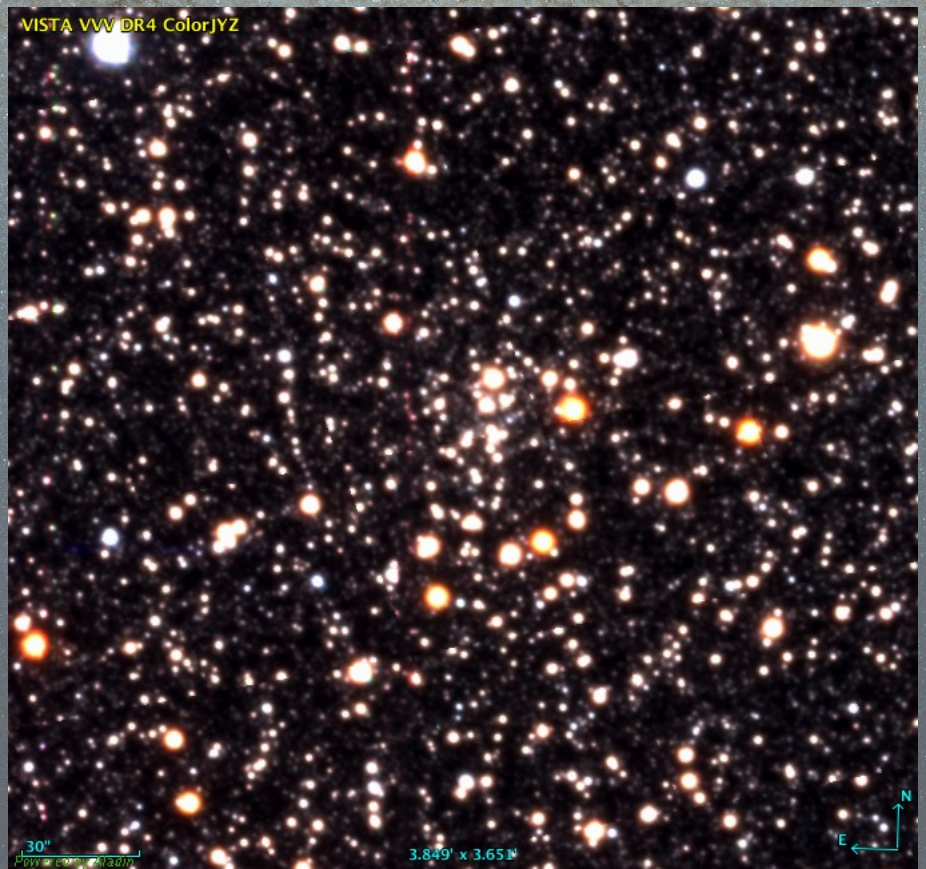
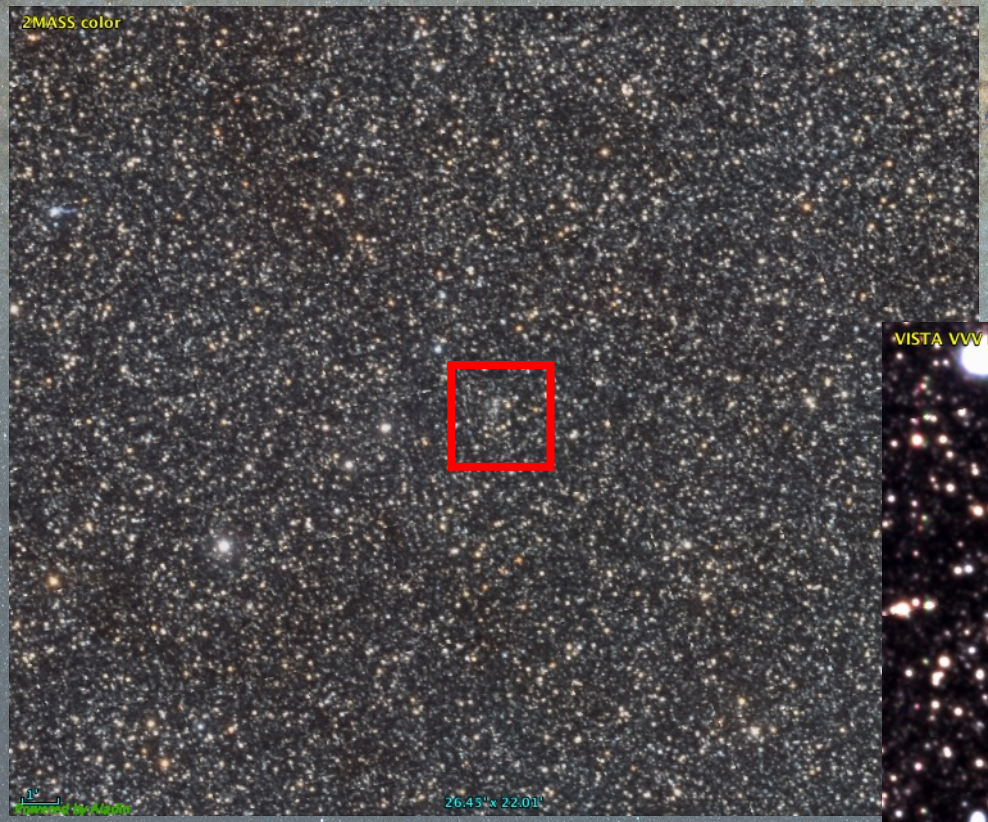
Hidden in the Haystack:
Low-luminosity GCs towards the MW bulge

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

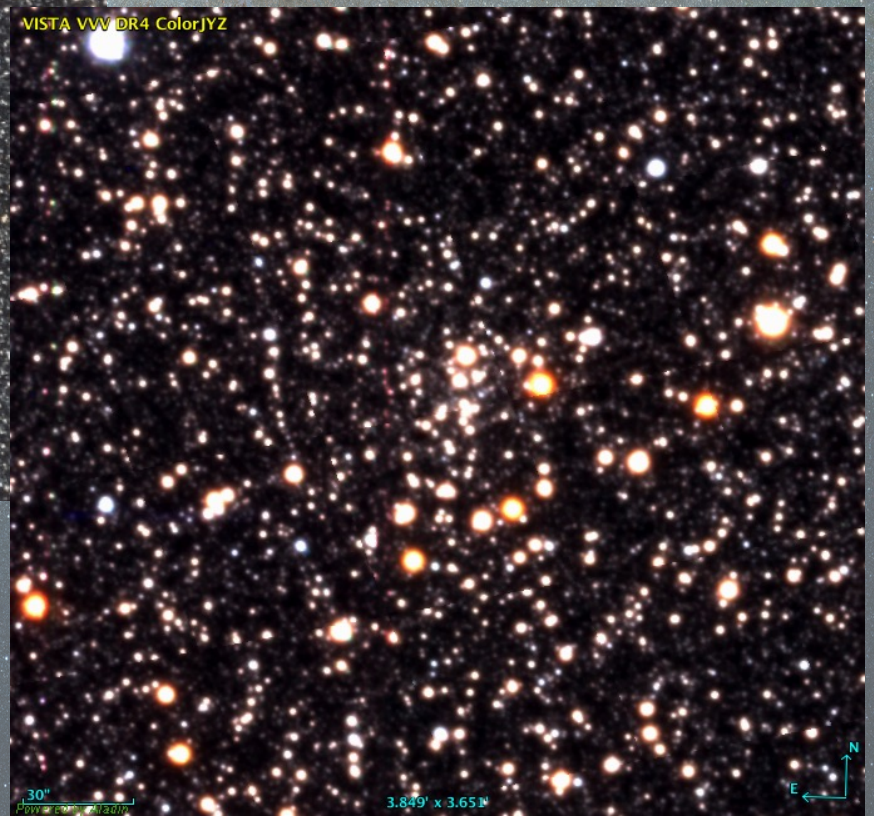


Gran et al. 2019

Hidden in the Haystack:
Low-luminosity GCs towards the MW bulge



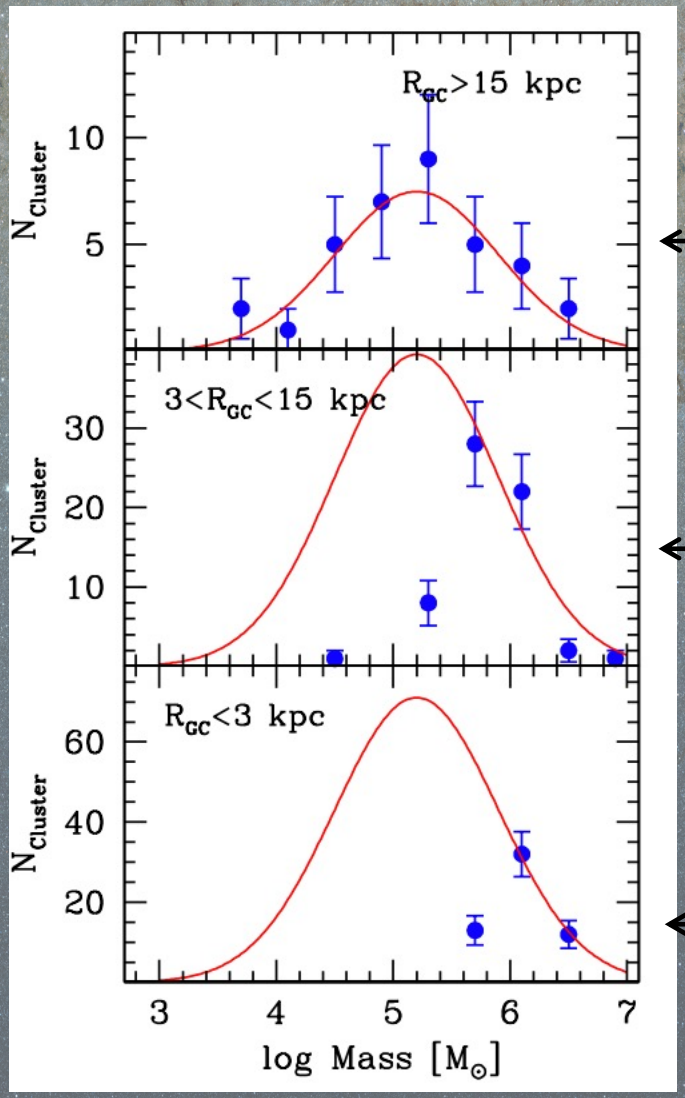
Gran et al. 2019 (A&A)
arXiv:1904.10872
Gran et al. 2021 (MNRAS)
arXiv:2108.11922



Globular clusters in the Milky Way

- ★ GCs contribution to the assembly of the Milky Way has been widely explored in numerical simulations (Renzini 2017; Kruijssen 2019; Kruijssen et al. 2019; Carlberg 2020).
- ★ No consensus has been reached on the total number of **bulge GCs** (Minniti et al. 2017).
- ★ Bulge GCs are tracers of the **MW formation and evolution**: *in situ* component (Myeong et al. 2018).

Initial mass distribution of GCs in the MW



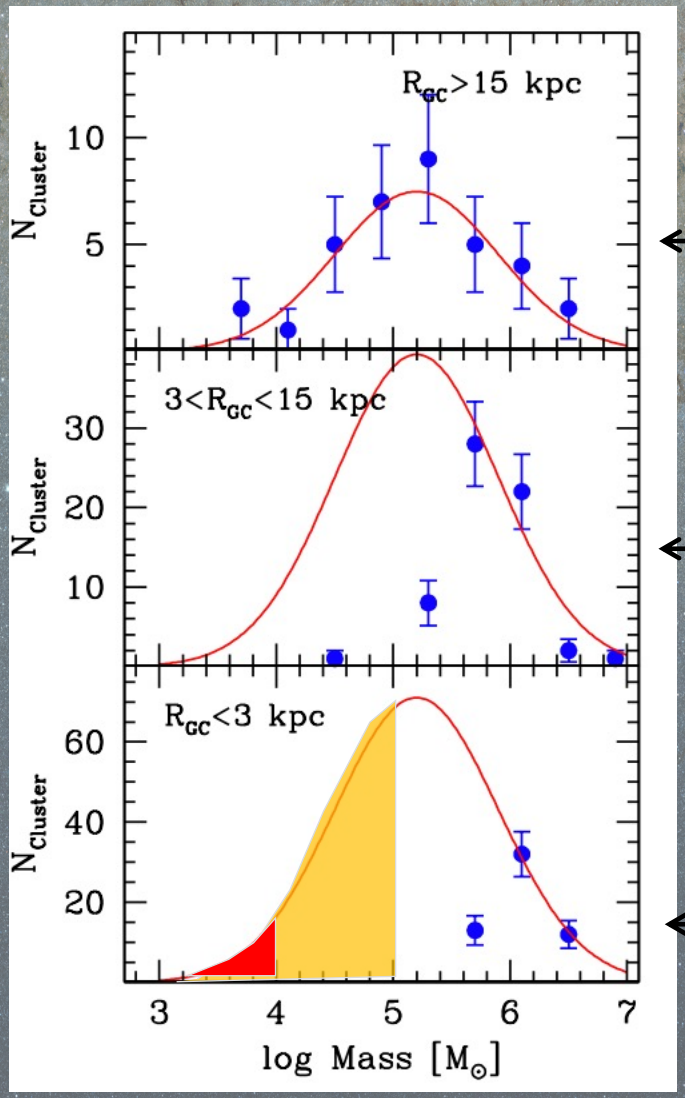
Baumgardt et al. 2018

~Halo GCs

~Disk GCs

~Bulge GCs

Initial mass distribution of GCs in the MW



Baumgardt et al. 2018

~Halo GCs

~Disk GCs

~Bulge GCs

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]

Photometric searches of GCs

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

Most of the recently

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

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

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

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

Sergey E. Koposov,[1,2★] V. Belokurov[1] and G. Torrealba[1]

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[2] *Department of Physics, McWilliams Center for Cosmology, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA*

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

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

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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★

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

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[1] ...ersity of Cambridge, Cambridge CB3 0HA, UK
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DISCOVERY OF A FAINT OU... IN THE SOUTHERN SKY

Dongwon Kim, Helm... and Gary S. Da Costa
Research School of Astronomy and Astr... Cotter Road, Weston, ACT 2611, Australia;

A NE... CLUSTE... SURVEY

THE DISCOVERY OF TWO EXTREMELY LO...

S. Koposov,[1,2] J. T. A. de Jo...
N. W. Evans,[2] G...
Receiv...

...KY WAY GLOBULAR CLUSTERS

...Rix,[1] D. B. Zucker,[2] ...d E. F. Bell[1]
...uly 6

THE DISCOVERY OF AN ULTRA-FAINT STAR CLUSTER IN THE CONSTELLATION OF URSA MINOR*

R. R. Muñoz[1,2], M. Geha[1], P. Côté[3], L. C. Vargas[1], F. A. Santana[2], P. Stetson[3], J. D. Simon[4], and S. G. Djorgovski[5,6]
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Received 2012 March 12; accepted 2012 April 24; published 2012 June 15

...globular cluster in the outer halo

...Bica[3] and B. Barbuy[4]†
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...o Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padua, Italy
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[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 Galactic star clusters

THE DISCOVERY OF TWO EXTREMELY LO

S. KOPOSOV,[1,2] J. T. A. DE JO

N. W. EVANS,[2] G

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STAR CLUSTER IN THE CONSTELLATION OF URSA MINOR*

A. SANTANA[2], P. STETSON[3], J. D. SIMON[4], AND S. G. DJORGOVSKI[5,6]

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Council of Canada, Victoria, BC V9E 2E7, Canada

3 Santa Barbara Street, Pasadena, CA 91125, USA

hnology, Pasadena, CA 91101, USA

4; *published 2012 June 15*

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

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THE SOUTHERN SKY

ND GARY S. DA COSTA

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Gaia 1 and 2. A pair of new Gala ters

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s Center for Cosmo

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5213, USA
US
DONGWO
Research School of Astr
au

THE DISCOVERY OF TWO EXTE

S. KOPOSOV,[1,2] J. T
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]

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)

, reston, ACT 2611, Australia;

THE DISC

R. R. MUÑ

Deep SO
companions

E. Luque,[1,2★] B. San
A. Drlica-Wagner,[4] A. G
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. Eiffer,[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

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]
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ONG,[15] A. NITTA,[18] AND S. A. SNEDDEN[15]

106 September 20

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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

Exponential growth of globular cluster candidates towards the bulge region: **near-IR photometric surveys**.

Minniti et al. 2017abc, Camargo 2018, Ryu & Lee 2018, **Gran et al. 2021**, **poster presentations: Garro & Obasi!**

VVV CL 001

Minniti et al. 2011, **Gran et al. 2019**

Clustering on a 5-D phase-space

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

+

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

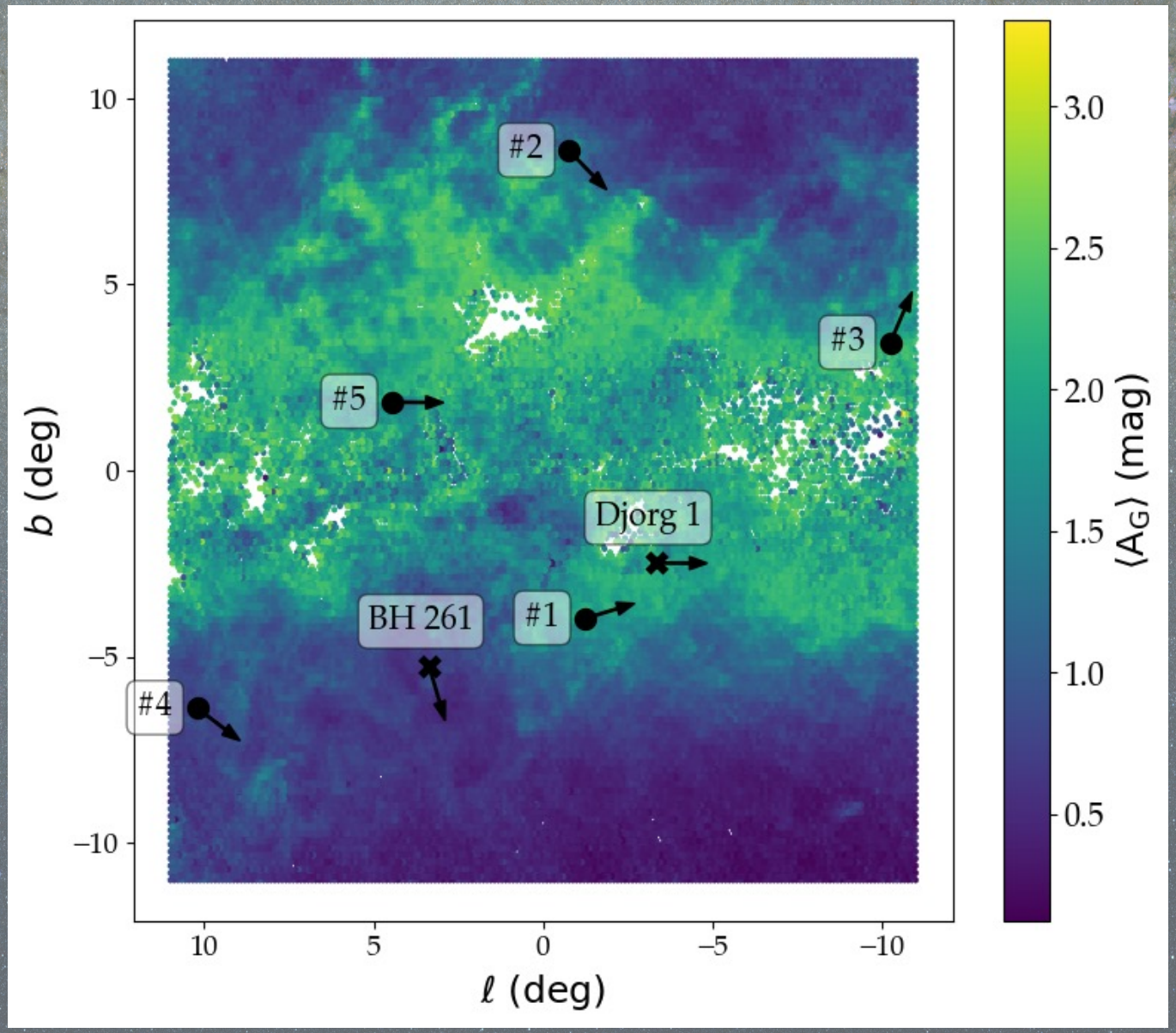
+

scikit learn: KDTree and DBScan

Candidate clusters in the 5-D phase space

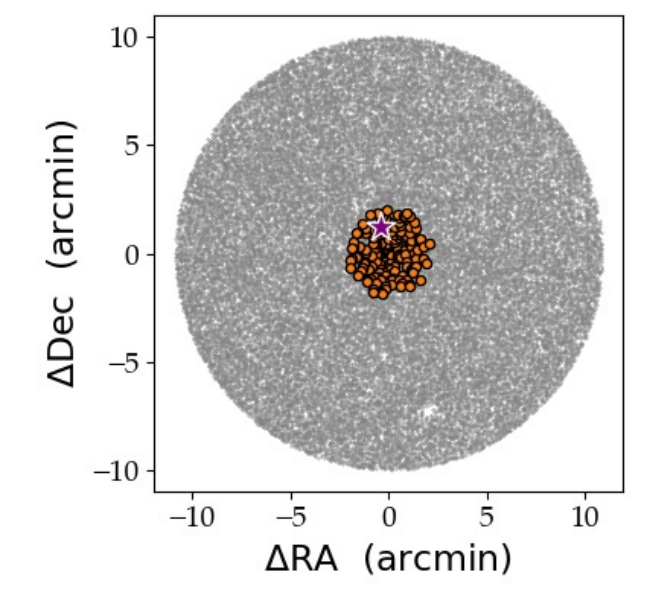
Pedragosa et al 2011
Hunt & Reffert 2020
see E. Hunt presentation (day 1)

Map of the new GCs



Gran et al. 2021
Background map:
Anders et al. 2019 (STARHORSE)

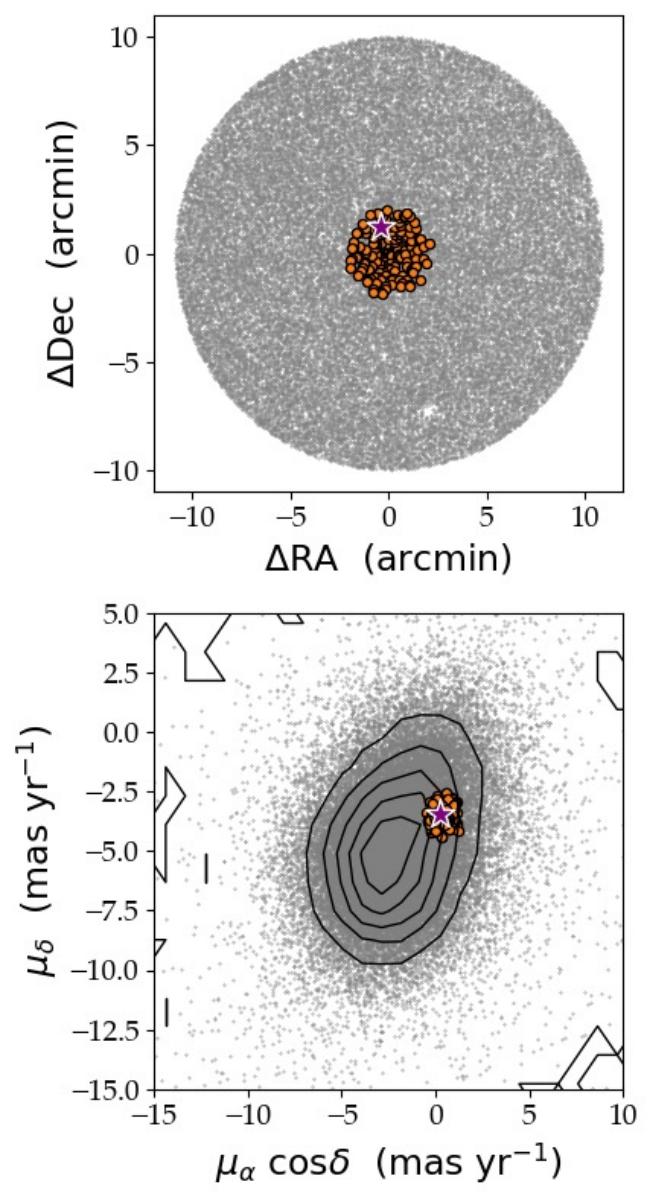
New GCs: #4



Clustering requirements:

- Grouped in space (ℓ,b)

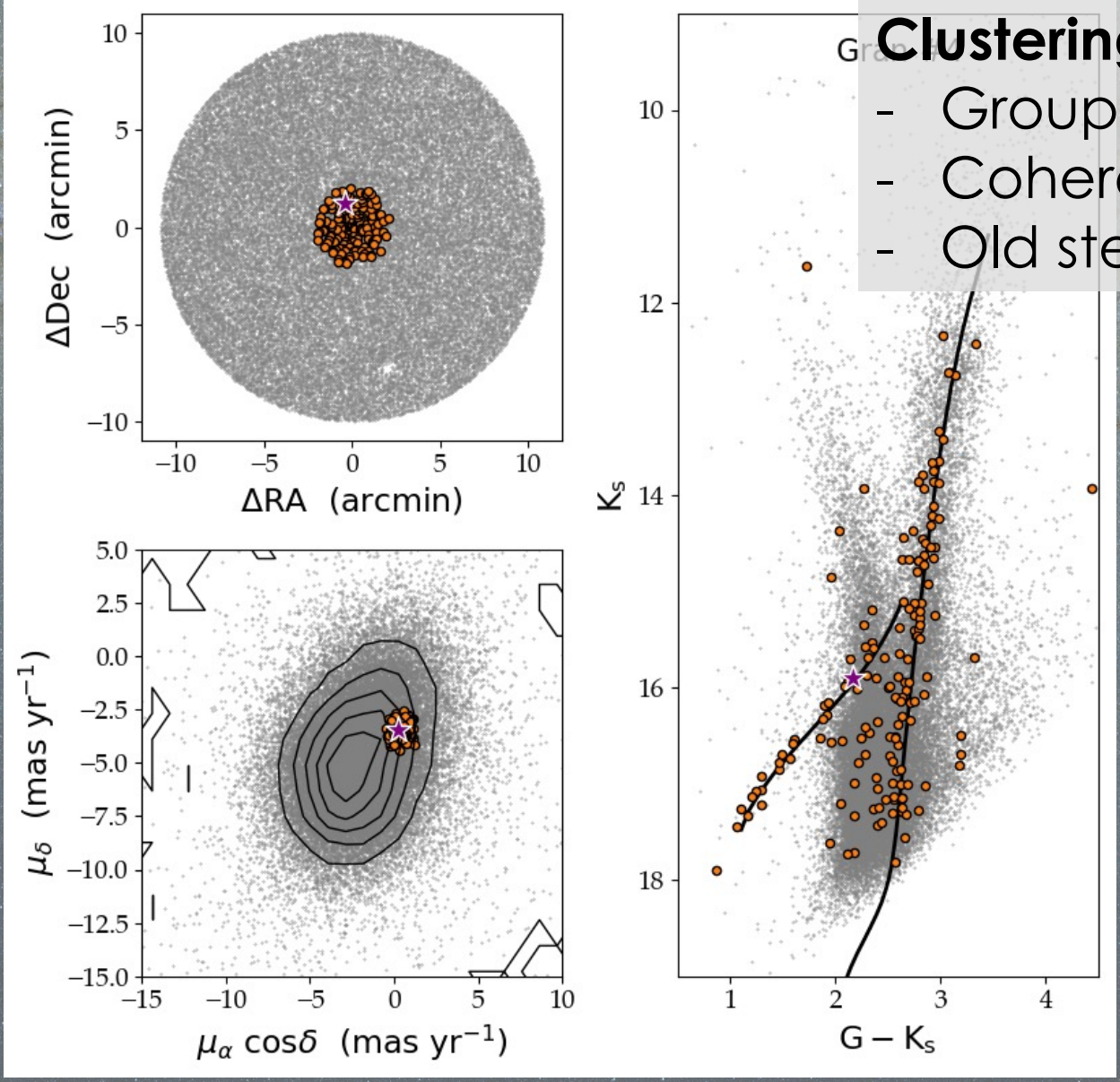
New GCs: #4



Clustering requirements:

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

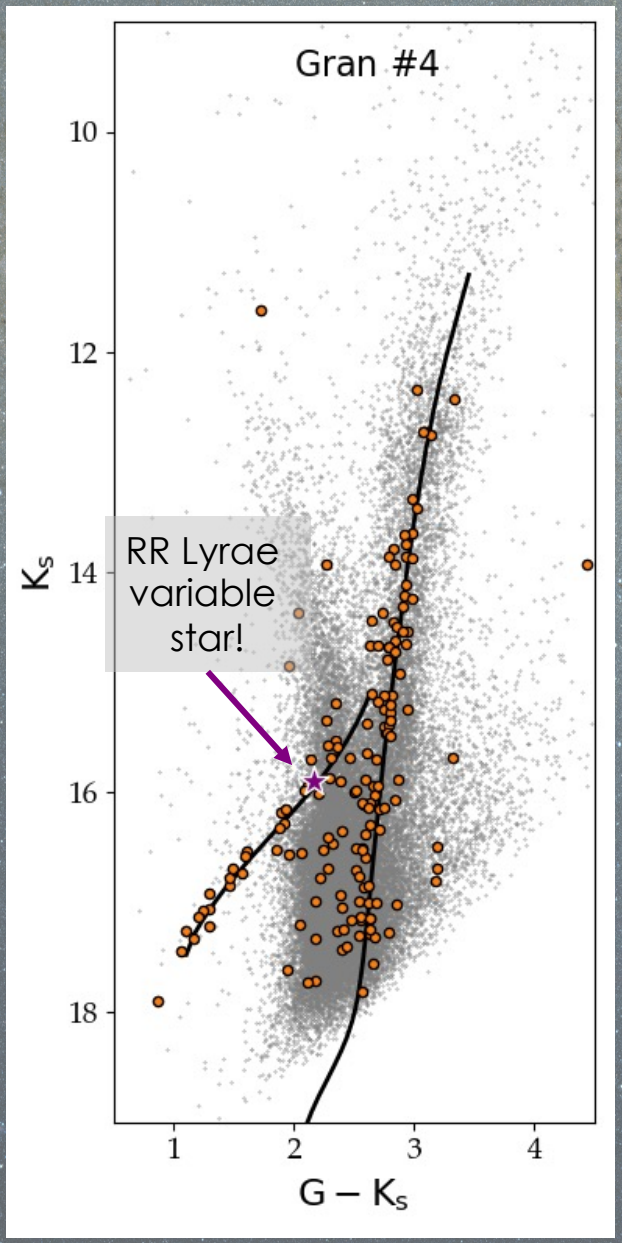
New GCs: #4



Clustering requirements:

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

New GCs: #4

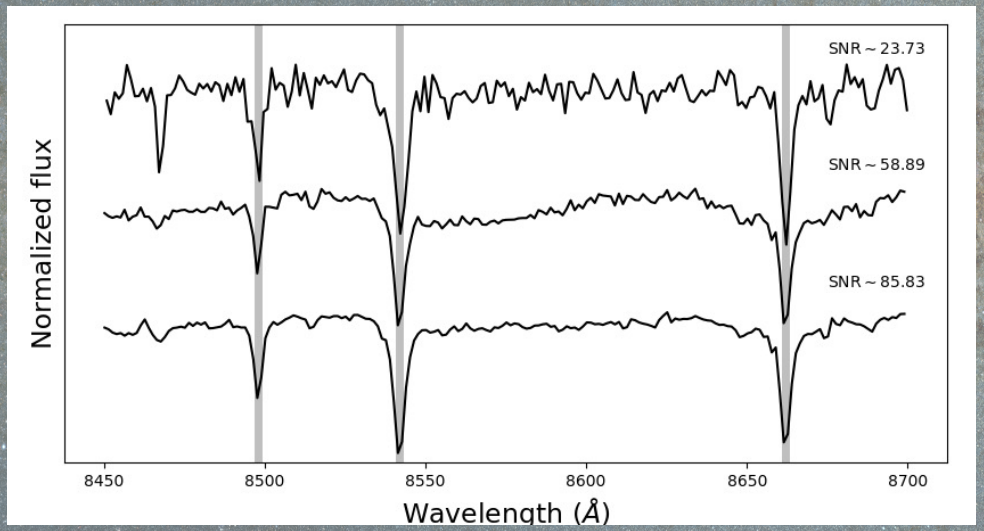


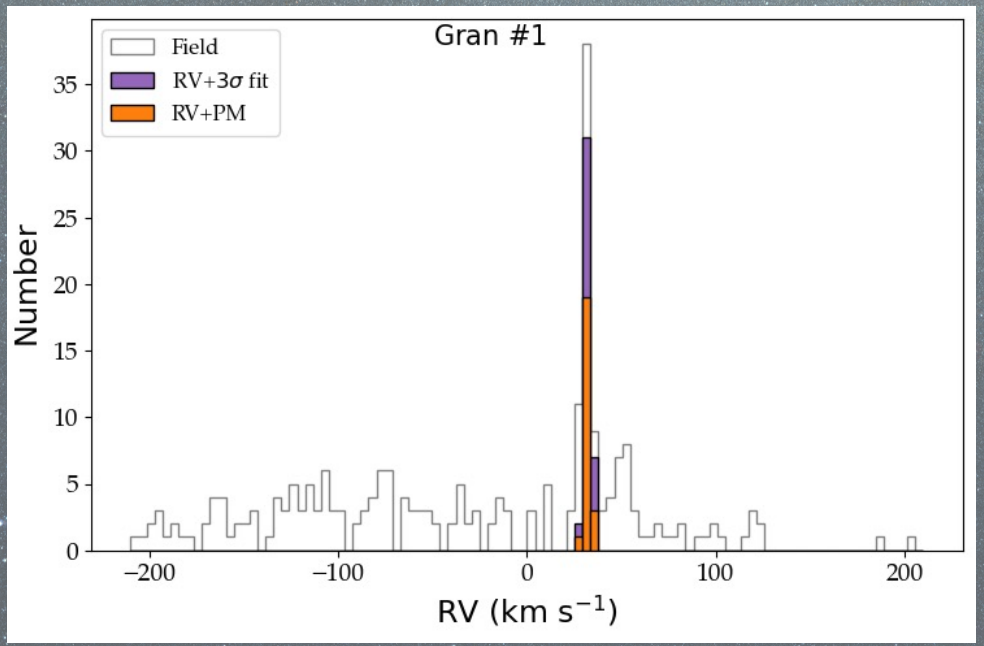
Gran et al. 2021

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

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

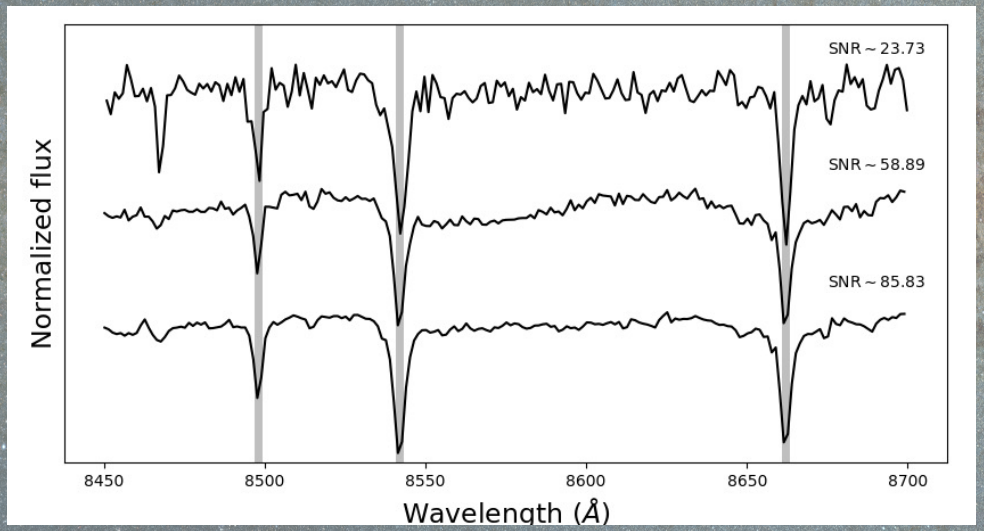
MUSE follow up observations

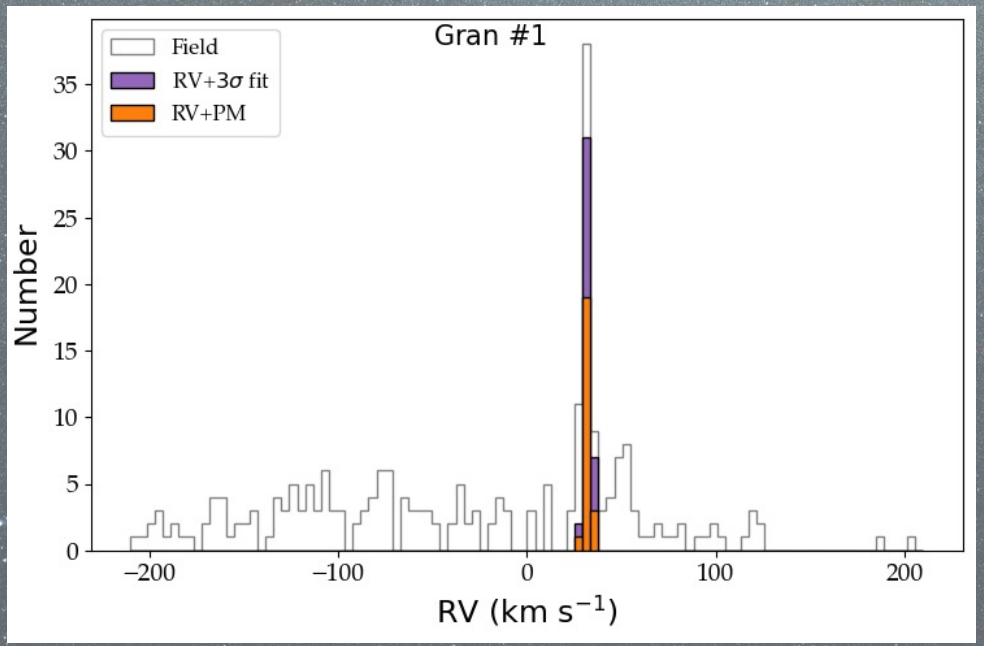


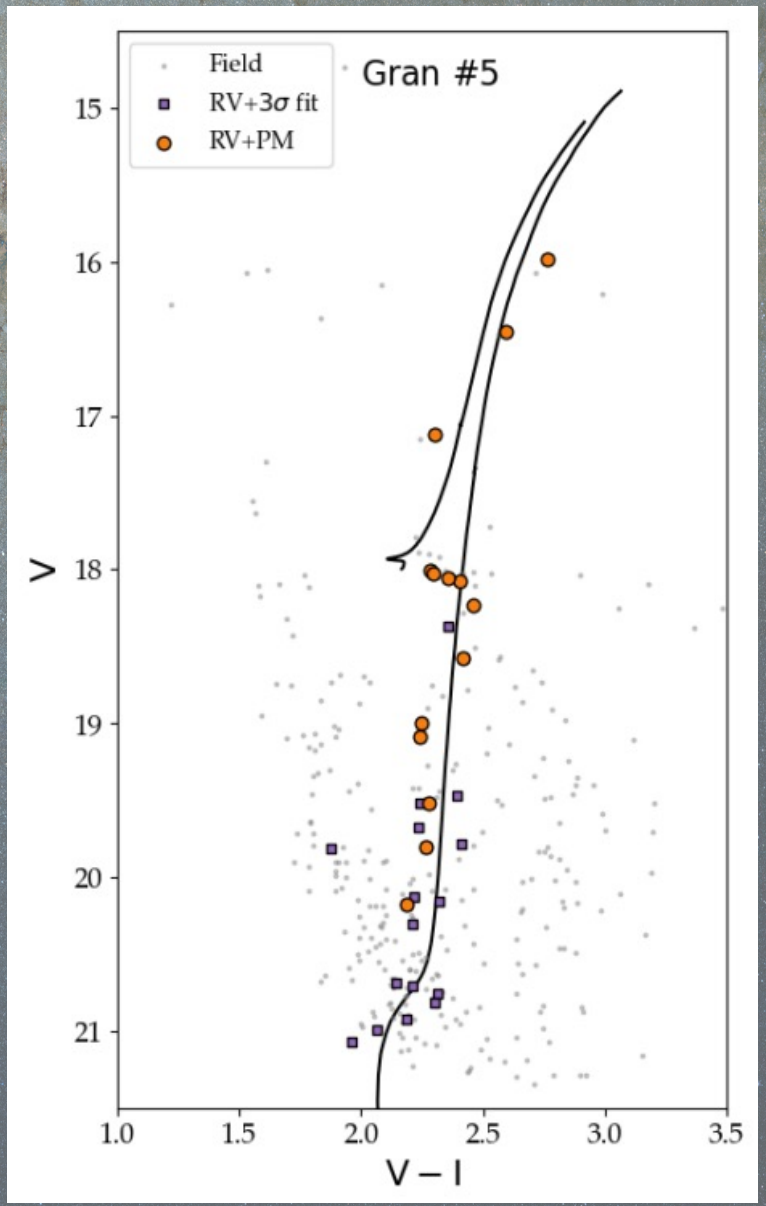


Gran et al. 2021

MUSE follow up observations

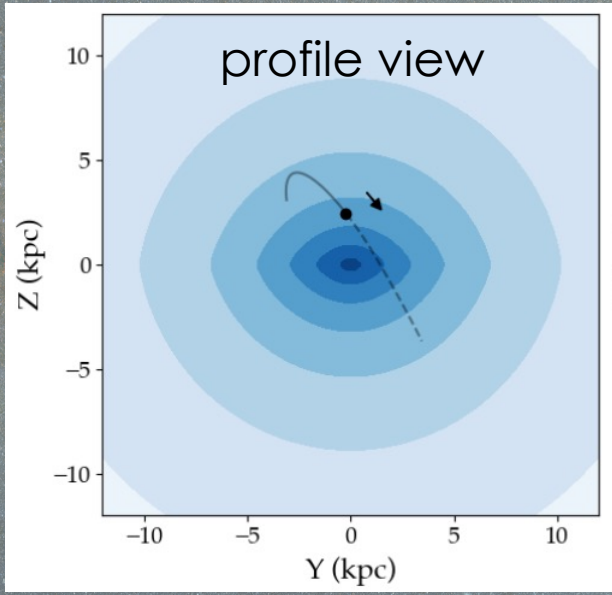


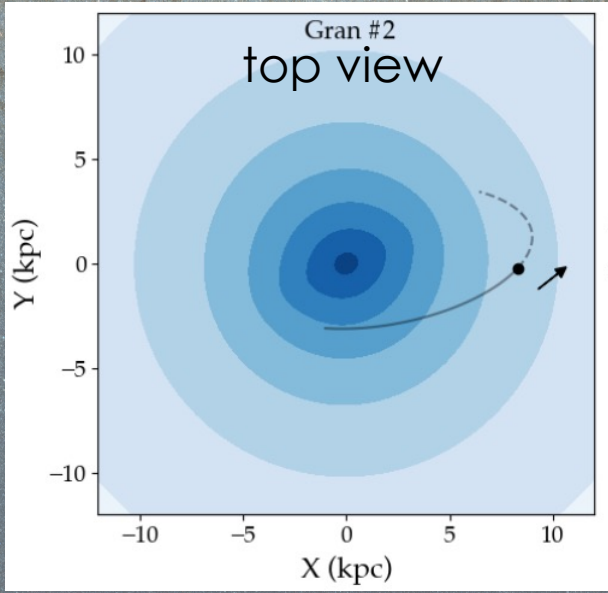


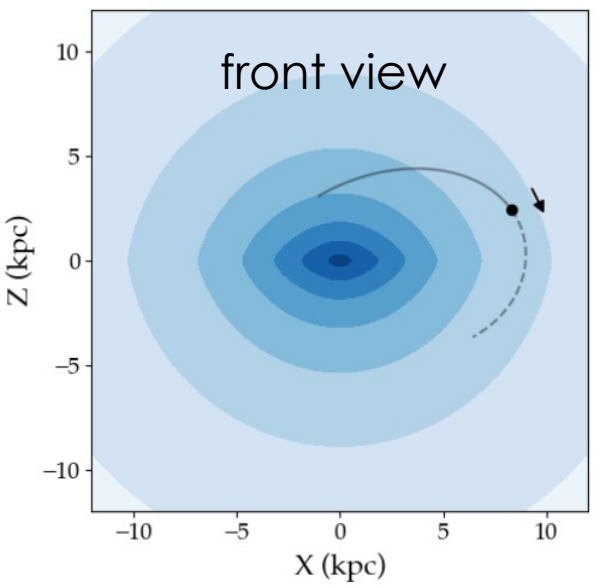


Gran et al. 2021

MUSE follow up observations



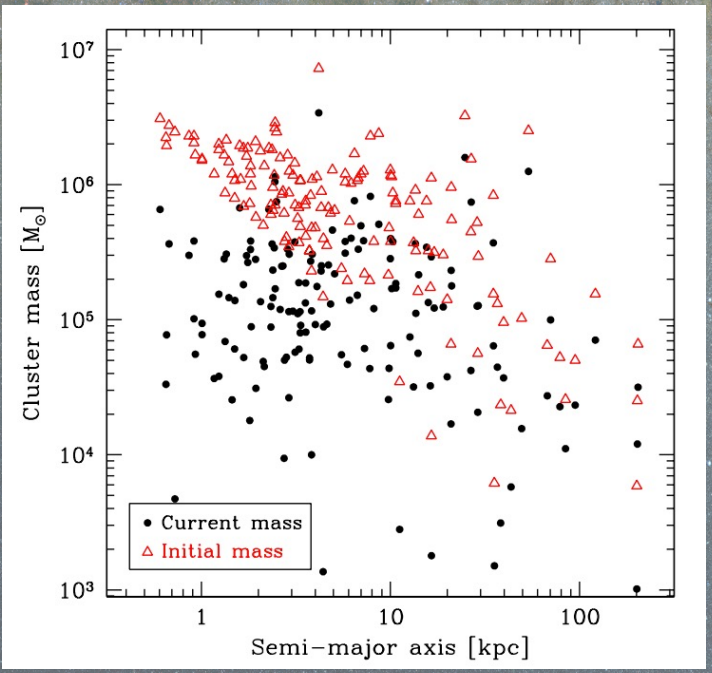




Gran et al. (2021)

Initial mass distribution of GCs in the MW

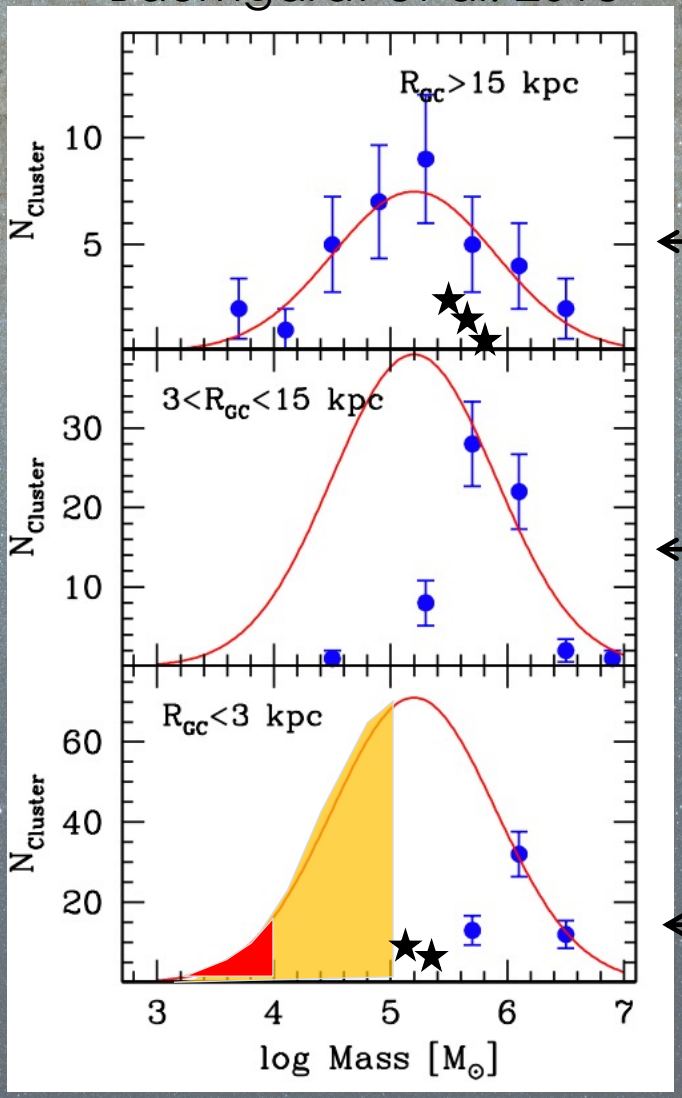
Baumgardt et al. 2018



Baumgardt et al. 2018

Gran 2 + 3 + 4

Gran 1 + 5



← ~Halo GCs

← ~Disk GCs

← ~Bulge GCs

Summary and future work

★ 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!**

Thanks for your attention!

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