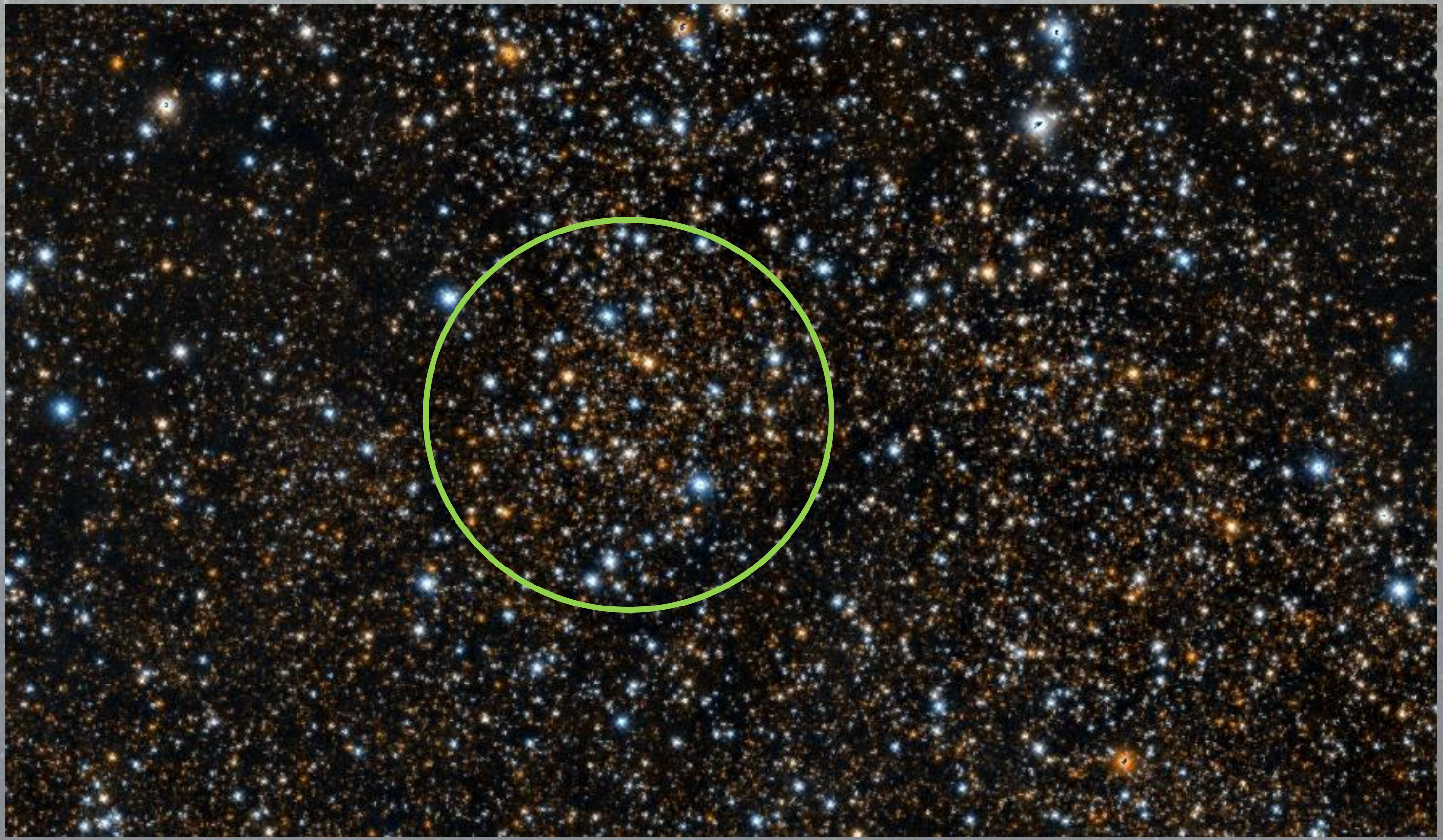

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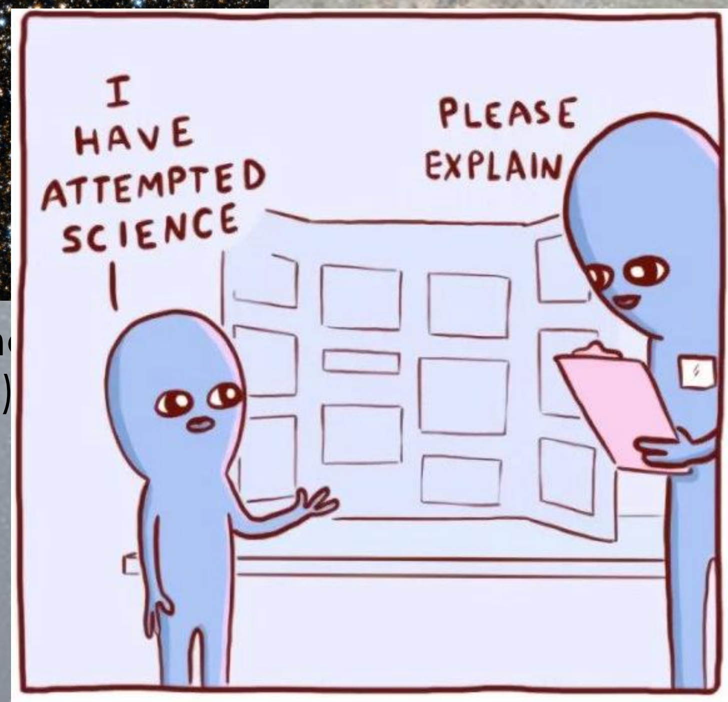

@nathanwpyle: STRANGE PLANET

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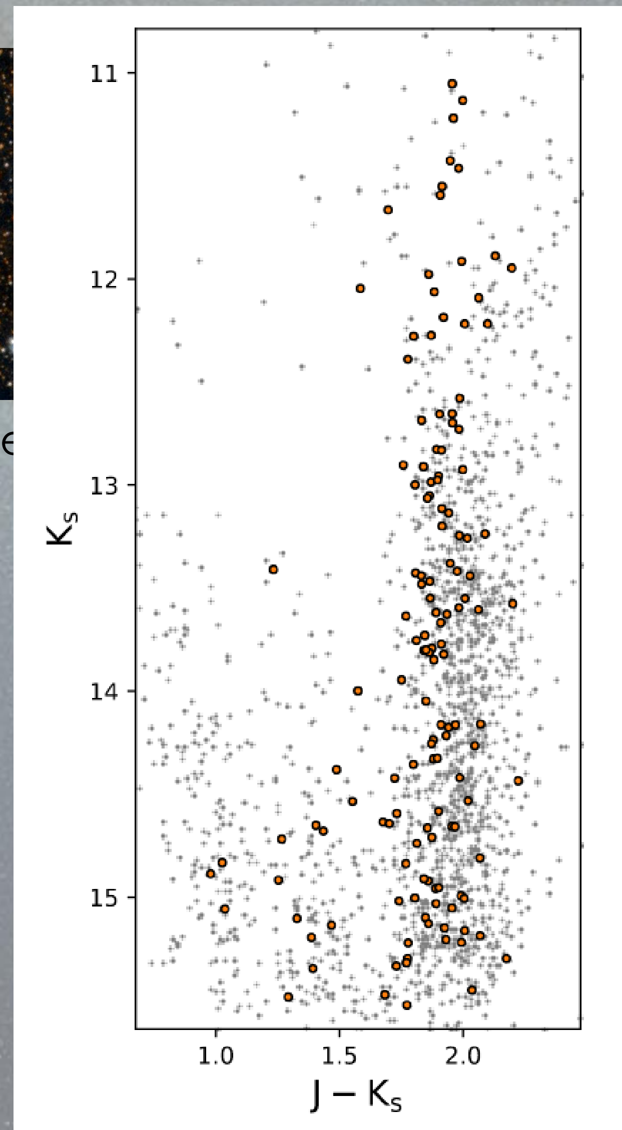

Gran et al. 2019

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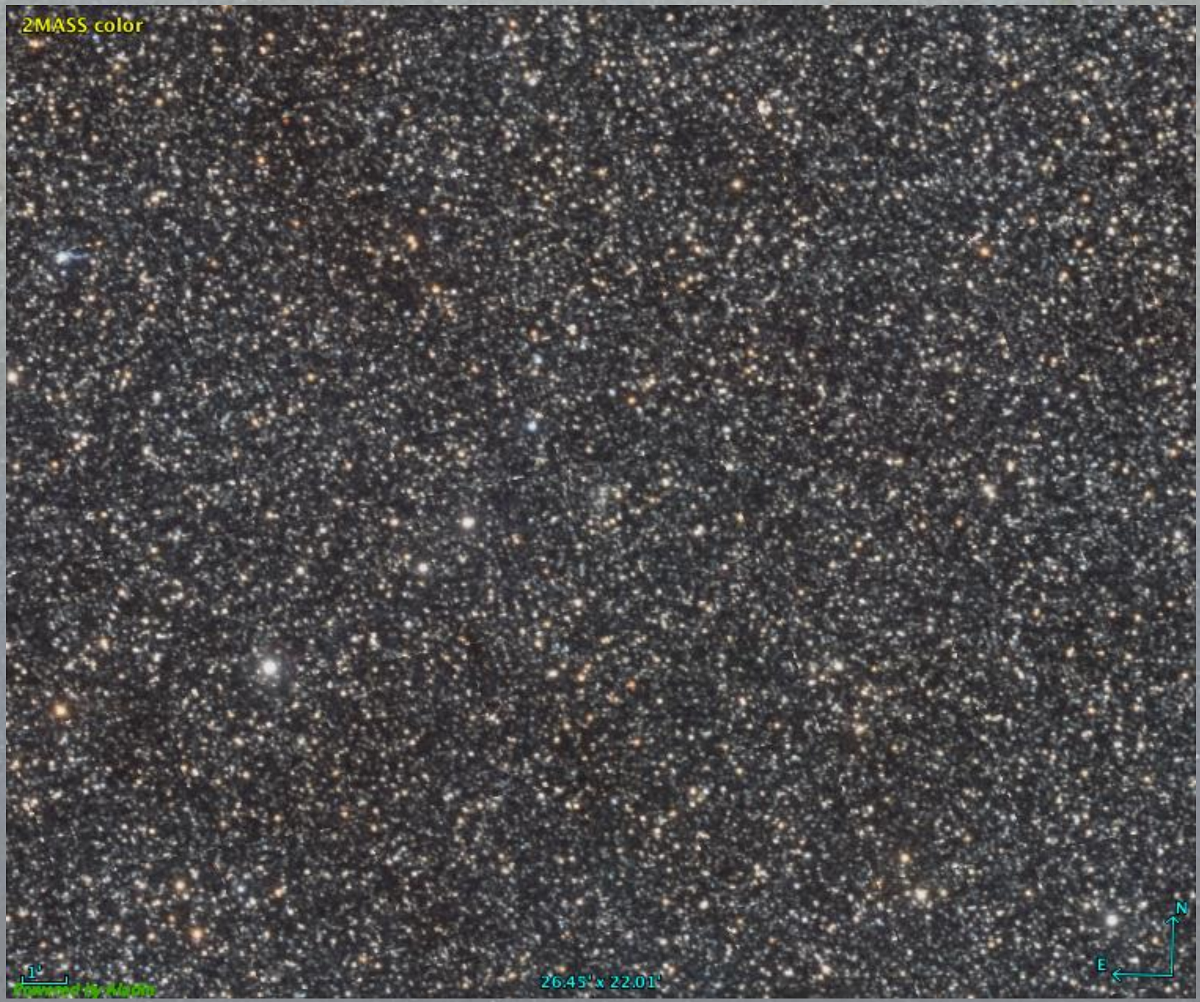

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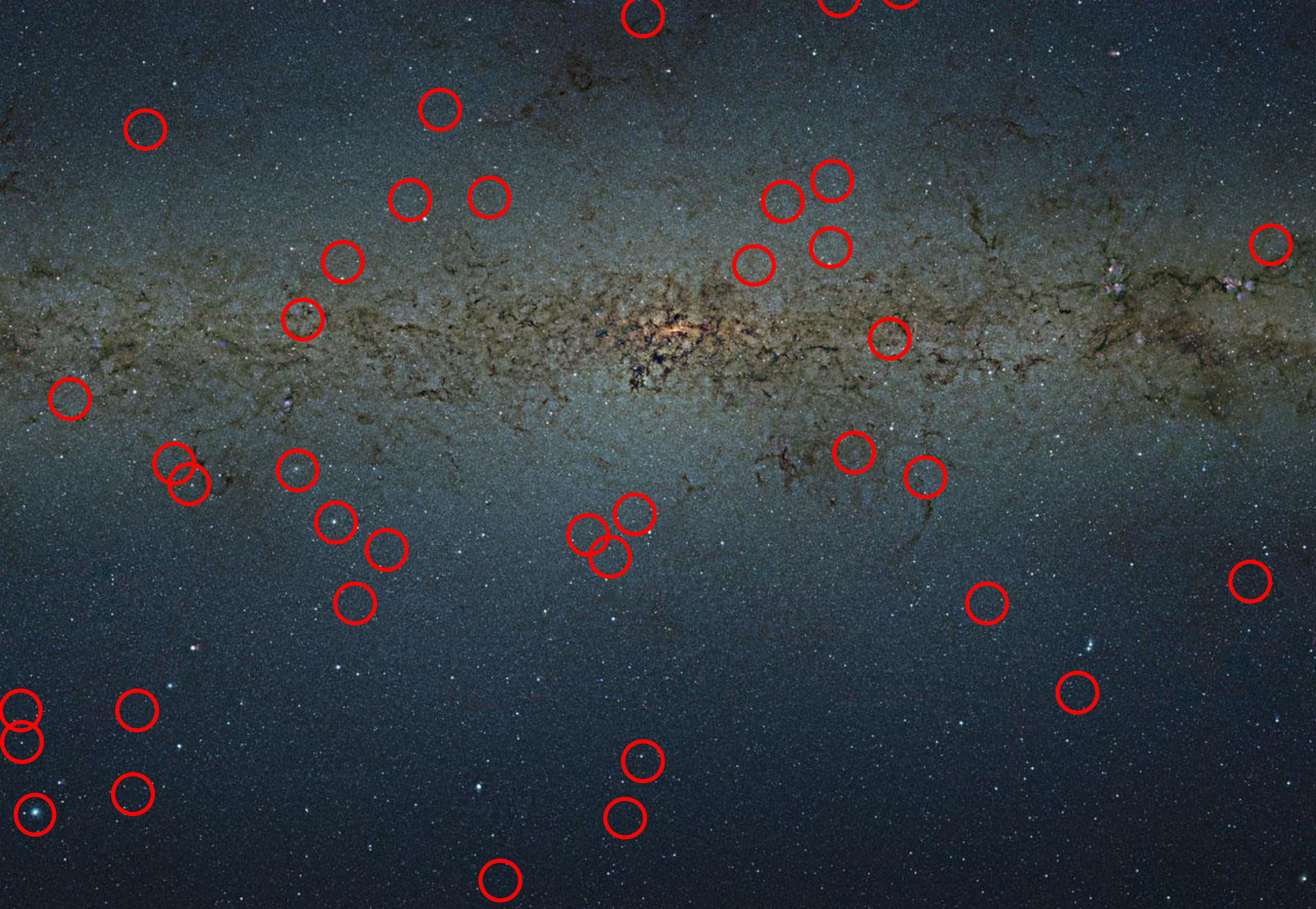
Aladin Sky Atlas (Bonnarel et al. 2000, Boch & Fernique 2014)

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

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

…AR CLUSTER IN THE CONSTELLATION OF CENTAURUS

Dongwon … Mackey, Gary S. Da Costa, and Antonino P. Milone
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Re… February 12; published 2016 March 29

DISCOVERY OF A FAINT O… CLUSTER IN THE SOUTHERN SKY

Dongwon Kim, Helmut Jerjen, A… and Gary S. Da Costa
Research School of Astronomy and Astrophysics, The Australian Nat… …tter Road, Weston, ACT 2611, Australia;
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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[2] INAF-Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padua, Italy
[3] Universidade Federal do Rio Grande do Sul, Departamento de Astronomia, CP 15051, Porto Alegre 91501-970, Brazil
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…s Center for Cosmology, Carnegie Mellon University, 5… …5213, USA

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Recei…

…AR CLUSTER IN THE … …US

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

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
…nology, Pasadena, CA 91125, USA

…: published 2012 June 15

…Y OF A FAINT … …IN THE SOUTHERN SKY

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

…KY WAY GLOB… …RVEY

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

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THE DISC…

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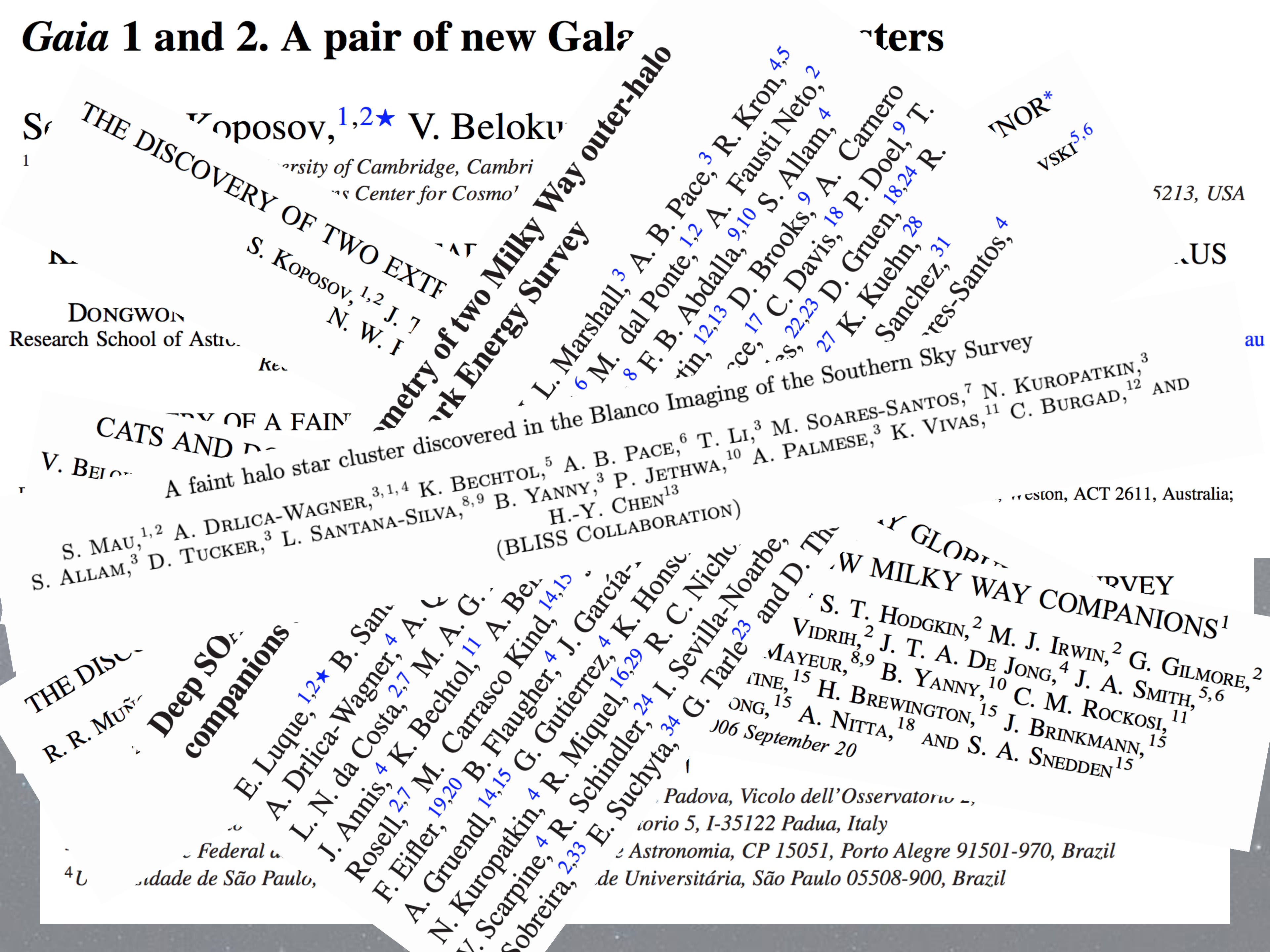
Gaia 1 and 2. A pair of new Gala... ...sters
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S. KOPOSOV, 1,2 J. ...
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6 M. dal Ponte, 1,2 A. Fausti Neto, 2
8 F. B. Abdalla, 9,10 S. Allam, 4
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A 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
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H.-Y. CHEN 13
(BLISS COLLABORATION)
CATS AND D...
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...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
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R. R. MUÑ...
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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-...
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...Scarpine, 4 R. Schindler, 24 I. Sevilla-Noarbe, ...
...Sobreira, 2,33 E. Suchyta, 34 G. Tarle 23 and D. Th...
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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

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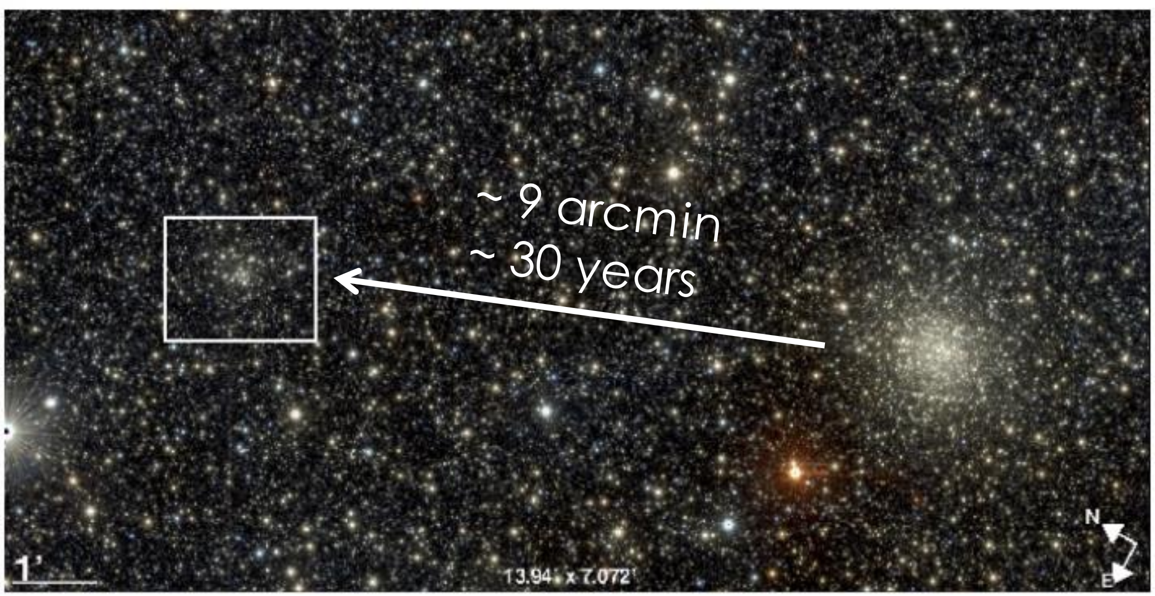

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Photometric searches of GCs

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**):

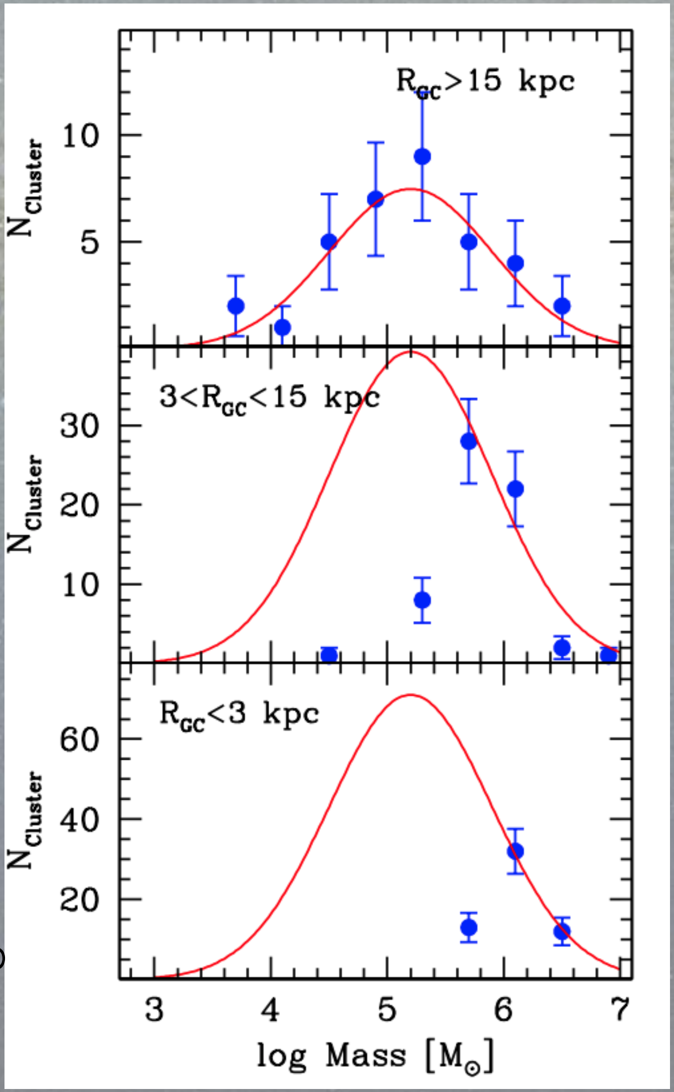
★ Spatial overdensities ☑

★ CMD different from field ⚠

★ Coherent space motion 🛑

Initial mass distribution of GCs in the MW

Baumgardt et al. 2018

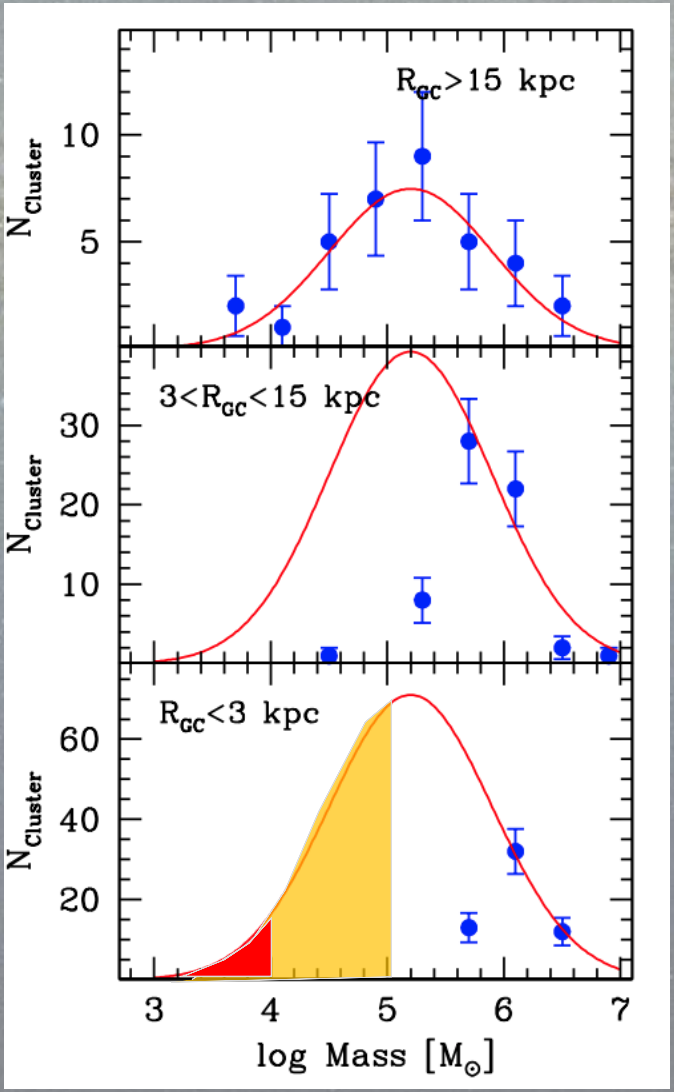


~Halo GCs

~Disk GCs

~Bulge GCs

Initial mass distribution of GCs in the MW



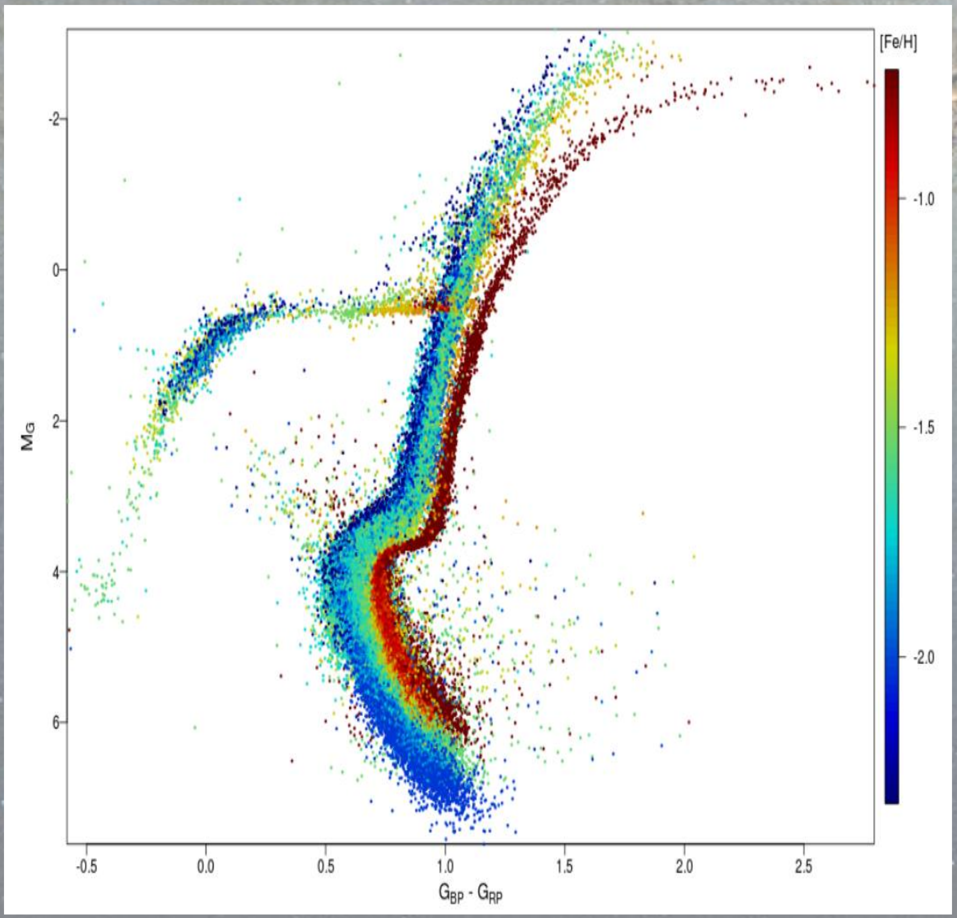
Baumgardt et al. 2018

~Halo GCs

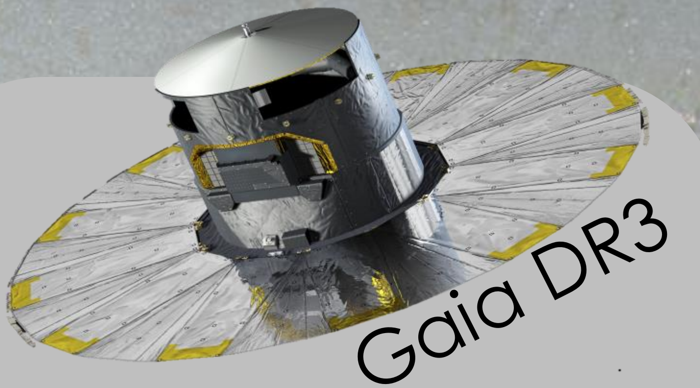
~Disk GCs

~Bulge GCs

Gaia DR3 proper motion catalogue



Gaia Collaboration et al. 2018



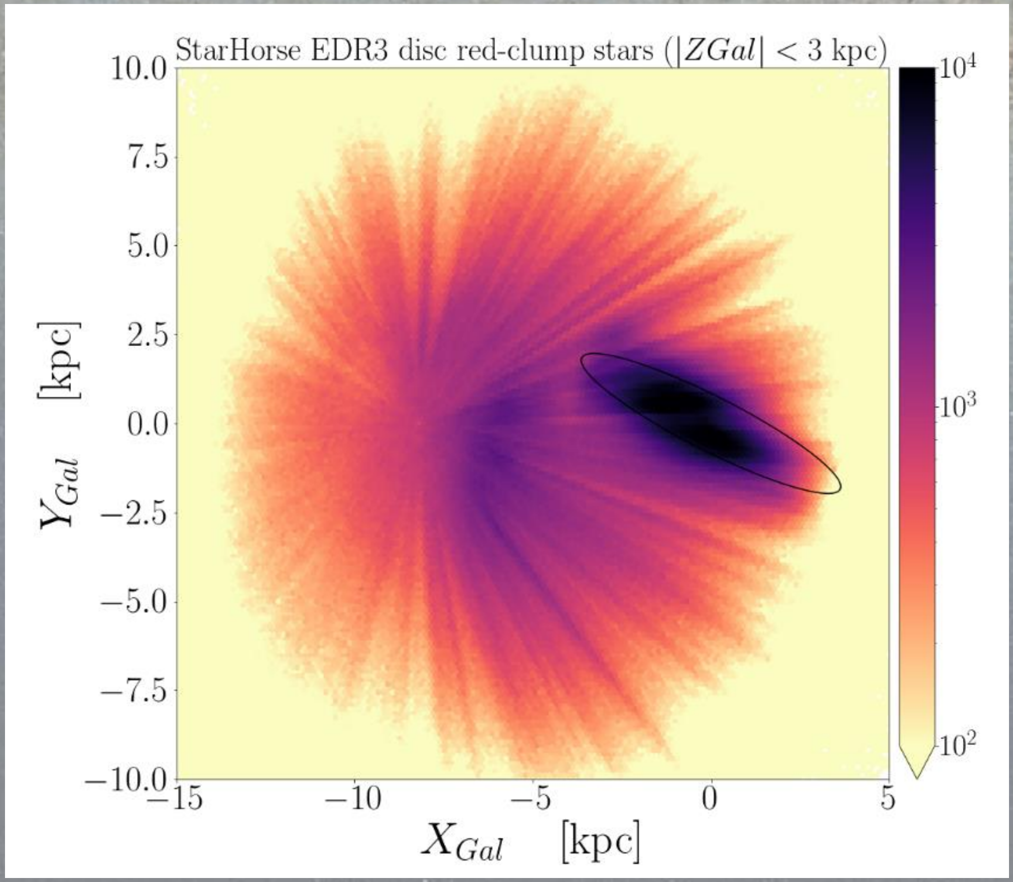
Optical survey
(G,G_{BP},G_{RP},
G_{RVS}, XP spectra)

Valid for $|b| \geq 2°$

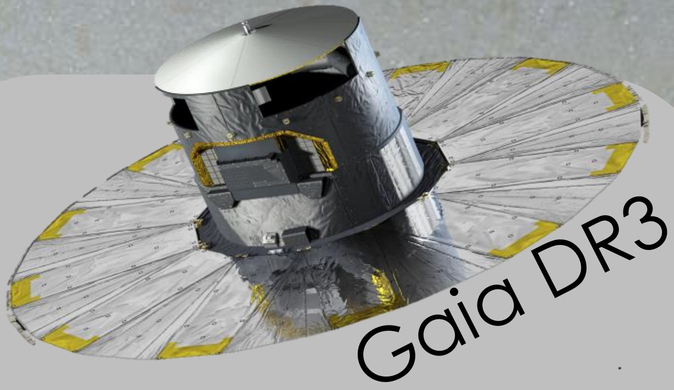
Absolute proper motions:
$\mu_\alpha \cos(\delta)$, μ_δ

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

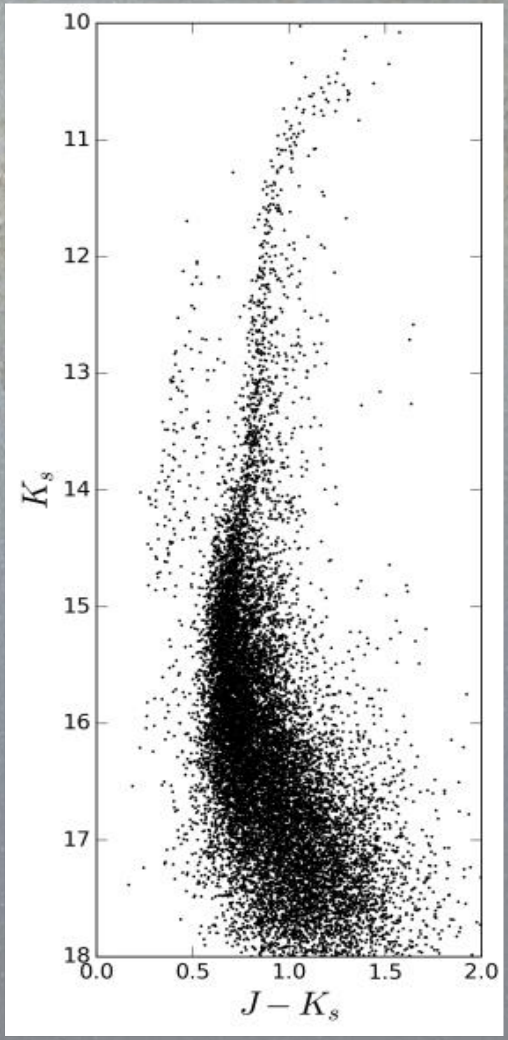
Gaia Collaboration 2018

VVV survey catalogue

Near-IR survey
(ZYJH**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

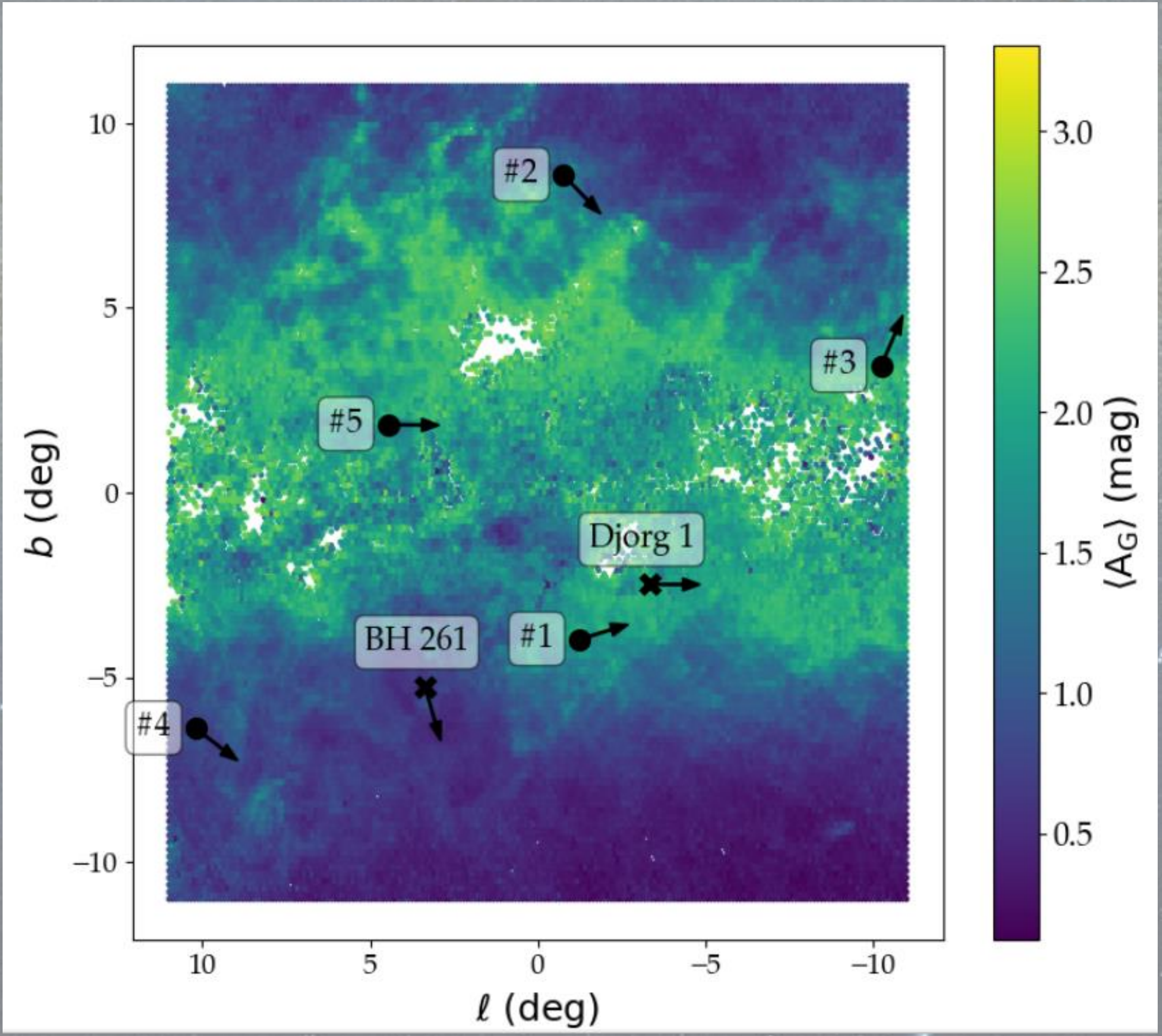
+

scikit learn: KDTree and DBScan

Pedragosa et al 2011

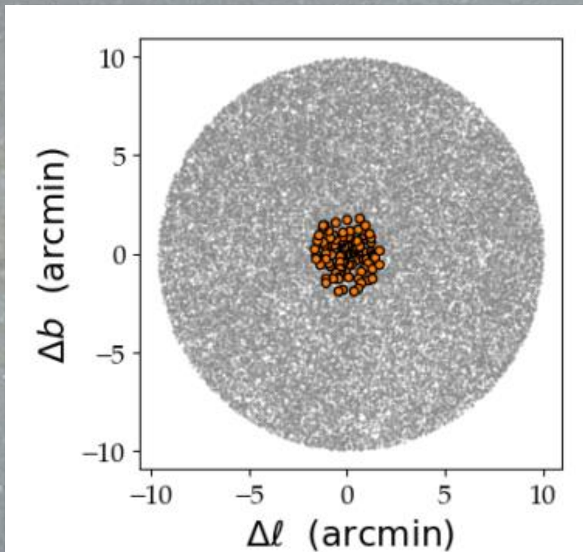
¡ Candidate clusters in the 5-D phase space !

Map of the new GCs



Gran et al. 2022

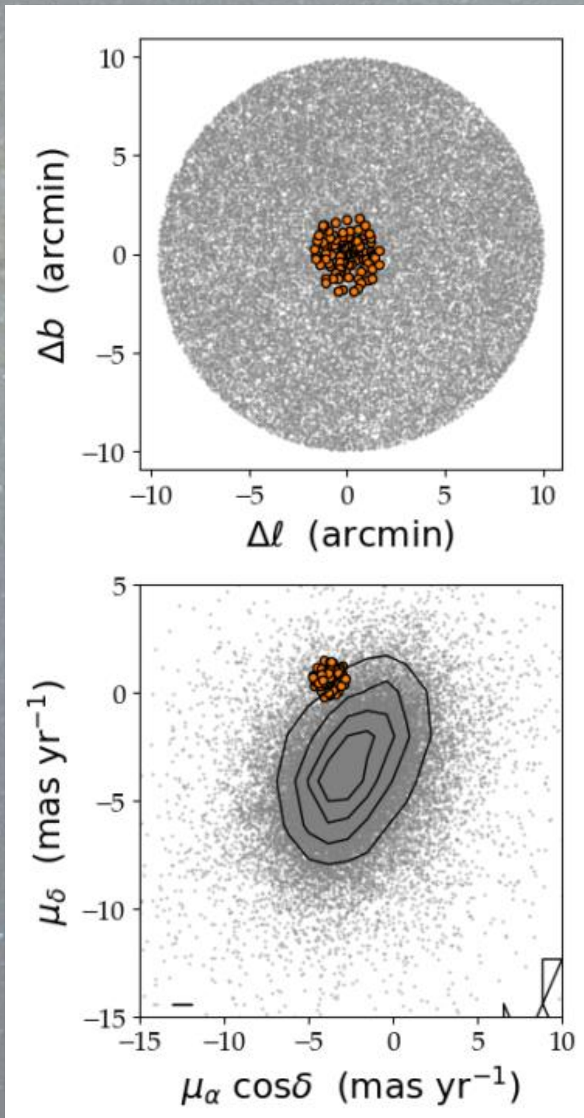
New GCs: the case of Gran 3



Clustering requirements:

- Grouped in space (ℓ,b)

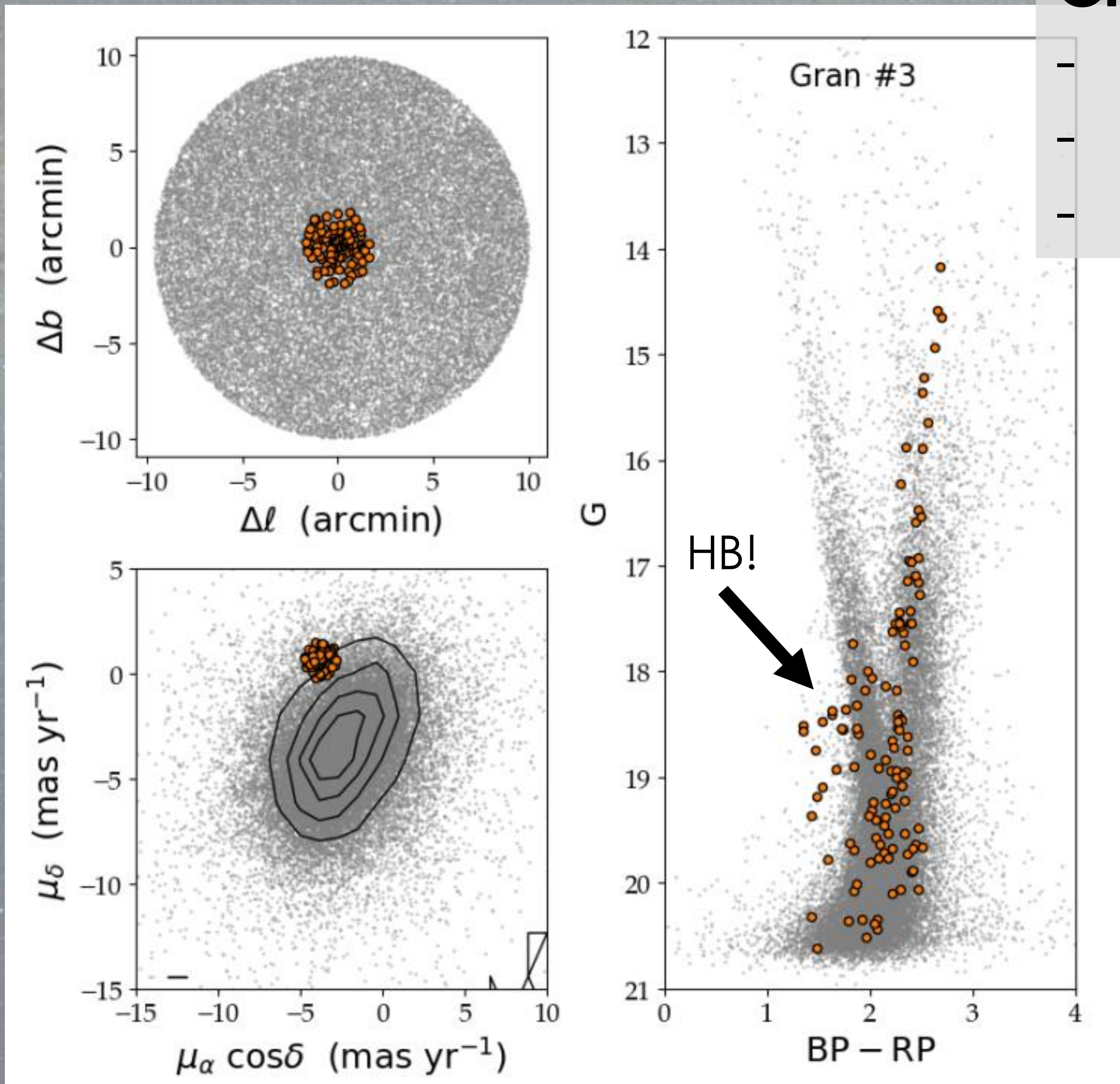
New GCs: the case of Gran 3



Clustering requirements:

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

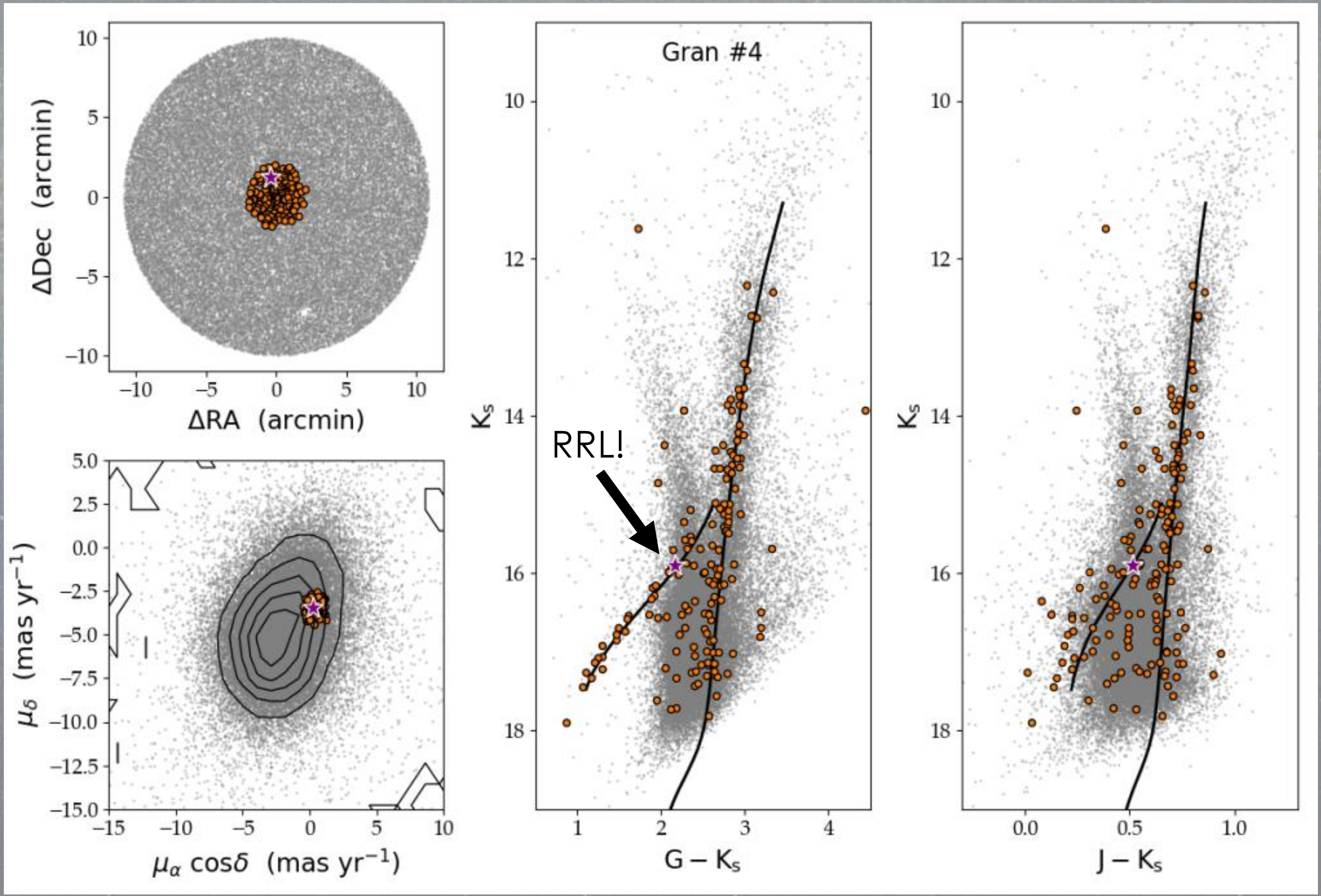
New GCs: the case of Gran 3



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

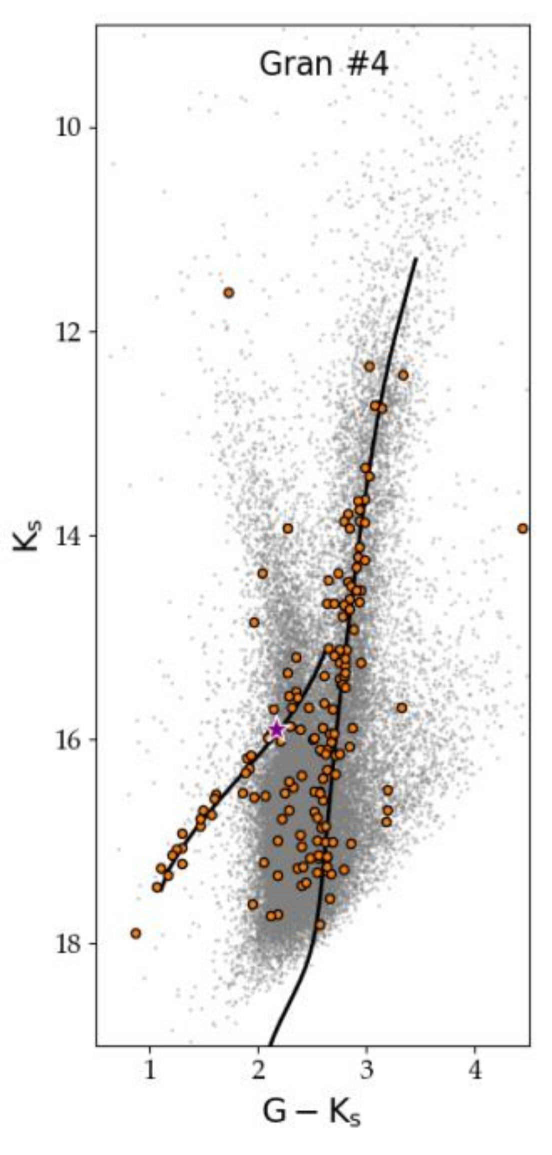
Gran et al. 2022

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} ~ 4×10^5 $M_\odot$

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

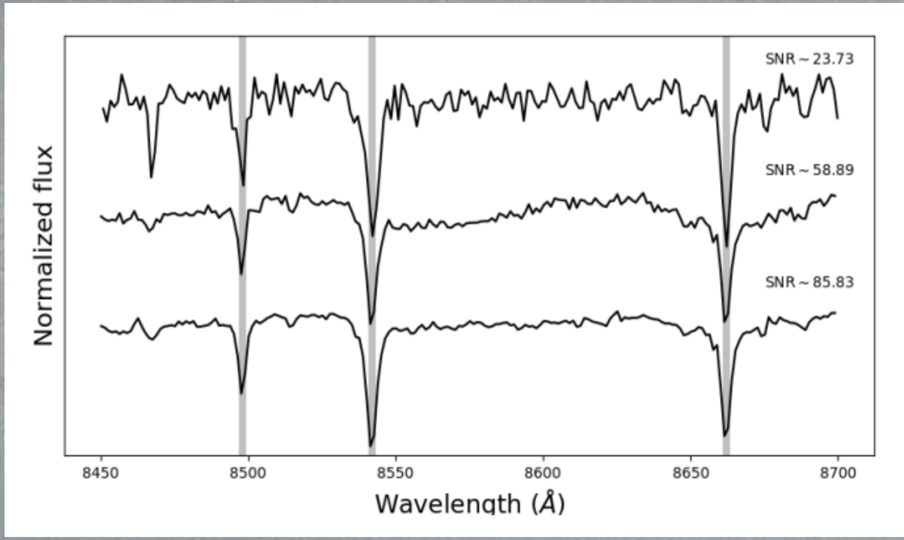
Gran et al. 2022

New GCs: MUSE observations

ESO P103-105
PI: F. Gran

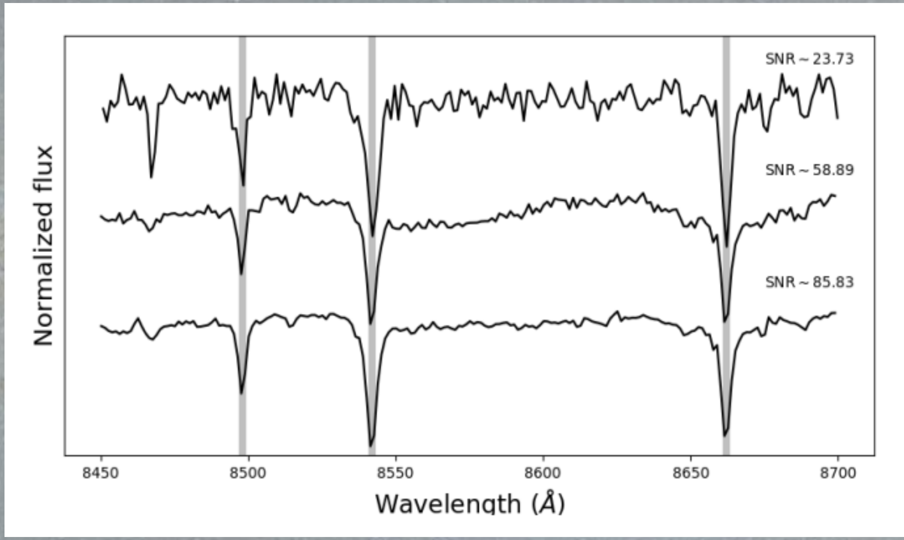
14 hours
WFM ~ 1 arcmin^2
4650 < λ (Å) < 9300
R @ 8800 Å ~ 4000

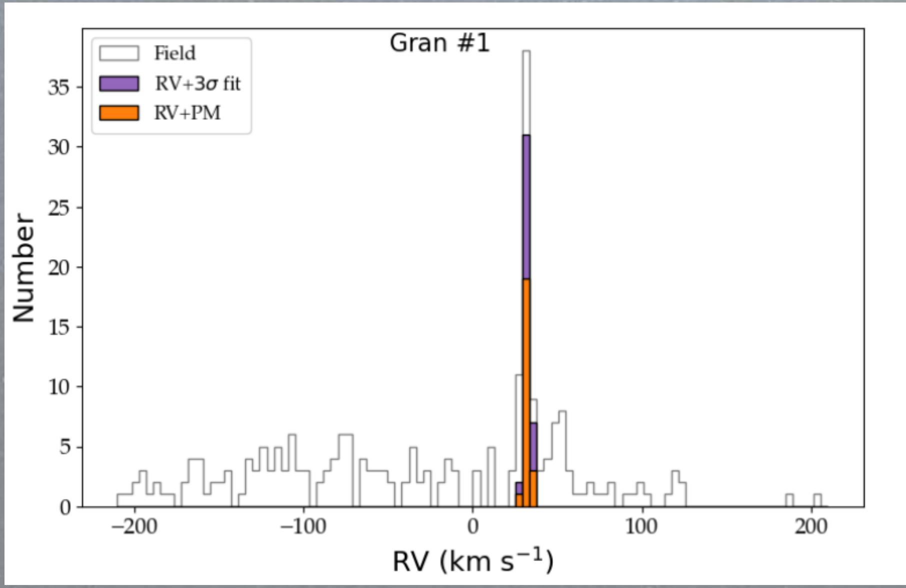
New GCs: MUSE observations



Gran et al. 2022

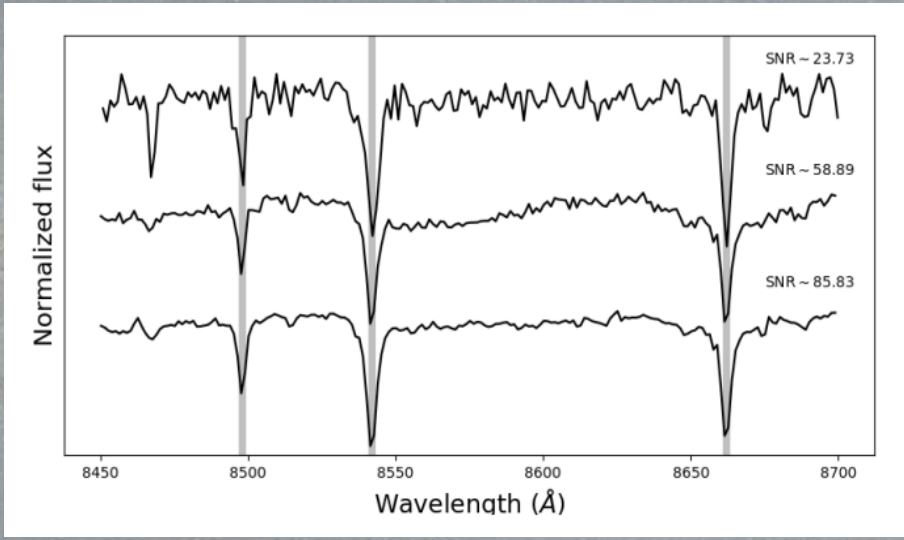
New GCs: MUSE observations

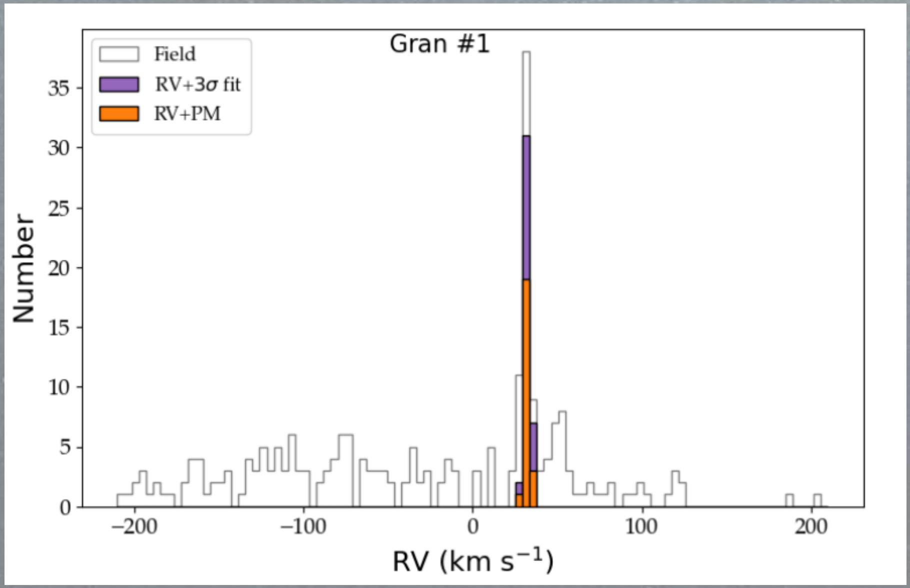


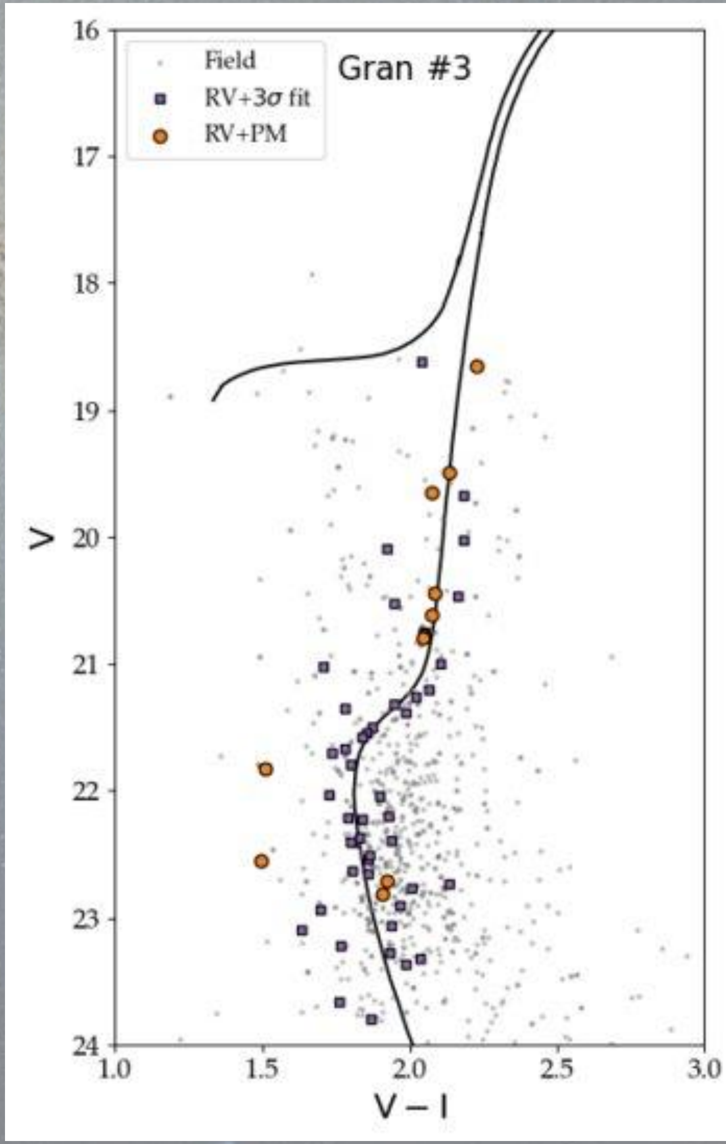


Gran et al. 2022

New GCs: MUSE observations







Gran et al. 2022

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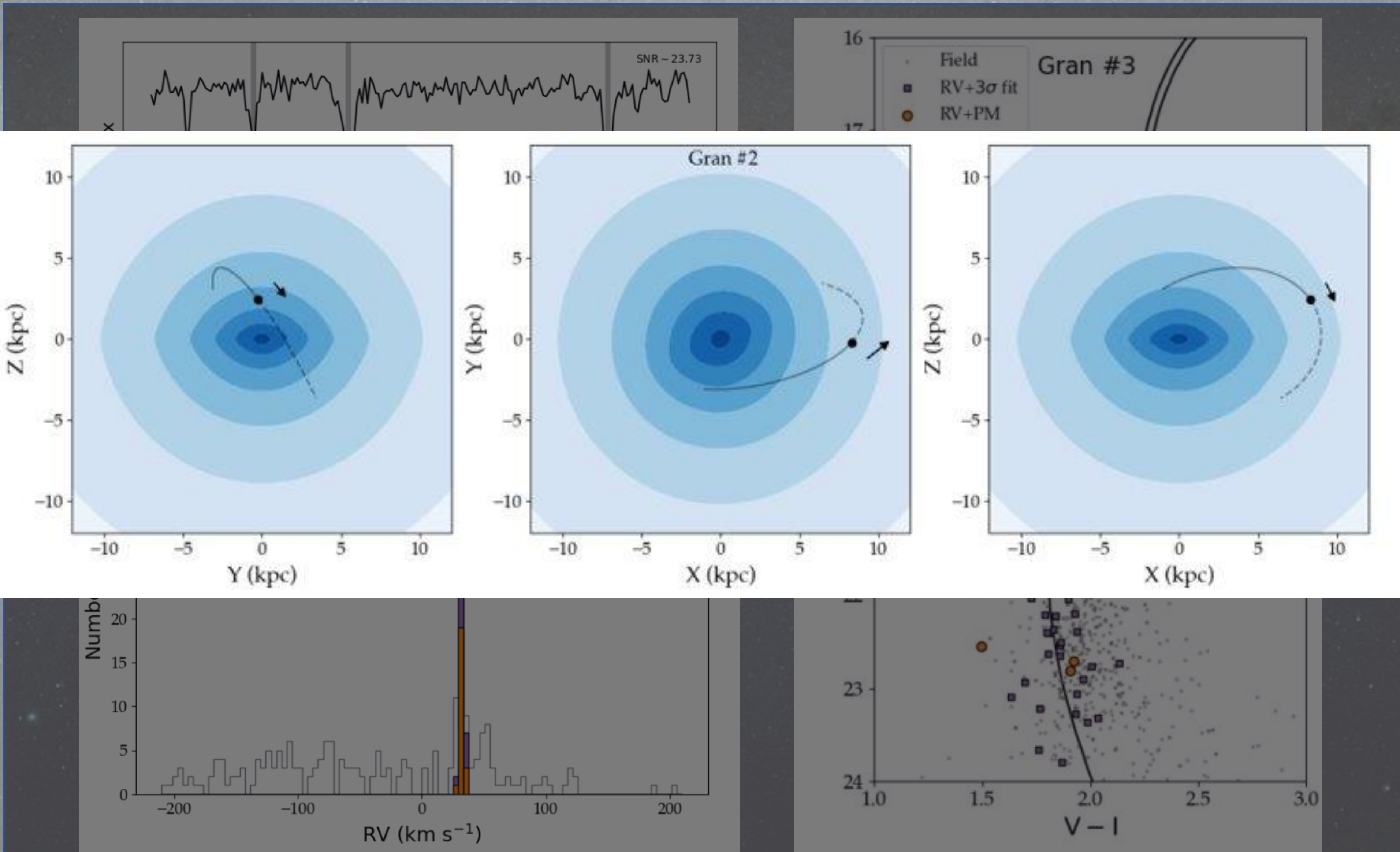


Gran et al. 2022

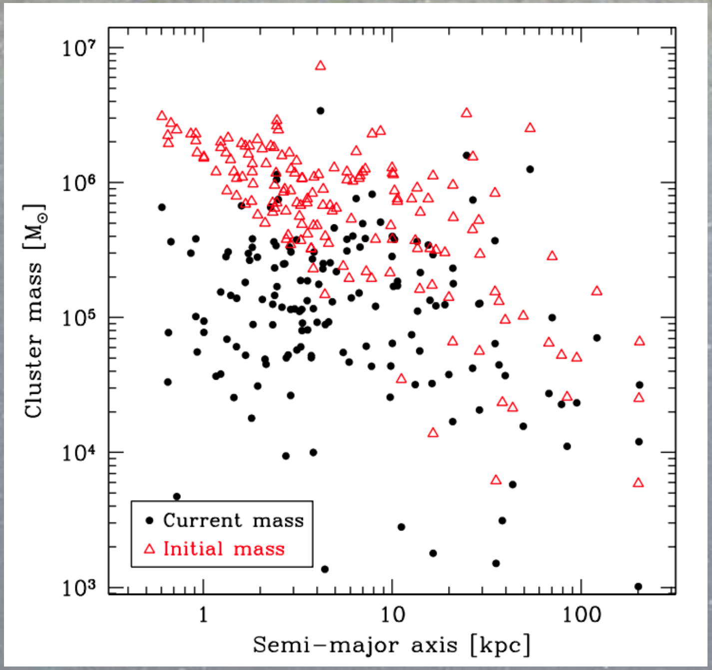
New GCs: MUSE observations

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

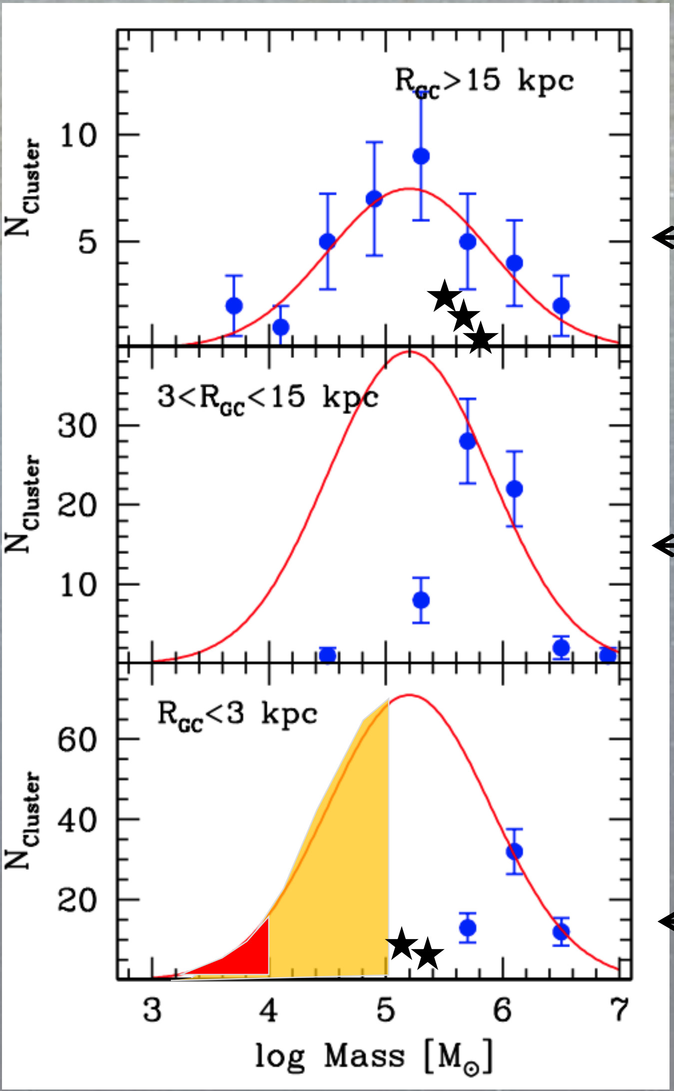
New GCs: Galactic context
Initial mass distribution



Baumgardt et al. 2018

Gran 2 + 3 + 4

Gran 1 + 5



← ~Halo GCs

← ~Disk GCs

← ~Bulge GCs

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**.

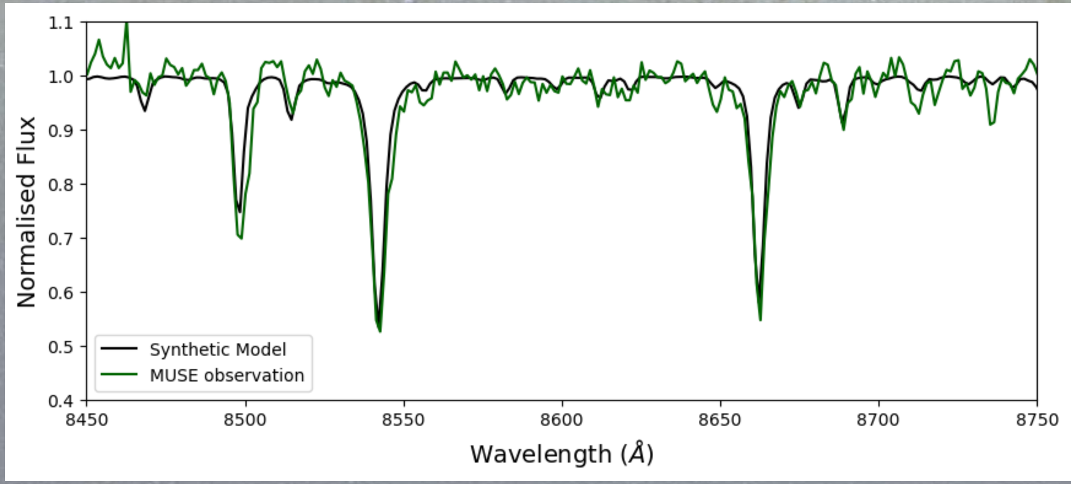
★ Using a clustering algorithm, we were able to discover **5 new** clusters with old stellar sequences.

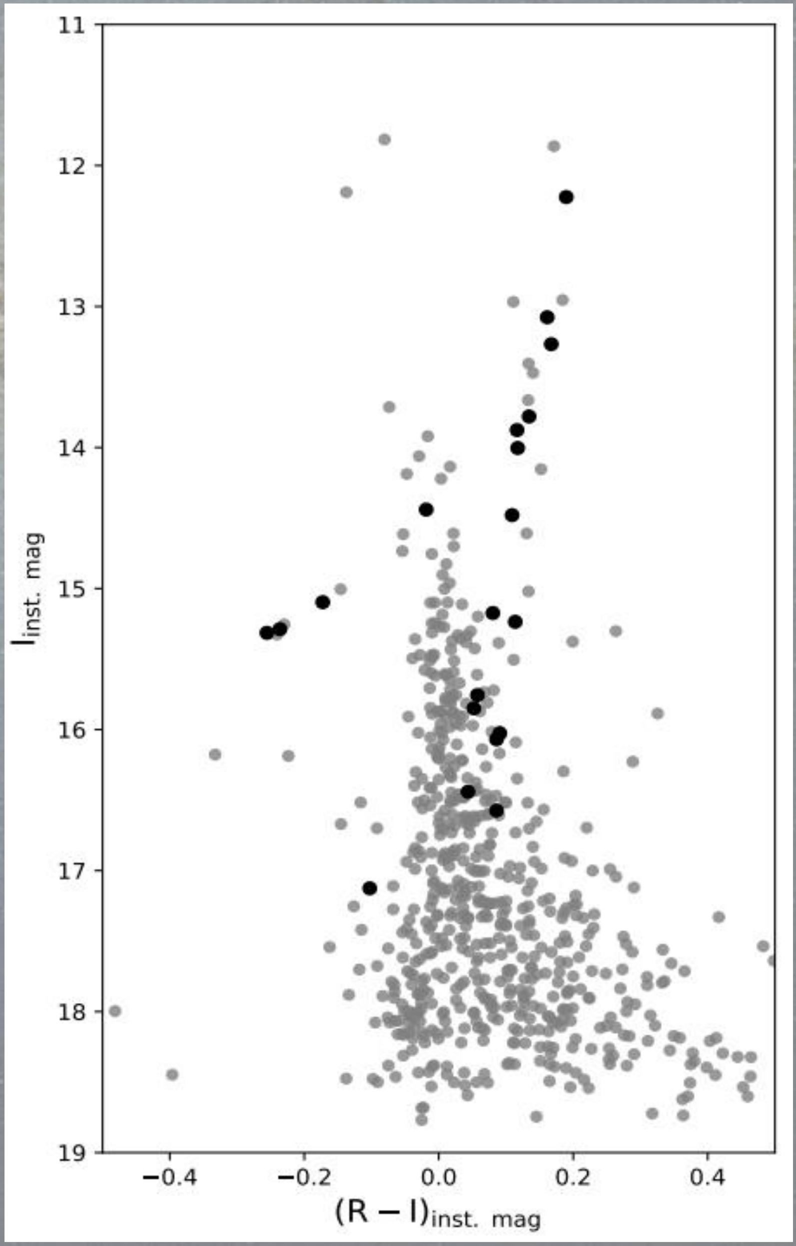
★ Orbital parameters and metallicities from the analysis of 5 **MUSE** cubes.

★ Key observable: **proper motions!**

Future work

★ Derive clusters metallicity via synthetic models



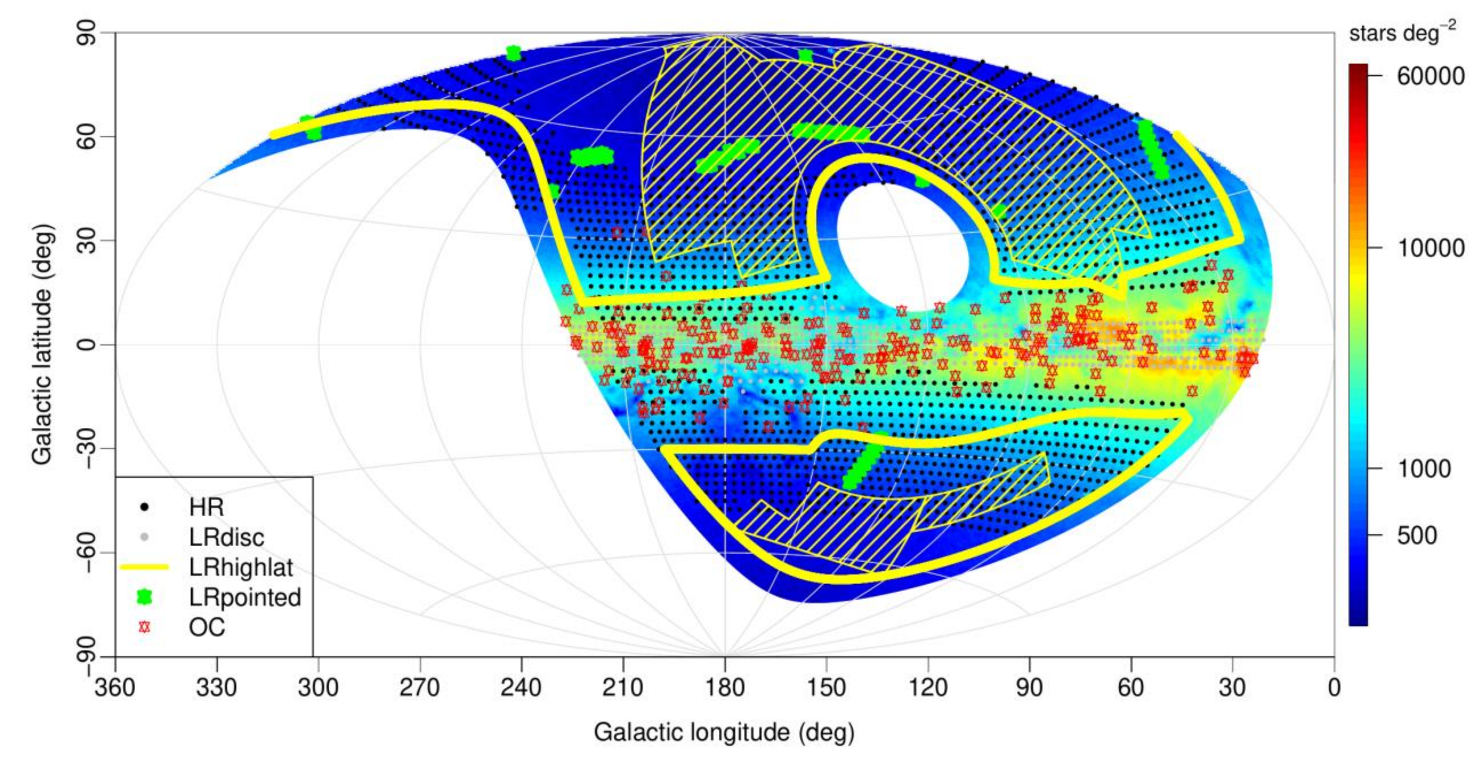


Future work

★ 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

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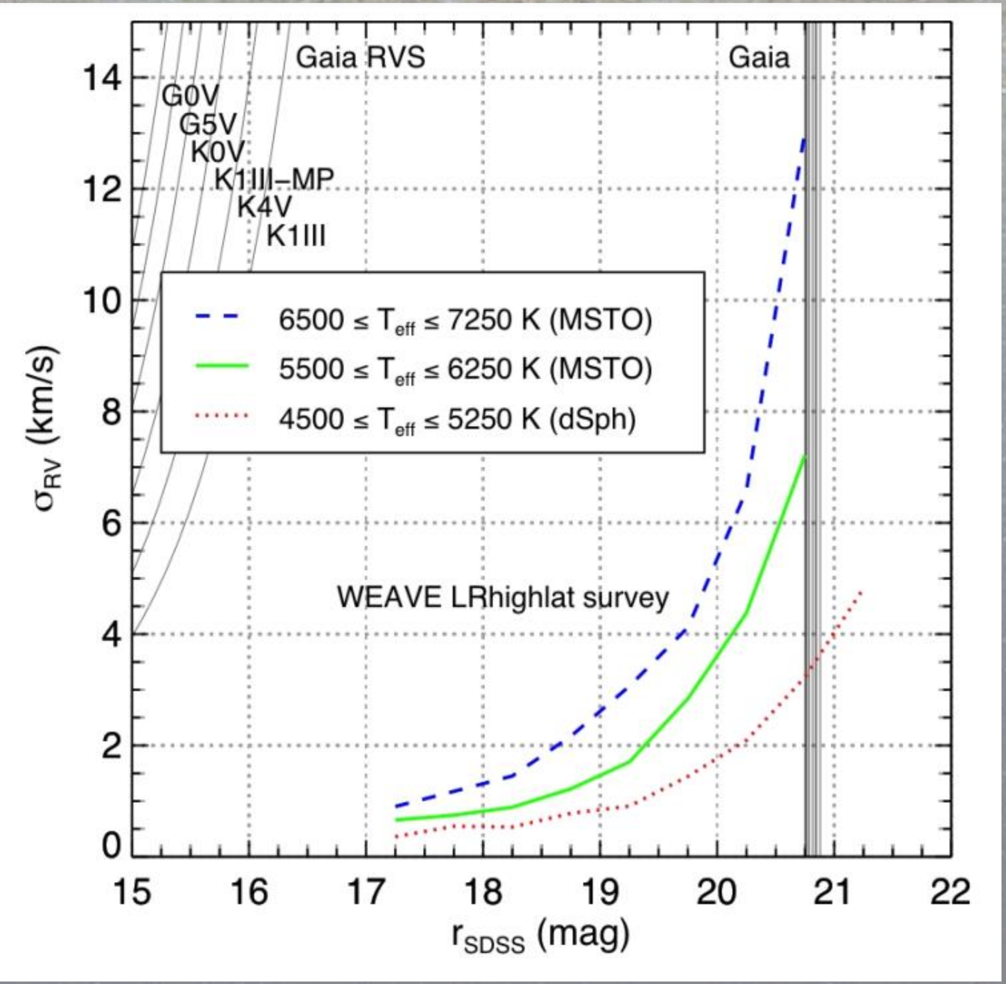
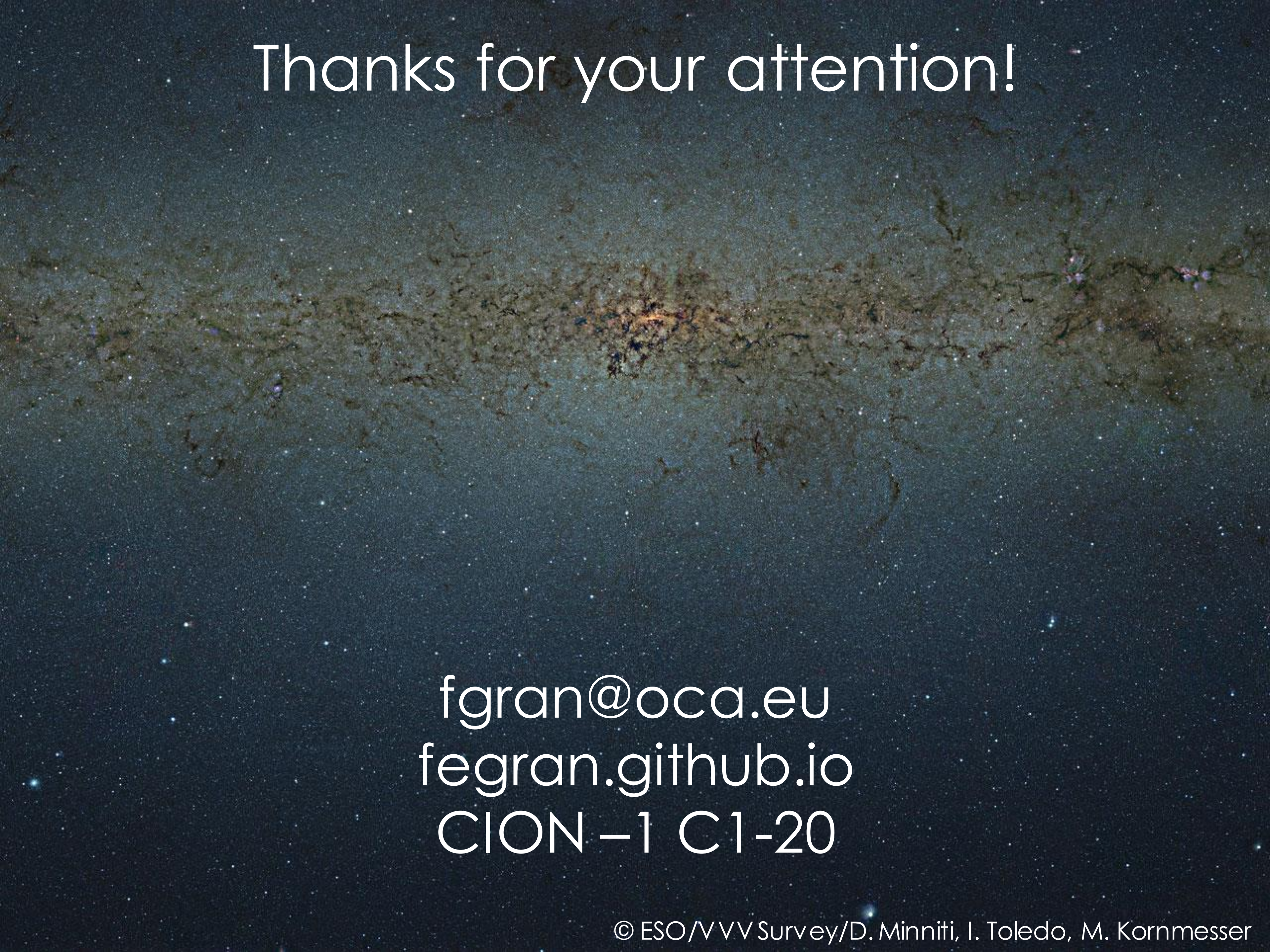


Jin et al. 2022



Thanks for your attention!

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fegran.github.io
CION –1 C1-20