PhD Thesis defense – March 25, 2022

# Unleashing the proper motions: revolution in the inner Galaxy

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Ivo Saviane (ESO Chile)

**Committee**: Márcio Catelan
Julio Chanamé
Ricardo R. Muñoz (UChile)

CONICYT
Ministerio de Educación
Gobierno de Chile

INSTITUTO DE ASTROFISICA
FACULTAD DE FISICA

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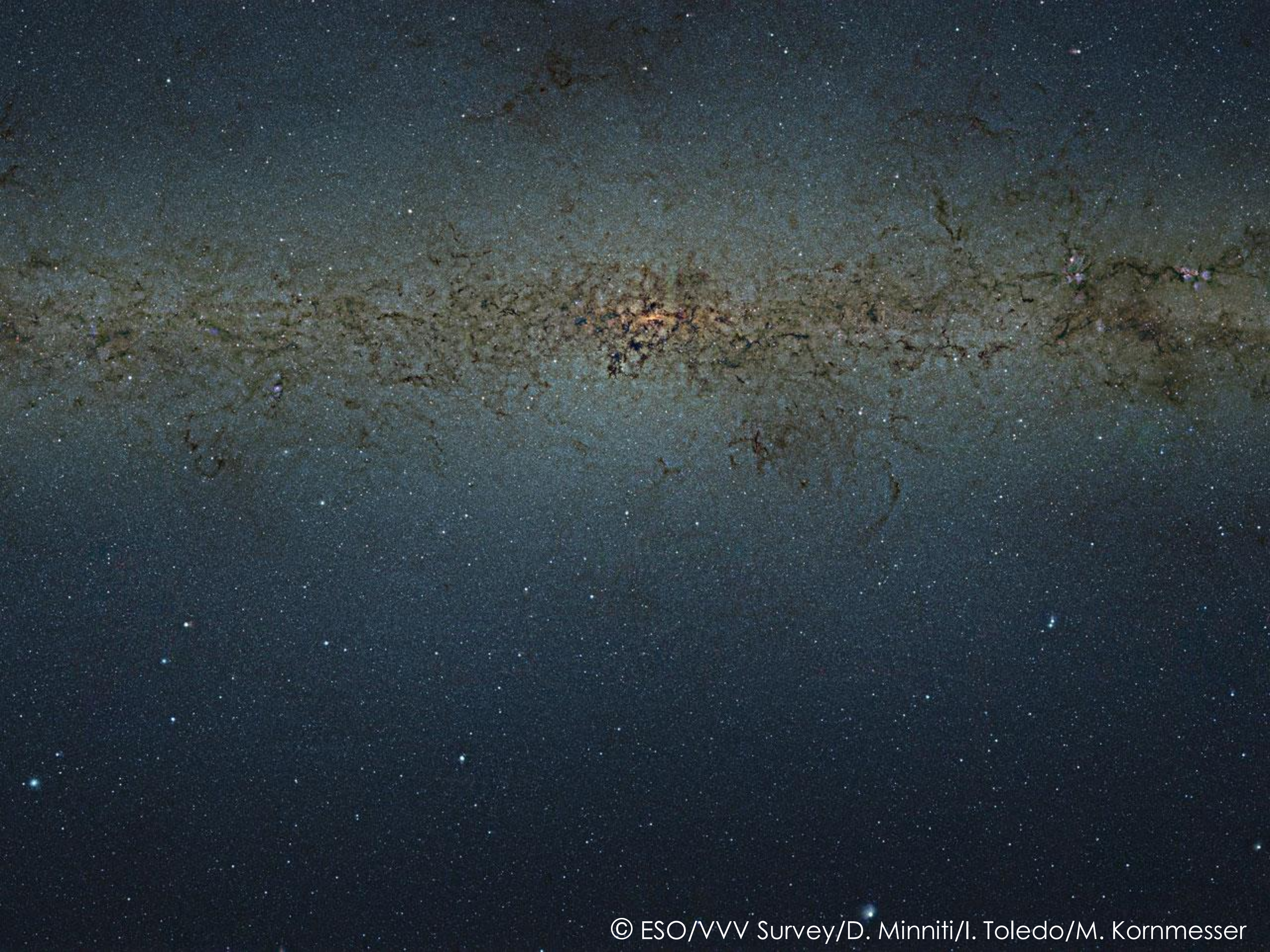
Gran et al. 2019

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



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

# Unleashing the proper motions: revolution in the inner Galaxy

- ★ Introduction

- ★ The chaotic phases of a PhD thesis:
  - ★ APOGEE observations: the stellar content of the inner Galaxy
    - ★ NGC 6544 as the learning case

  - ★ The *intermezzo:* GCs and PMs
    - ★ Analysis of the inner Galaxy

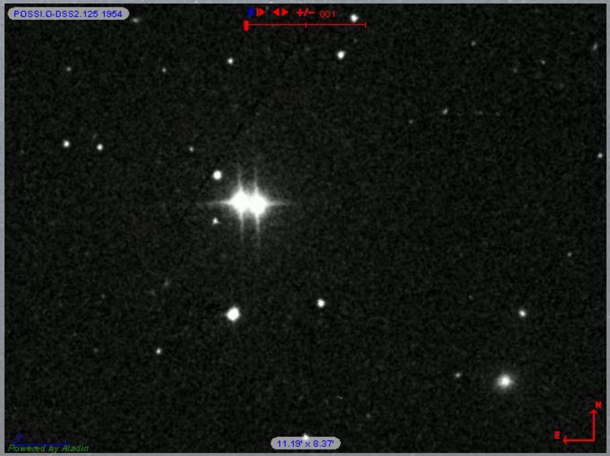
  - ★ Hidden in the haystack:
    - ★ 5 bonafide GCs towards the Galactic bulge

- ★ Future work and summary

# Key concept #1: stellar proper motions

POSS1, POSS2, DSS


Steve Quirk, Wikipedia Commons

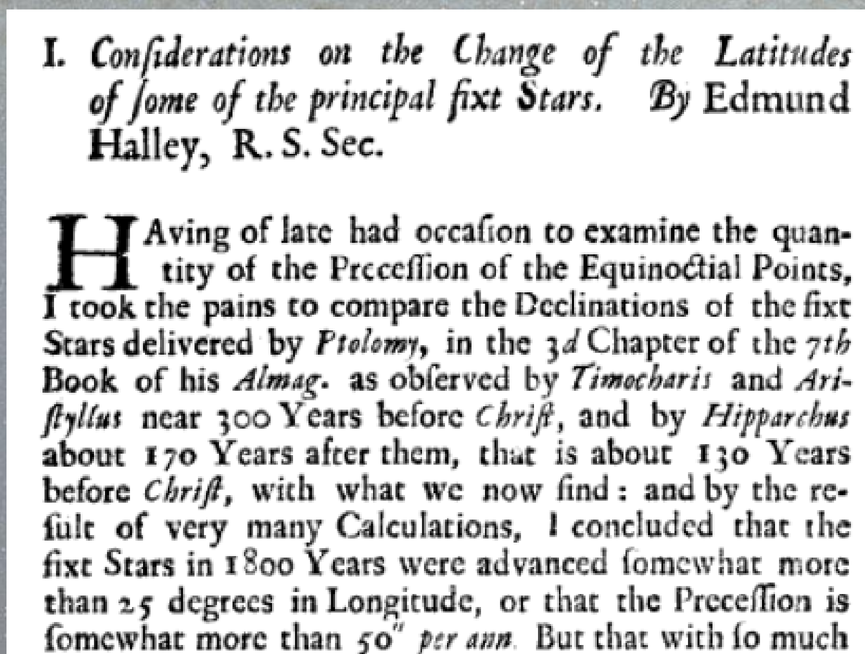



DSS/STScI

# Key concept #1: stellar proper motions

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

- ★ Halley 1717: ~**few** stars



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

HAving of late had occaſion to examine the quantity of the Preceſſion of the Equinoctial Points, I took the pains to compare the Declinations of the fixt Stars delivered by *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

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POSS1, POSS2, DSS


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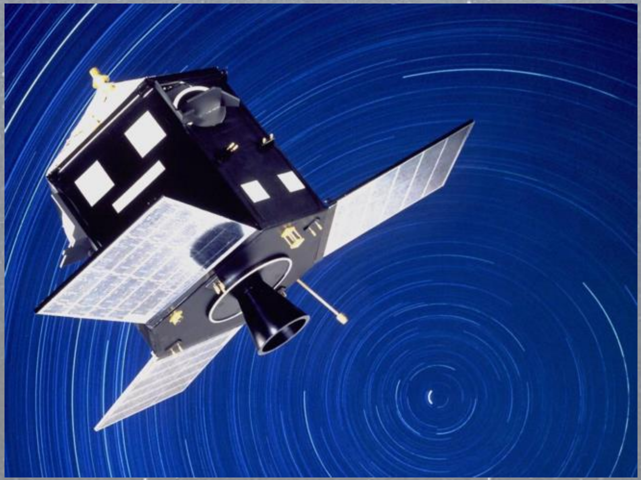

ESA, Hipparcos


Steve Quirk, Wikipedia Commons

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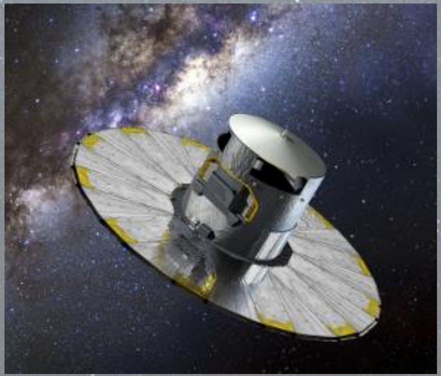
- ★ ESA Gaia space mission (active): ~**1.46 billion** stars ~**1.460.000.000** stars

POSS1, POSS2, DSS


Steve Quirk, Wikipedia Commons

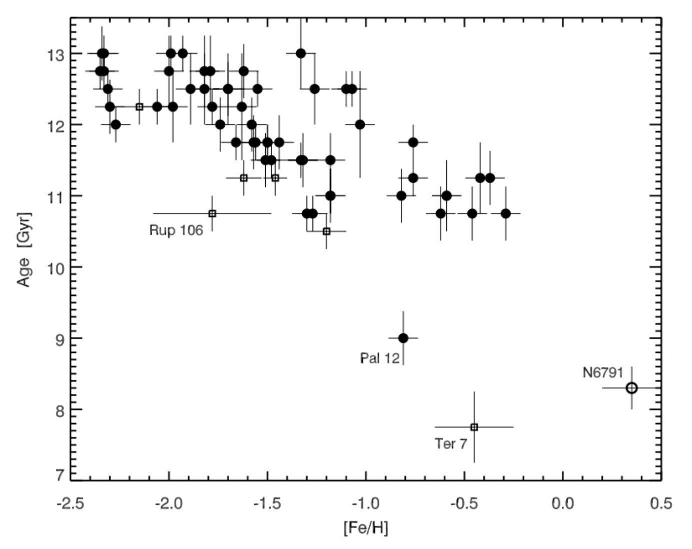


ESA, Gaia

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

★ **Globular clusters** are one of the most valuable **tracers** when trying to understand **galaxy evolution**.

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




Leaman et al. 2013

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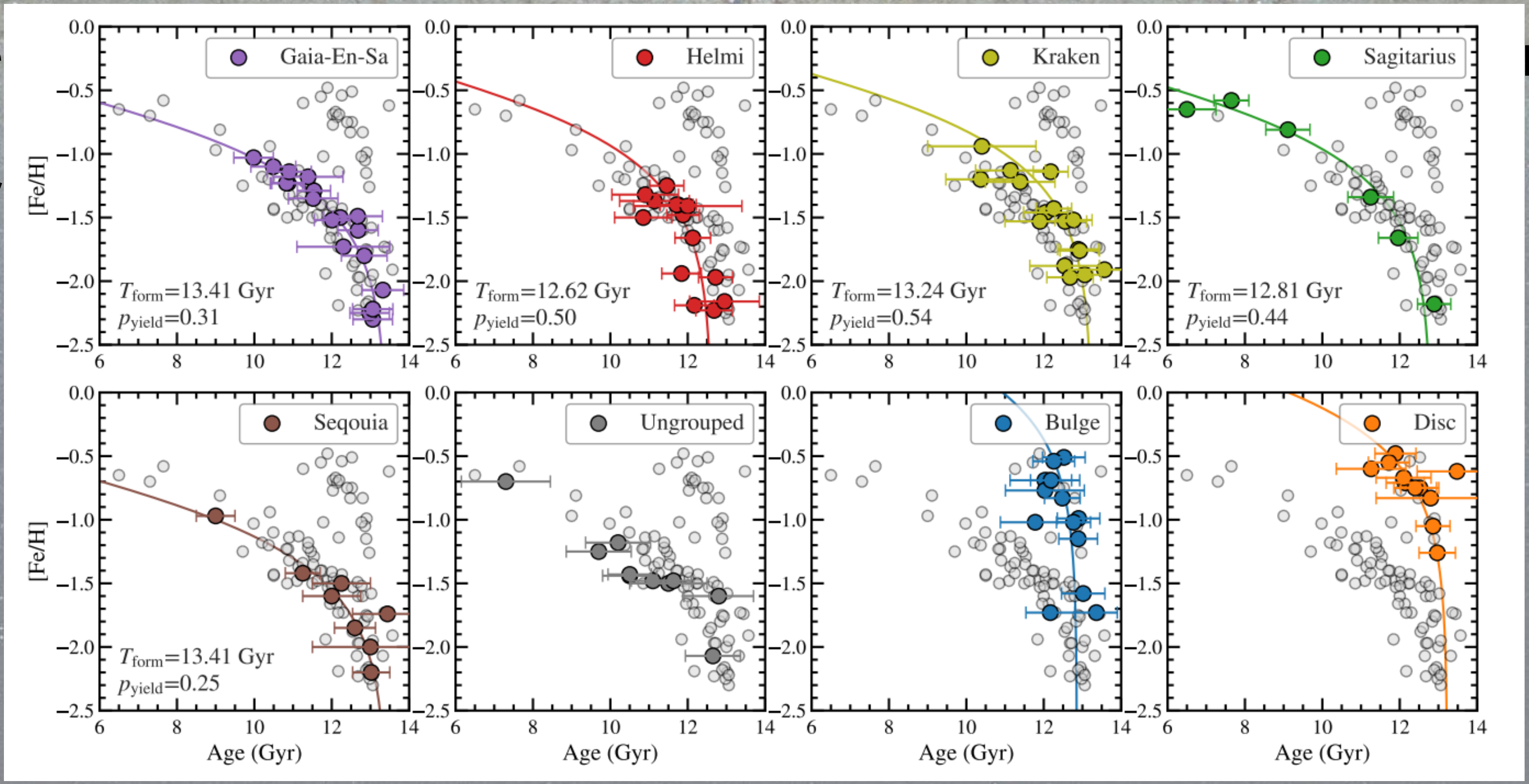
★ We … ry
lab …
**enr** …




Callingham et al. 2022

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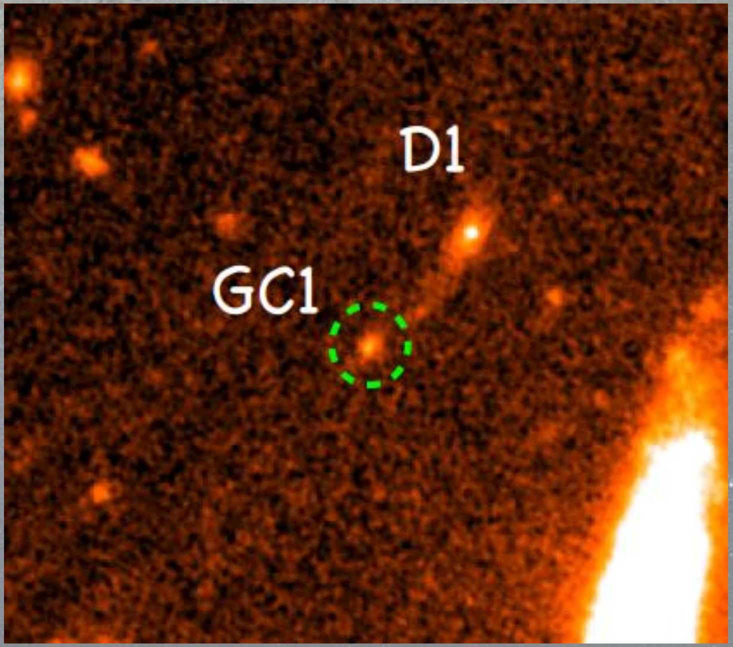
- ★ We can constrain **ages**, **masses**, and **distances**: the primary laboratory of stellar evolution including **chemical** and **enrichment processes**.

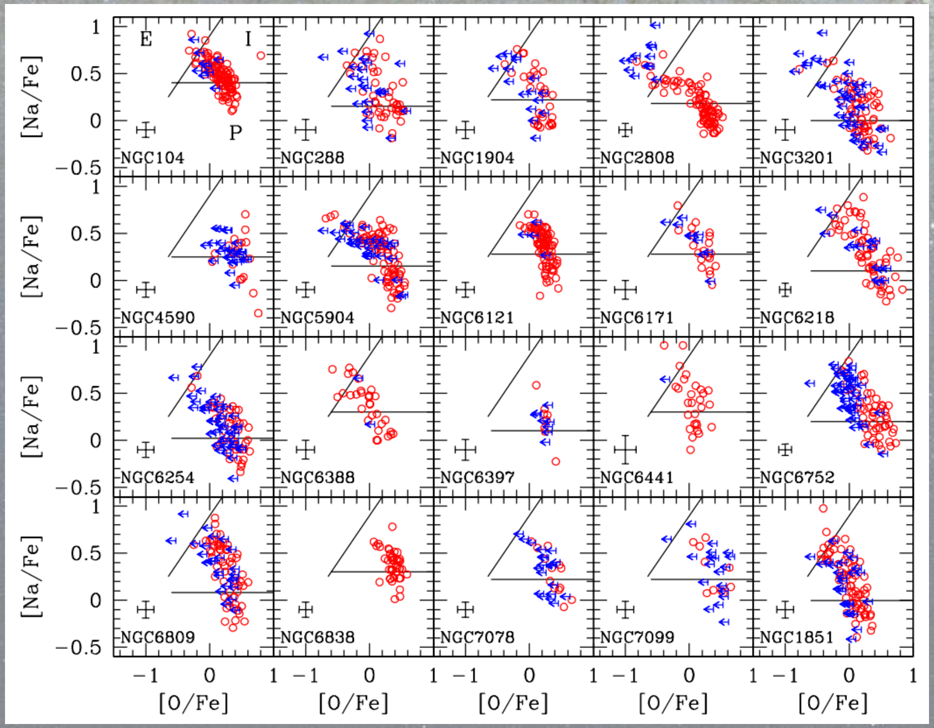
- ★ **Observations** and **simulations** can work together to account the different properties of **nowadays** clusters and the ones formed at **high redshift**.



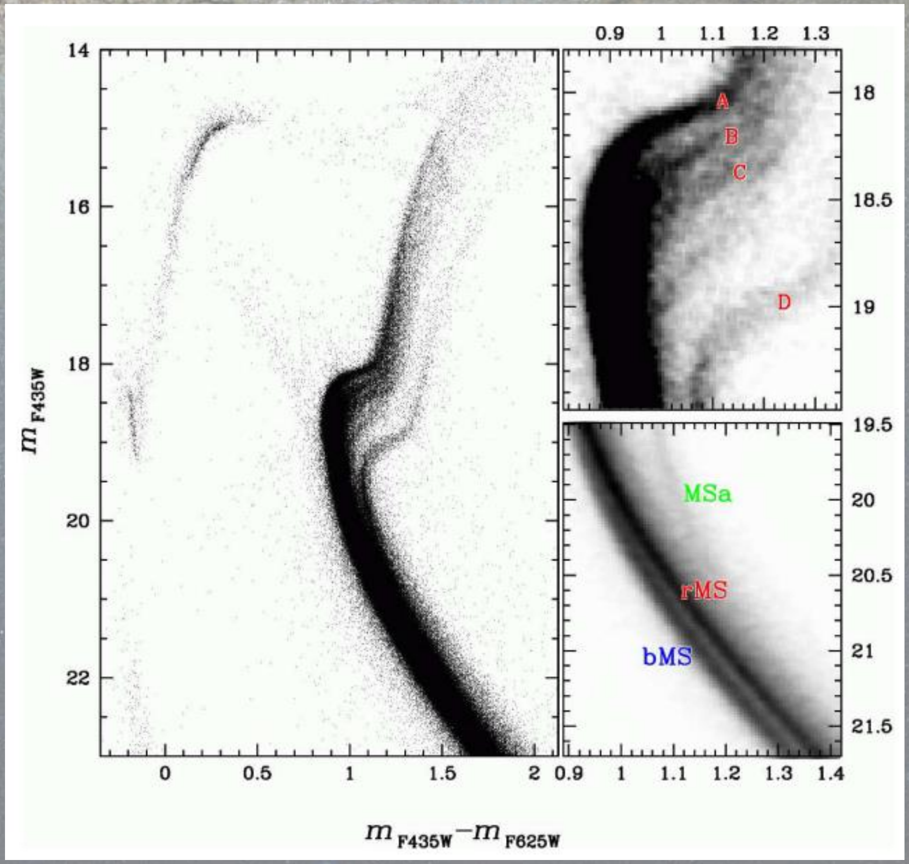

Vanzella et al. 2017

# Key concept #3: multiple stellar populations within globular clusters

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




Carretta et al. 2009




Bellini et al. 2010, 2017

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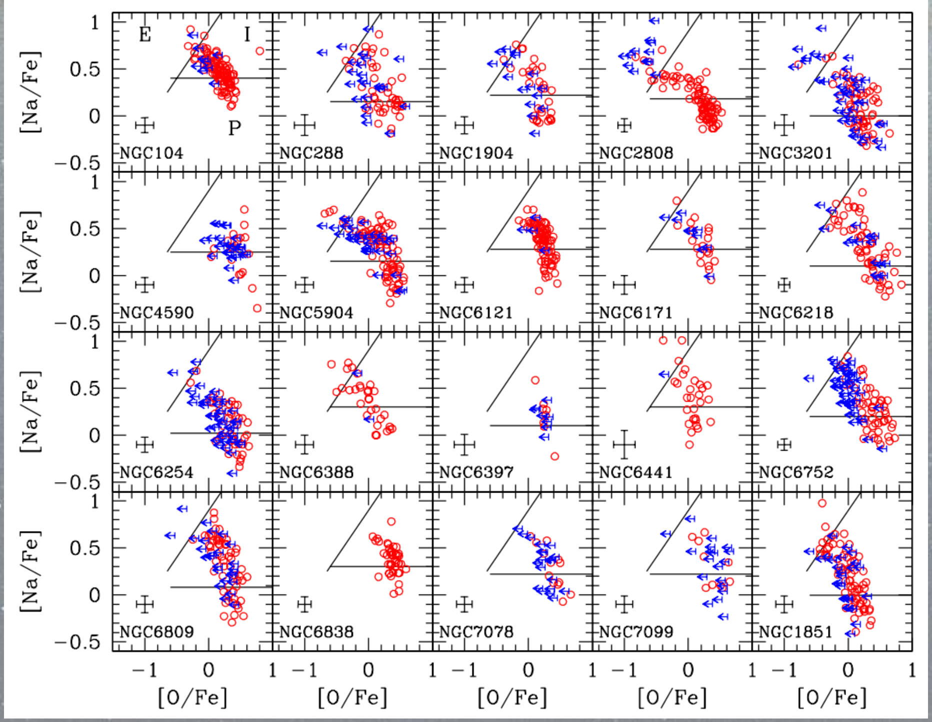



Carretta et al. 2009

★ Fe enrichment in only a limited cases: massive clusters

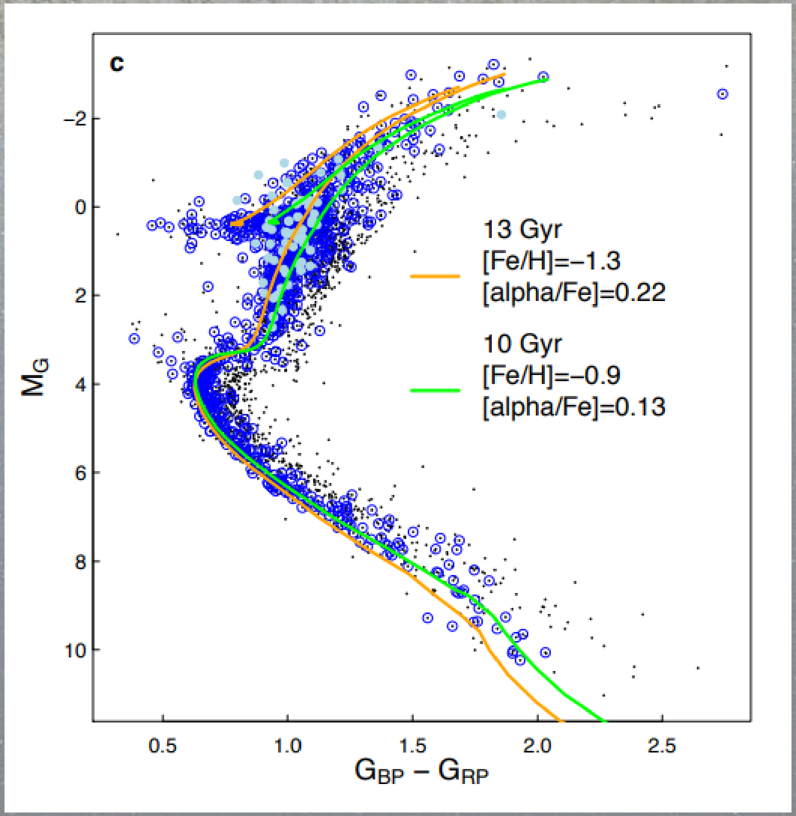
★ Light-element (proton capture) variations!
  ★ C, N, O, Na, Mg, Al, Si, … among others!

★ AGB and massive fast rotators: most likely contributors

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

★ The Gaia satellite change our understanding of the Milky Way, giving us **dynamical information** of ~1.8 billion stars.

- ★ Discovery of a major Milky Way merger from orbital parameters
- ★ Star formation history of the Galaxy
- ★ Isolation of the Sagittarius dwarf galaxy across the entire sky




Helmi et al. 2018;
Belokurov et al. 2018

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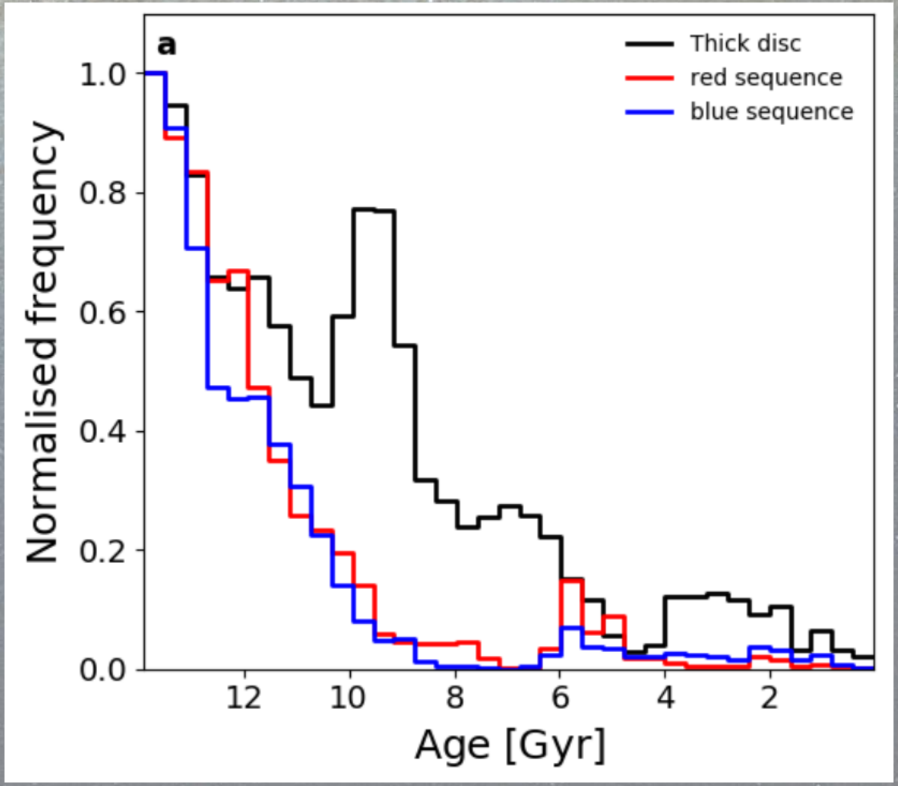


Gallart et al. 2019

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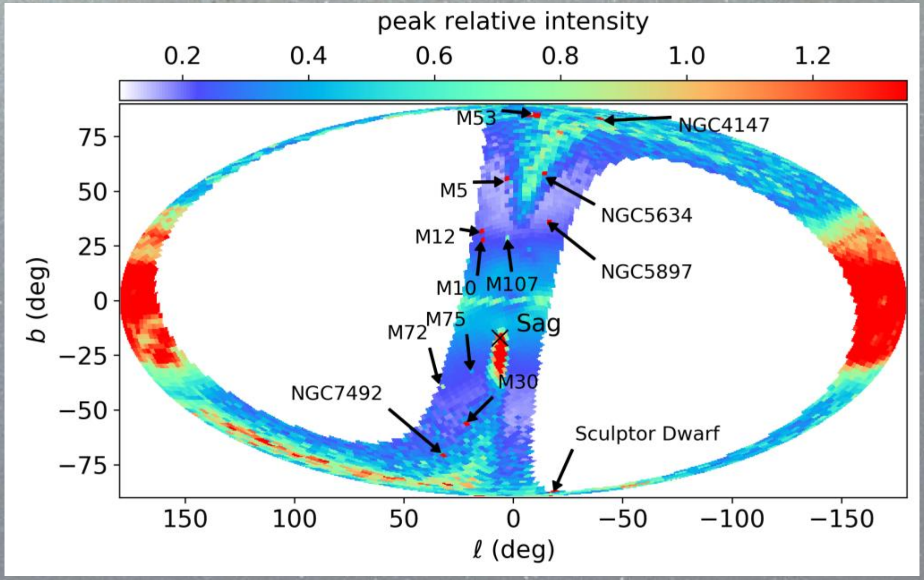


Antoja et al. 2020; Ramos et al. 2020

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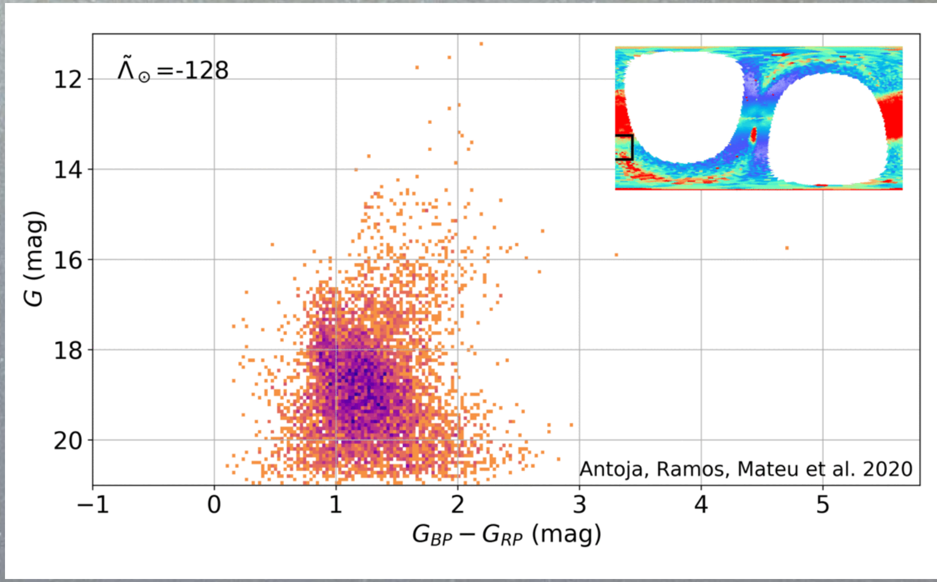


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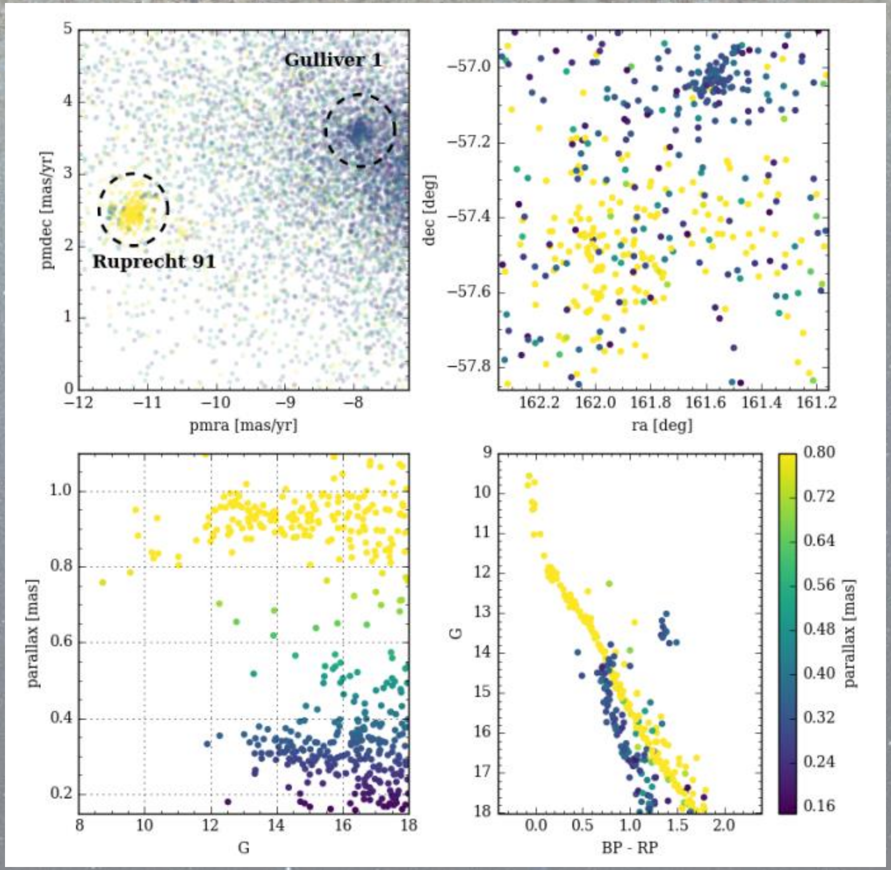
★ **CLUSTER SCIENCE!**




Cantat-Gaudin et al. 2018

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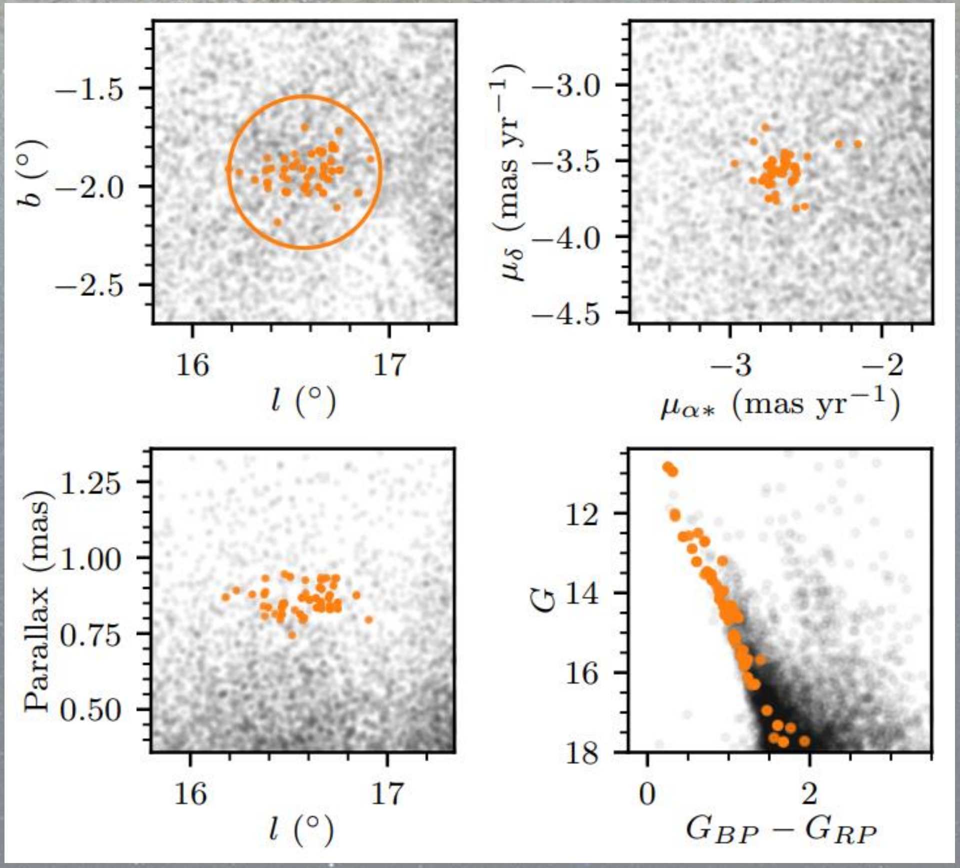


Hunt & Reffert 2021

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

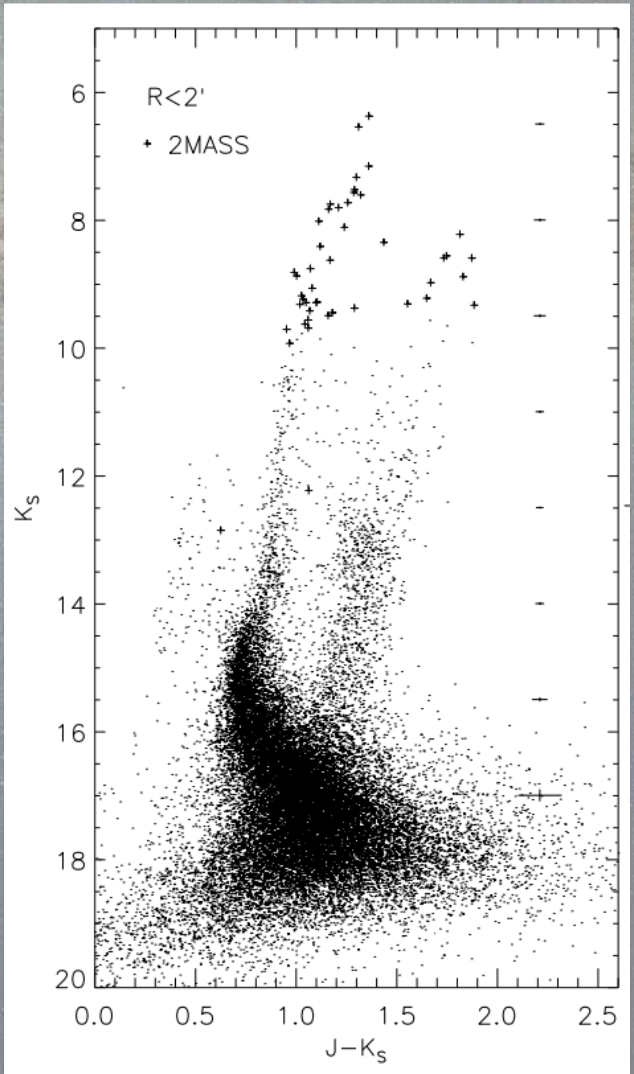
# APOGEE view of the globular cluster NGC 6544

# Context and history of NGC 6544

★ NGC 6544 ($\ell = 5.84°, b = -2.2°$) is located at **low Galactic latitudes**

★ Nearby globular cluster ~2.4 kpc

★ Poorly characterized due to highly variable **differential reddening**:
E(B-V)= 0.79 mags



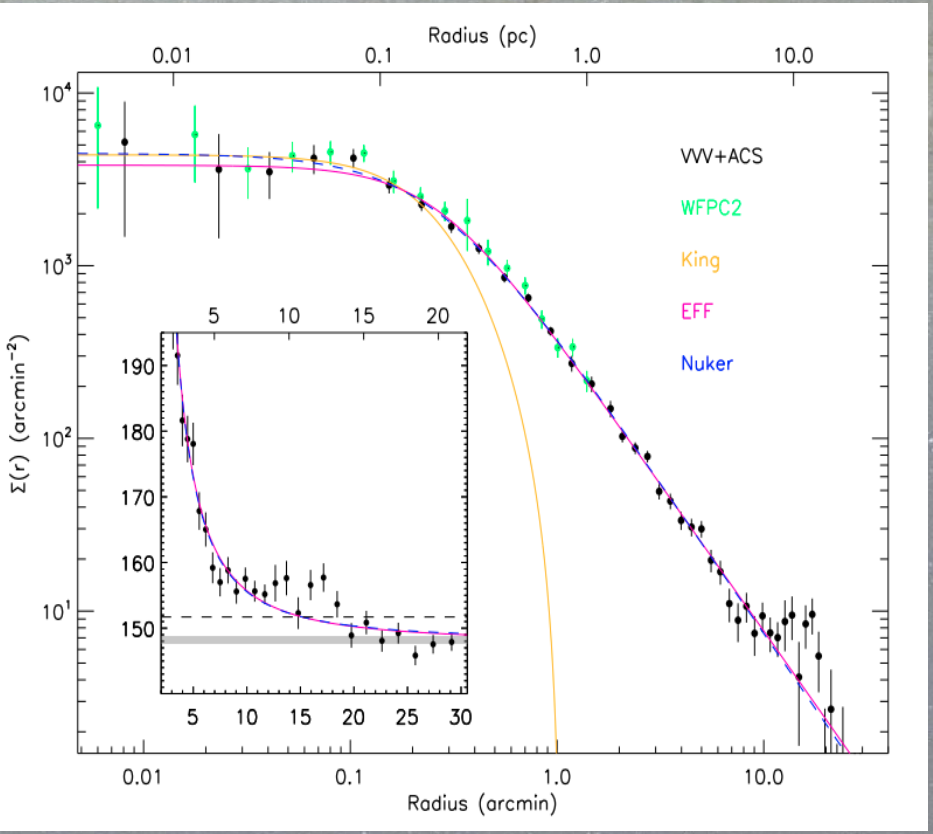

Cohen et al. 2014

# Context and history of NGC 6544

★ NGC 6544 ($\ell = 5.84°, b = -2.2°$) is located at **low Galactic latitudes**

★ Clear evidence of **tidal interaction** with the MW

★ Metallicity only constrained by **low-resolution spectra**




Cohen et al. 2014

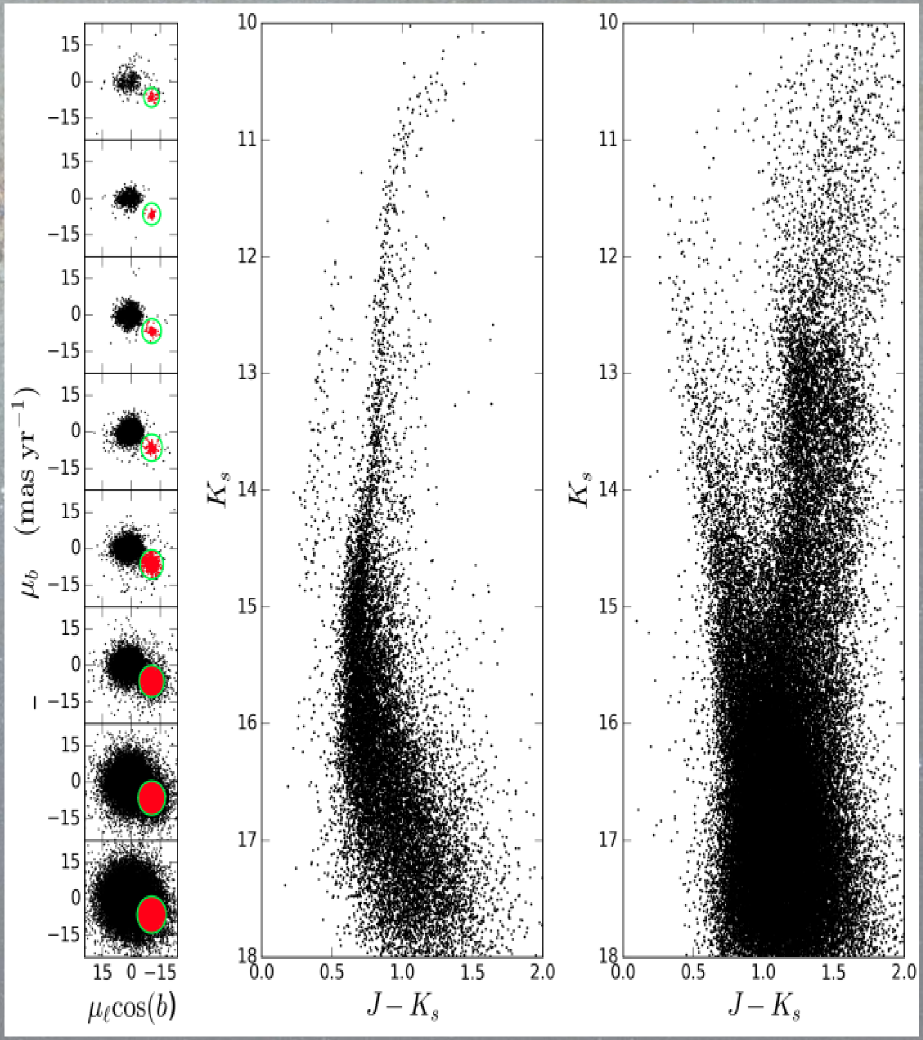
# NGC 6544 in VVV/x survey

VVV X Survey

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

~100+ $K_s$ epochs

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




Minniti et al 2010, Contreras Ramos et al. 2017

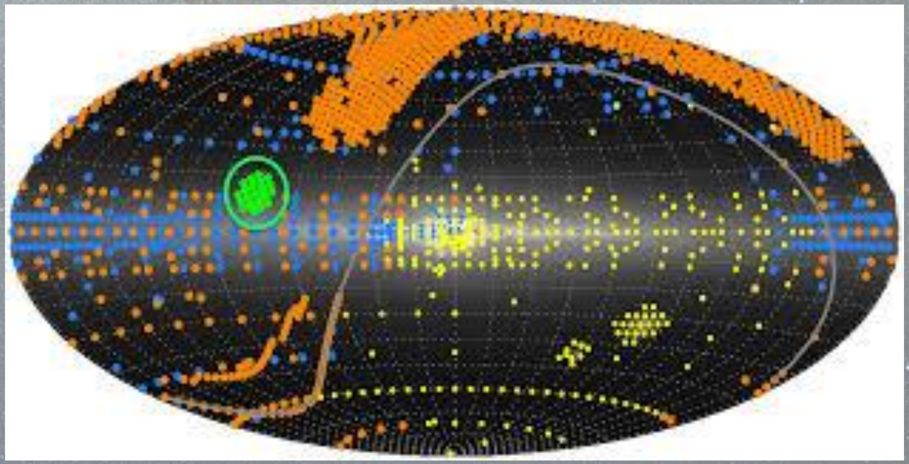
# NGC 6544 in APOGEE survey

Near-IR (H-band),
high-resolution (R~20000)
high-SNR (~100)
20+ abundances

~470000 spectra
~430000 stars

DR16 publicly available

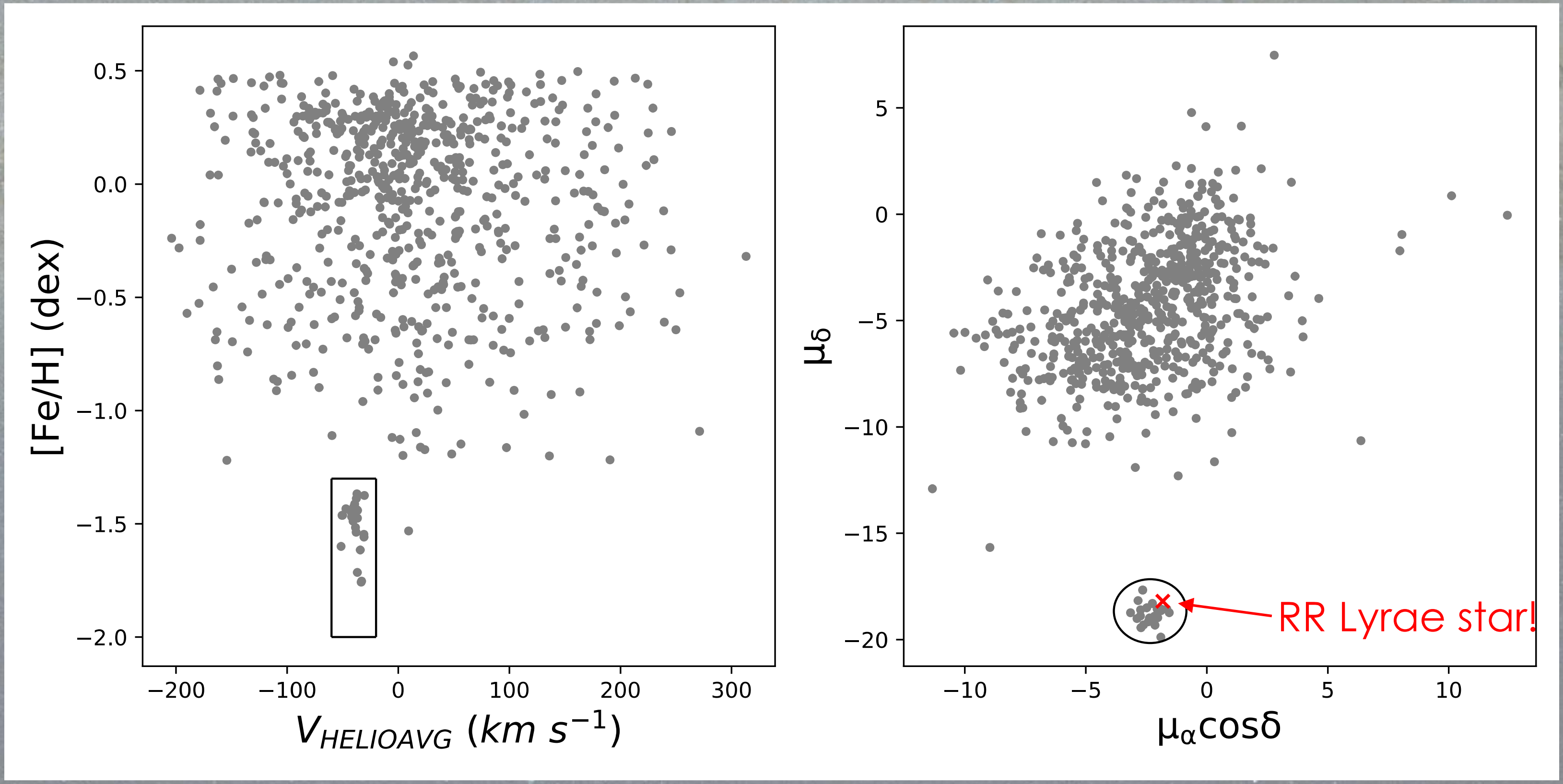
- ★ Part of the SDSS collaboration (SDSS-III and SDSS-IV)
- ★ **Chilean Participation Group**: access to proprietary data



All-sky observations from APO and LCO.

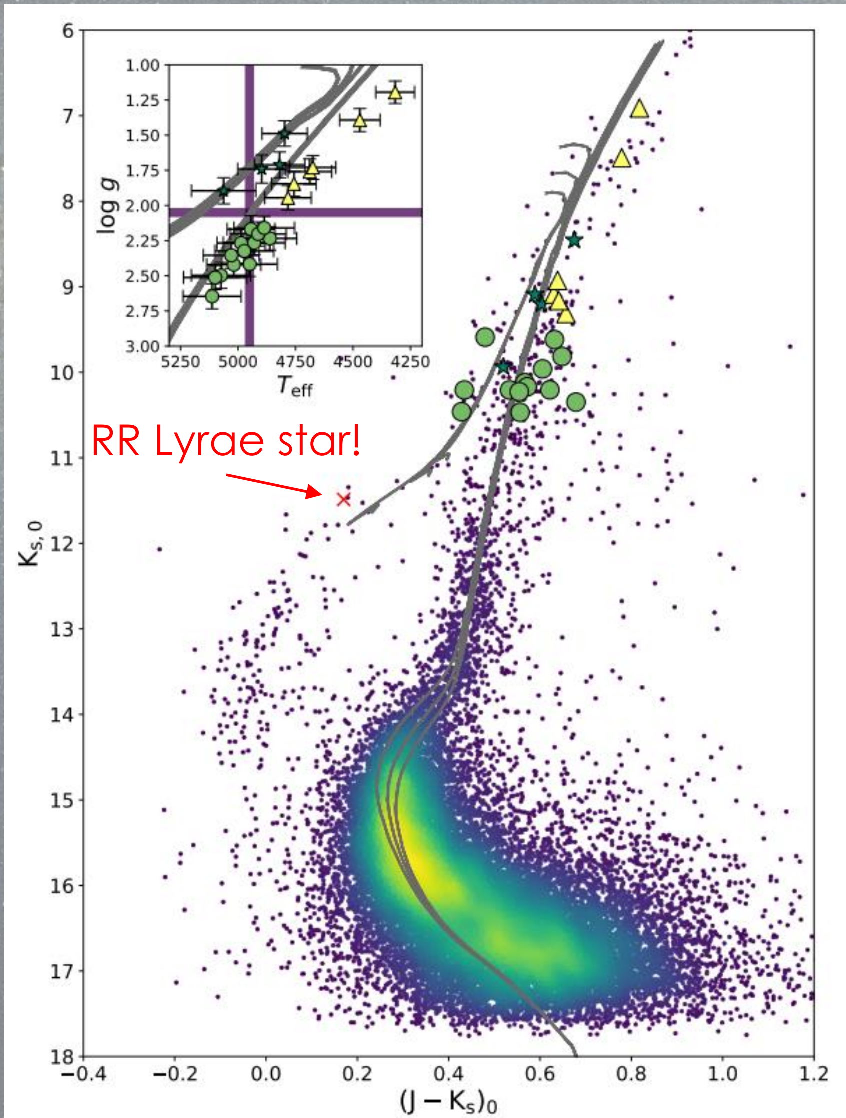
Eisenstein et al. 2011, Majewski et al. 2017, Blanton et al. 2017

# Selection of NGC 6544 members




(**Left**) APOGEE targets up to 45 arcmins from the cluster center.
(**Right**) Gaia DR2 VPD of the same stars around NGC 6544.

# Fundamental properties of NGC6544



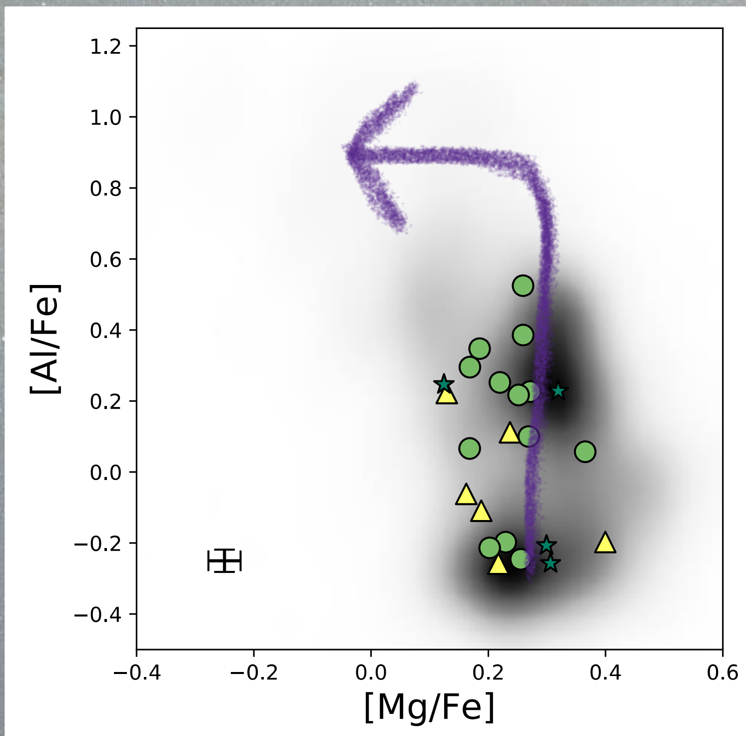

A total of 23 members were located:

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

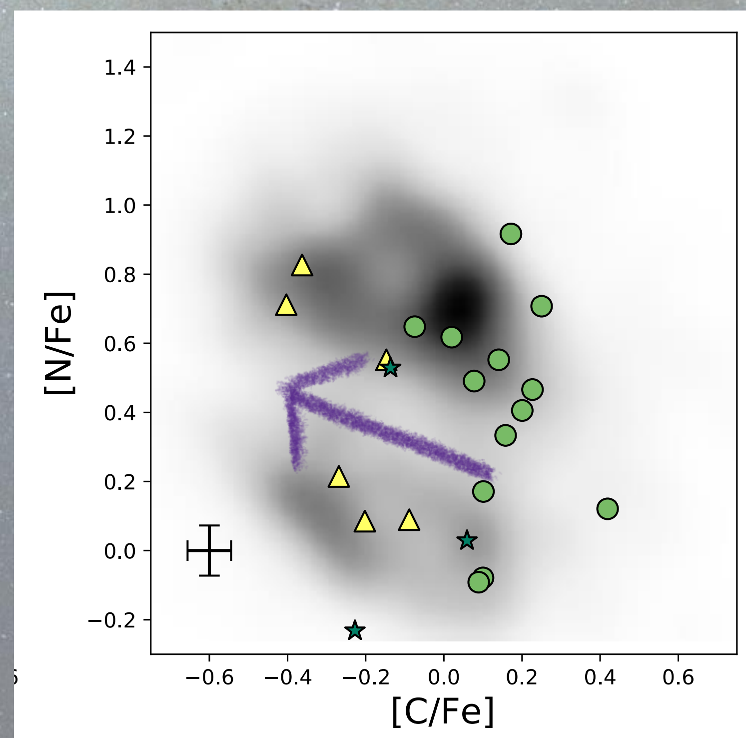
$V_{\rm HELIOAVG}$ = -38.2 $\pm$ 3.7 $\mathrm{km\ s^{-1}}$
[Fe/H] = -1.44 $\pm$ 0.04 dex
[$\alpha$/Fe] = 0.20 $\pm$ 0.04 dex

Dereddened VVV-2MASS CMD of NGC 6544

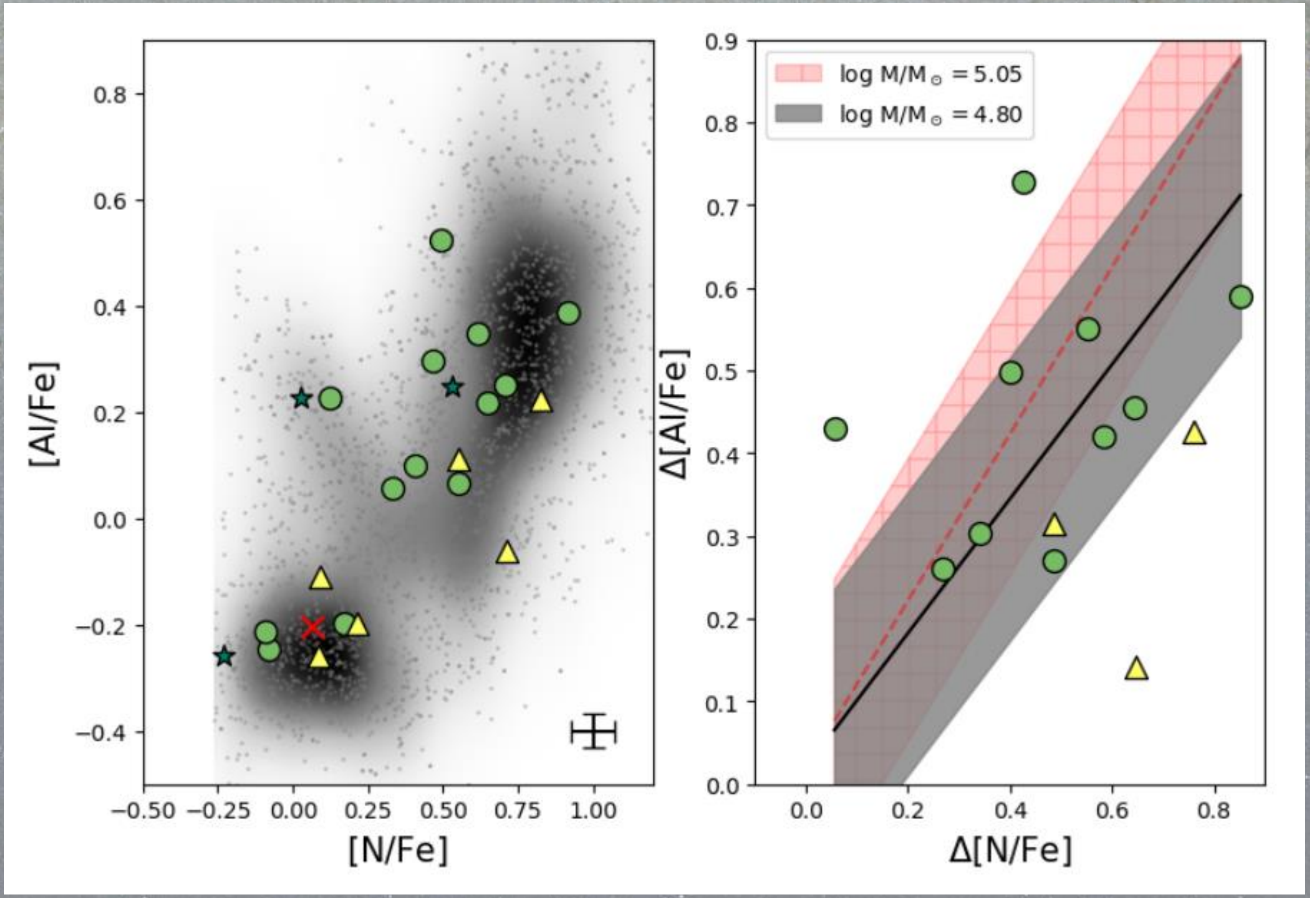
# Known anticorrelations in NGC 6544




Lower RGB (below the bump)
Upper RGB (above the bump)
AGB
Background: APOGEE clusters



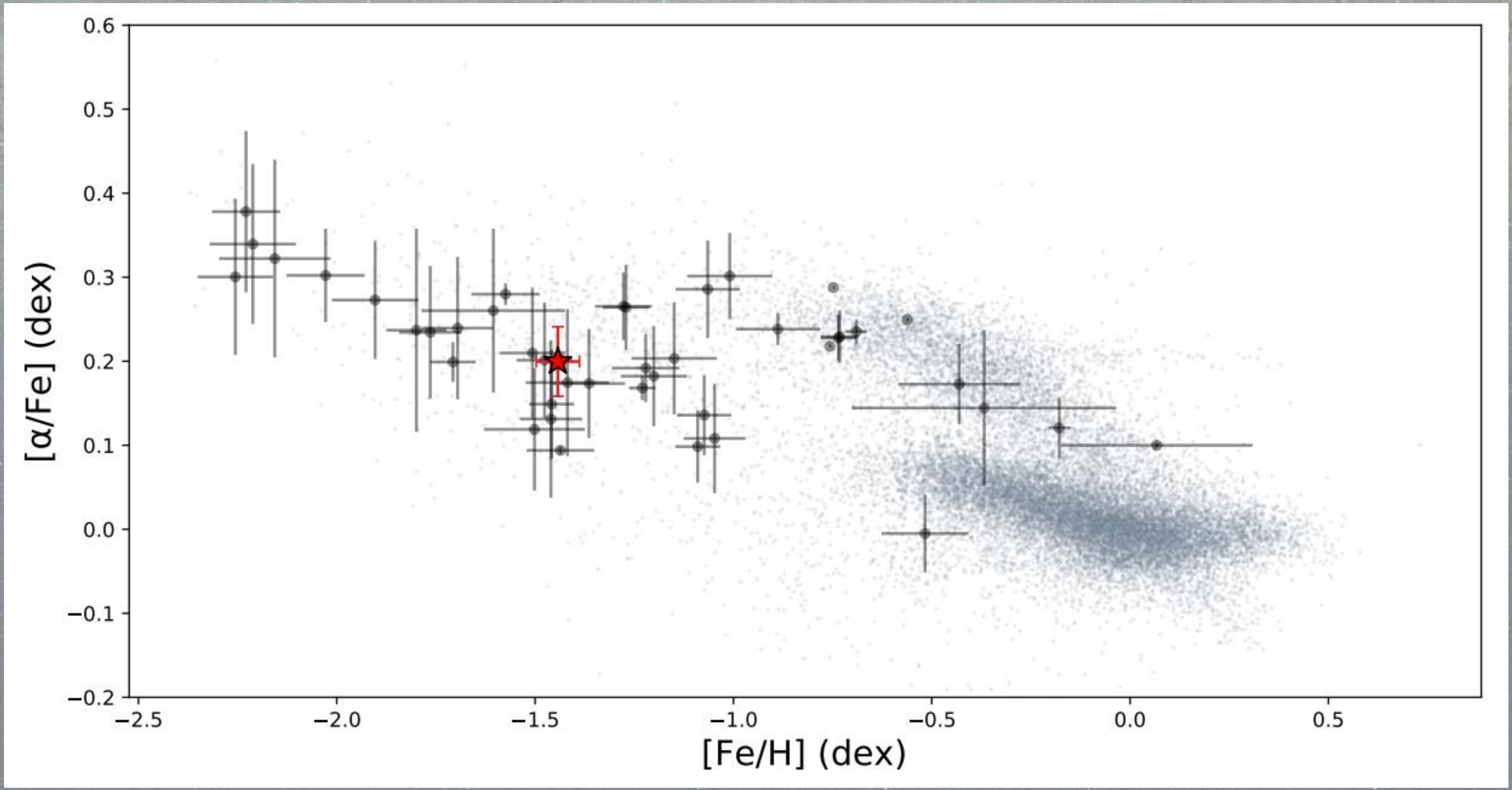
# Abundance patters and the mass of NGC 6544




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

# Galactic context: Tinsley diagram

Background sample: randomly selected 10% of all APOGEE DR16




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

# Summary #1

- ★ APOGEE observed **23 stars** from NGC 6544 (RGB+AGB)

- ★ Known anticorrelations were found (Mg-Al, C-N, Na-O)
- ★ with **distinct abundance patterns**:
  - ★ **9** first generation
  - ★ **14** second generation

- ★ Large [Al/Fe] spread and negligible [Mg/Fe] enrichment

- ★ Independent **distance measurement** (RR Lyrae star)

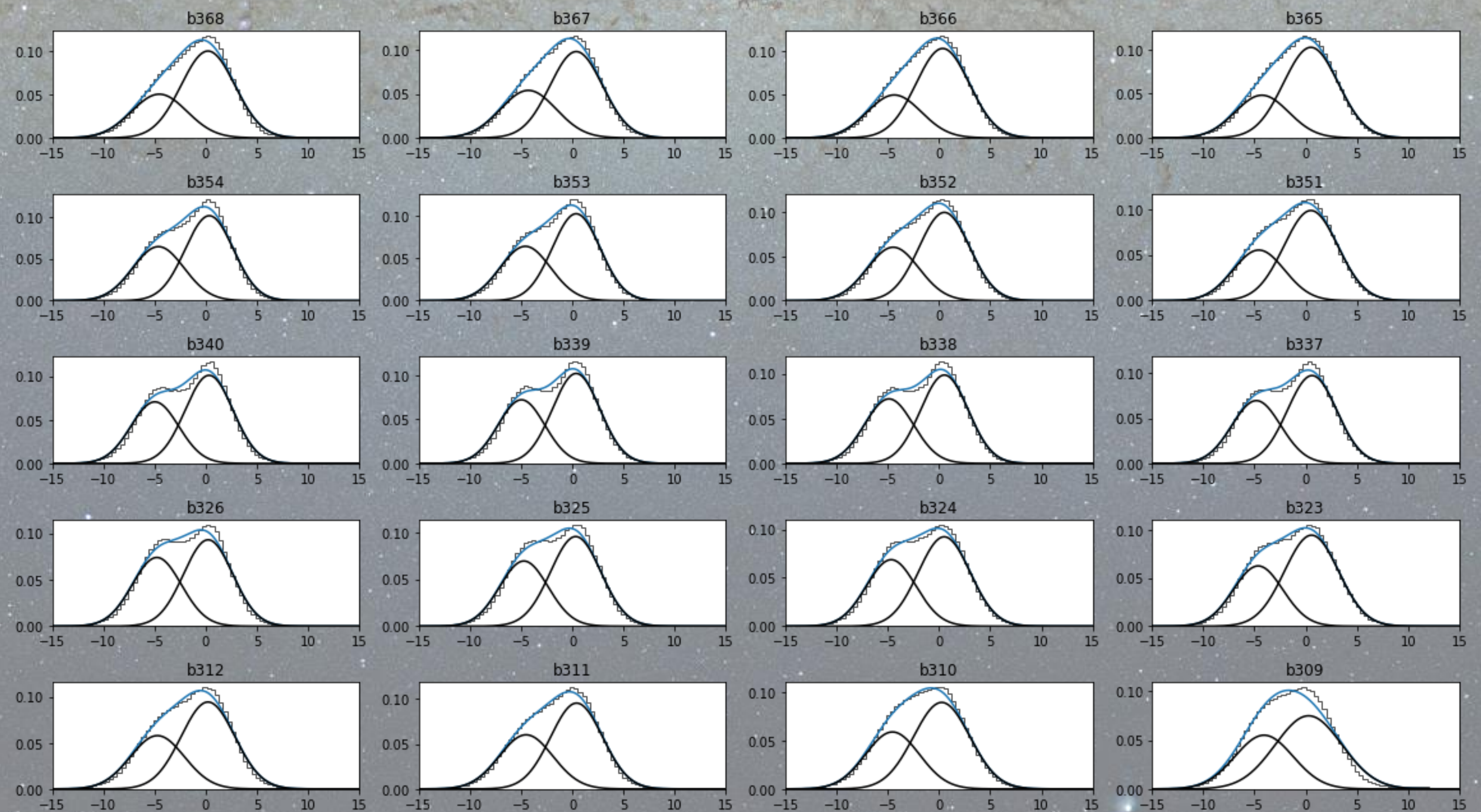
- ★ Consistent with the **metal-poor tail** of the canonical thick-disk

- ★ Multi-survey **synergies** (APOGEE, VVV, Gaia, 2MASS)

# The *intermezzo*: GCs and PMs

- ★ Clouds impede us to observe the APOGEE plates:
  - ★ Explore other possibilities or small projects

- ★ There were several ideas and all of them include the VVV PMs



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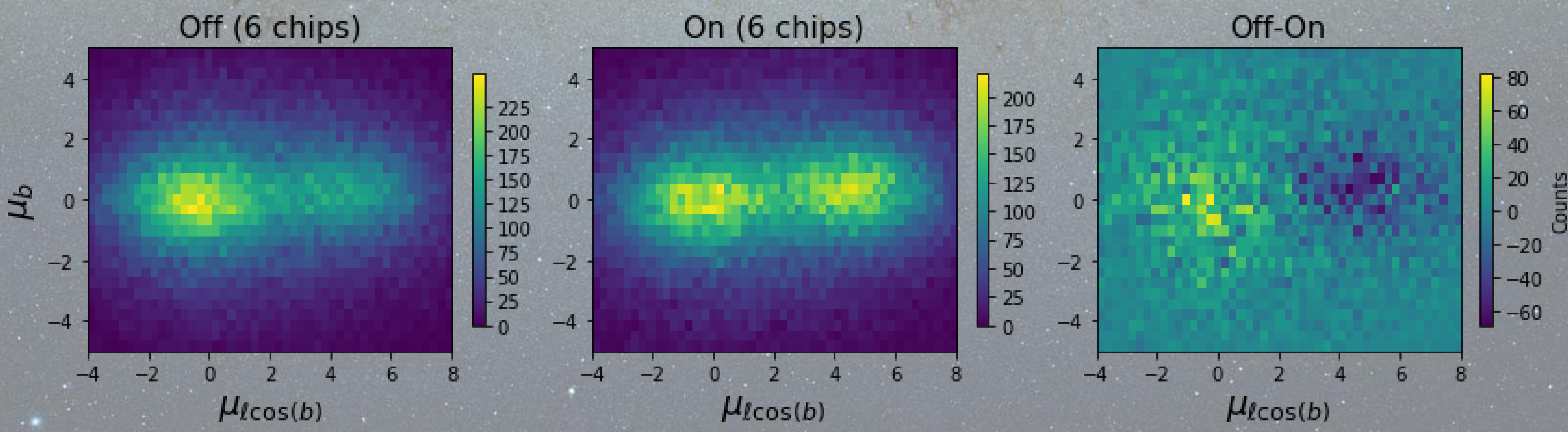
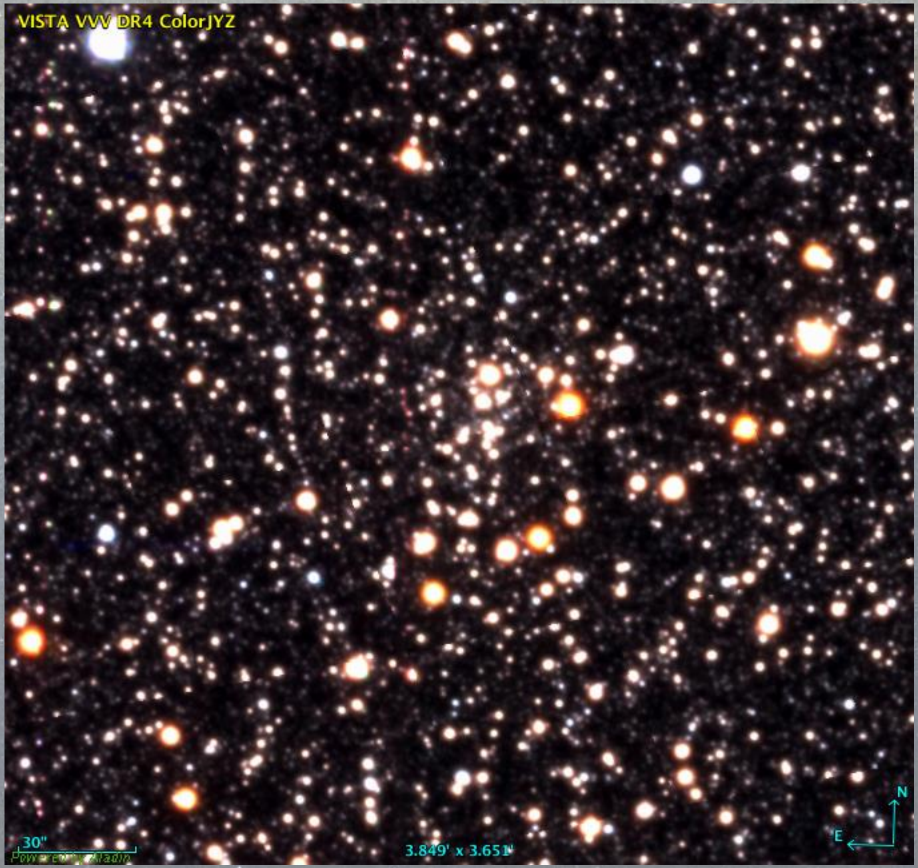


# **Hidden in the haystack**:

New globular clusters towards the Milky Way bulge




Gran et al. 2019

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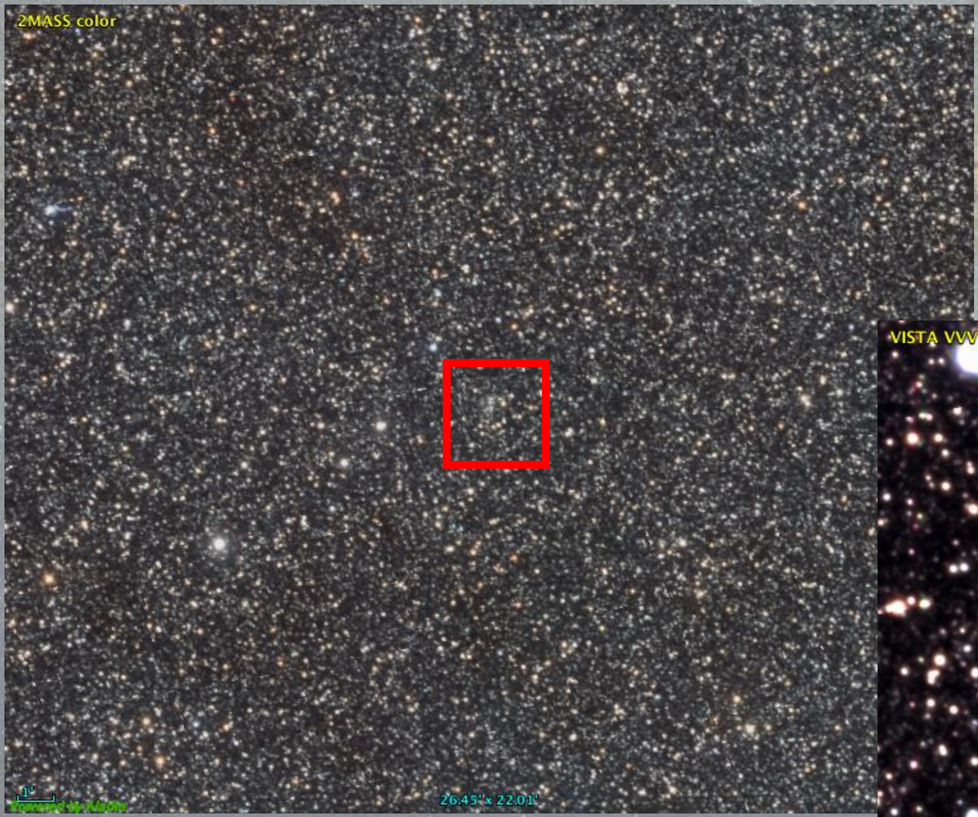
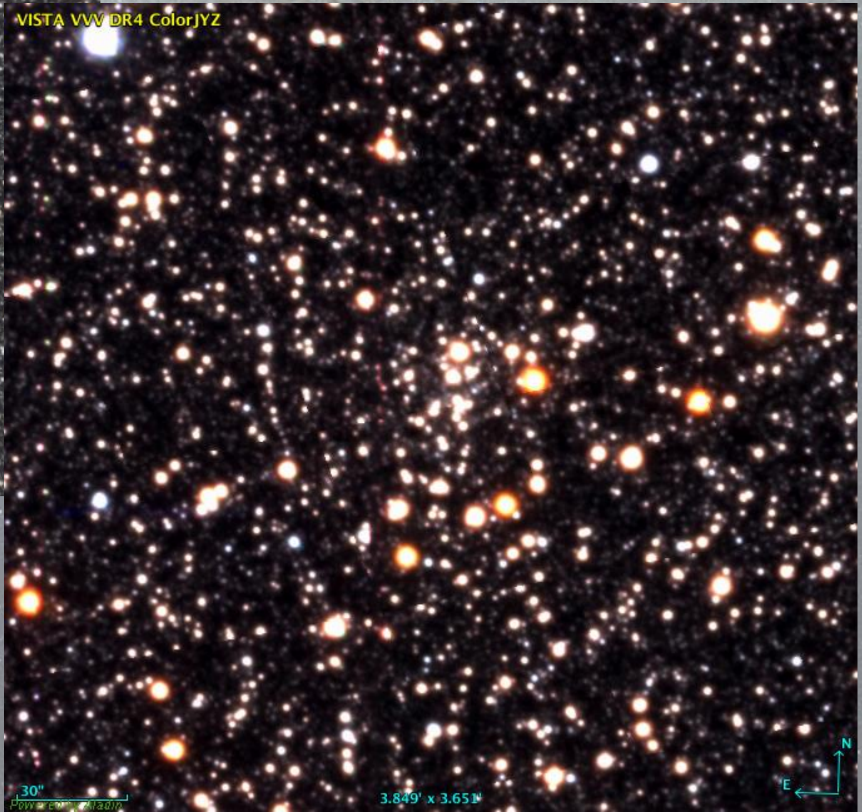


# **Hidden in the haystack**:
## New globular clusters towards the Milky Way bulge


★ Valuable tracers of understand the Milky Way evolution

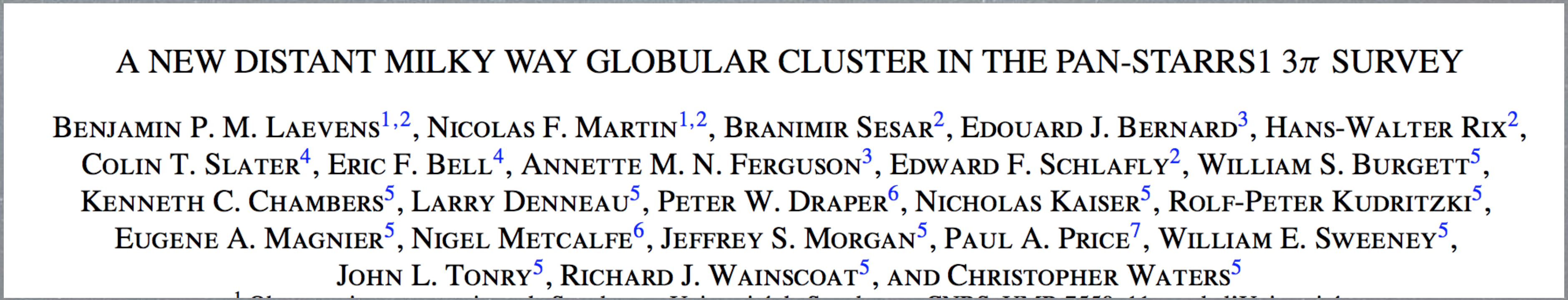
★ Galactic bulge GCs compose a major part of the ***in situ*** component (Myeong et al. 2018)

★ 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 $3\pi$ 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 3$\pi$ SURVEY

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

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

[1]*Dipartimento di Fisica e Astronomia Galileo Galilei, Università di Padova, Vicolo dell'Osservatorio 2, I-35122 Padova, Italy*
[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*
[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
Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia; dongwon.kim@anu.edu.au
*Received 2015 December 10; accepted 2016 February 12; published 2016 March 29*

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

Dongwon Kim, Helmut Jerjen, Antonino P. Milone, Dougal Mackey, and Gary S. Da Costa
Research School of Astronomy and Astrophysics, The Australian National University, Mount Stromlo Observatory, via Cotter Road, Weston, ACT 2611, Australia;
dongwon.kim@anu.edu.au
*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

S. Koposov,[1,2★] V. Belokurov[1] and G. Torrealba[1]
[1] …rsity of Cambridge, Cambridge CB3 0HA, UK
…s Center for Cosmology, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

…AR CLUSTER IN THE CONSTELLATION OF CENTAURUS

DONGWO… MACKEY, GARY S. DA COSTA, AND ANTONINO P. MILONE
Research School of Astr… University, Canberra, ACT 2611, Australia; dongwon.kim@anu.edu.au
Re… February 12; published 2016 March 29

DISCOVERY OF A FAINT OU… 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…

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

A NEW DISTANT MILKY WAY GLOBULAR CLUST… …RVEY

# Segue 3: the youngest globular cluster in th…

S. Ortolani,[1,2] E. Bica[3] and B. Barbuy[4†]
[1]Dipartimento di Fisica e Astronomia Galileo Galilei, Università di Padova, Vicolo dell'Osservatorio 2, I-35122 Padova, Italy
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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

S. Koposov,[1,2★] V. Belokurov[1] and G. Torrealba[1]
[1] ...ersity of Cambridge, Cambridge CB3 0HA, UK
...s Center for Cosmology, Carnegie Mellon University, 5... ...5213, USA

THE DISCOVERY OF TWO EXTREMELY LO...

S. Koposov,[1,2] J. T. A. de Jo...
N. W. Evans,[2] G...
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...AR CLUSTER IN THE ...US

Dongwon ... Macke... ...P. 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
...Council of Canada, Victoria, BC V9E 2E7, Canada
...3 Santa Barbara Street, Pasadena, CA 91101, USA
...hnology, Pasadena, CA 91125, USA
...; published 2012 June 15

...RY OF A FAINT O... ...N 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]

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] Observatorio...
[5] Astro...
Re...

...Bica[3] and B. Barbuy[4]
...e Astronomia Galileo Galilei, Università di Padova, Vicolo dell'Osservatorio 2,
...o Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padua, Italy
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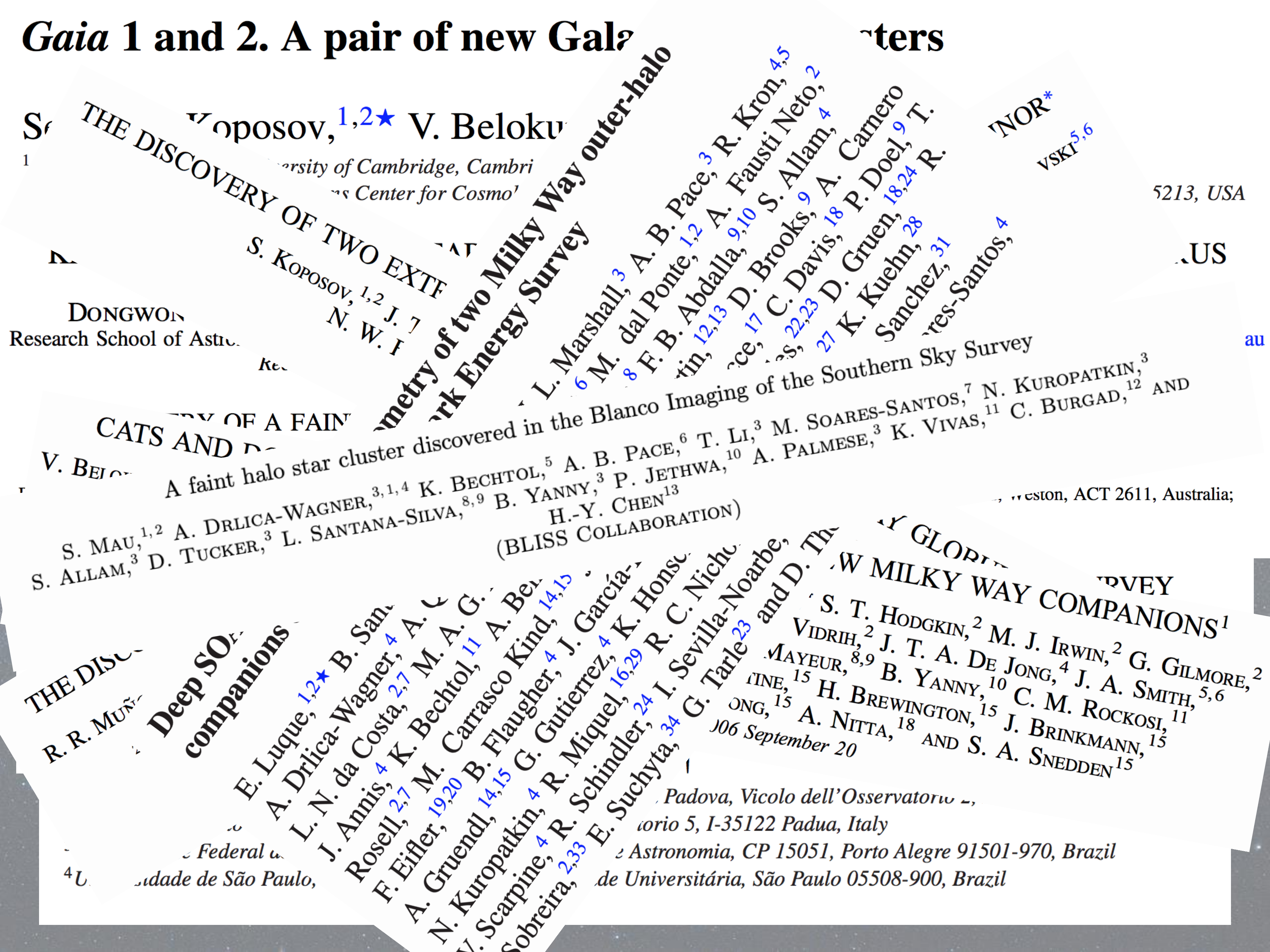
[4] U...idade de São Paulo, IAG, Rua do Matão 1226, Cidade Universitária, São Paulo 05508-900, Brazil


Gaia 1 and 2. A pair of new Gala
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S. Koposov,[1,2] J.
N. W.
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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]
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au
CATS AND D
V. Bel
Weston, ACT 2611, Australia;
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)
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companions
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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. Nich
V. Scarpine,[4] R. Schindler,[24] I. Sevilla-Noarbe,
Sobreira,[2,33] E. Suchyta,[34] G. Tarle[23] and D. Th
Y GLOB
W MILKY WAY COMPANIONS[1]
RVEY
S. T. Hodgkin,[2] M. J. Irwin,[2] G. Gilmore,[2]
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006 September 20
Padova, Vicolo dell'Osservatorio
orio 5, I-35122 Padua, Italy
Federal
Astronomia, CP 15051, Porto Alegre 91501-970, Brazil
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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**.

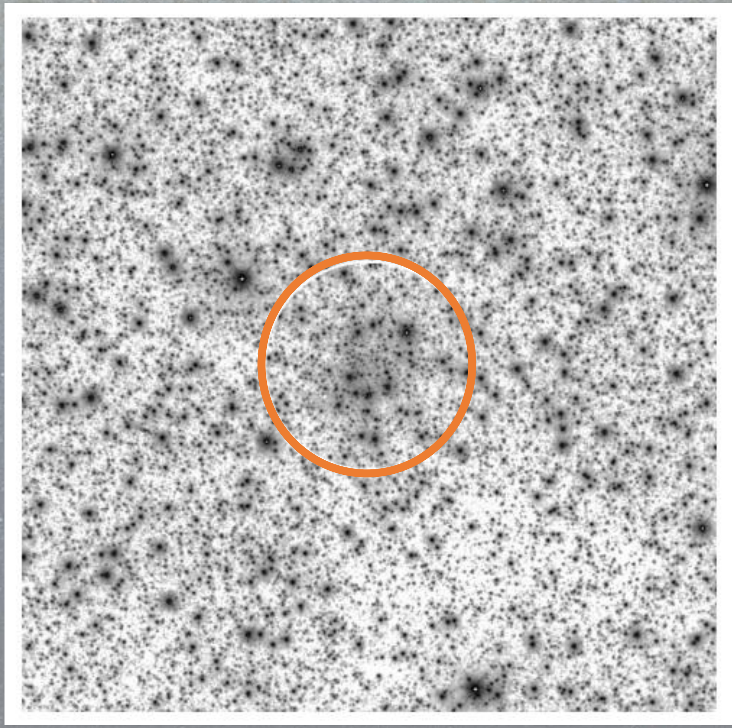

**VVV CL 001**

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

# Photometric searches of GCs

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

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



**VVV CL 002**

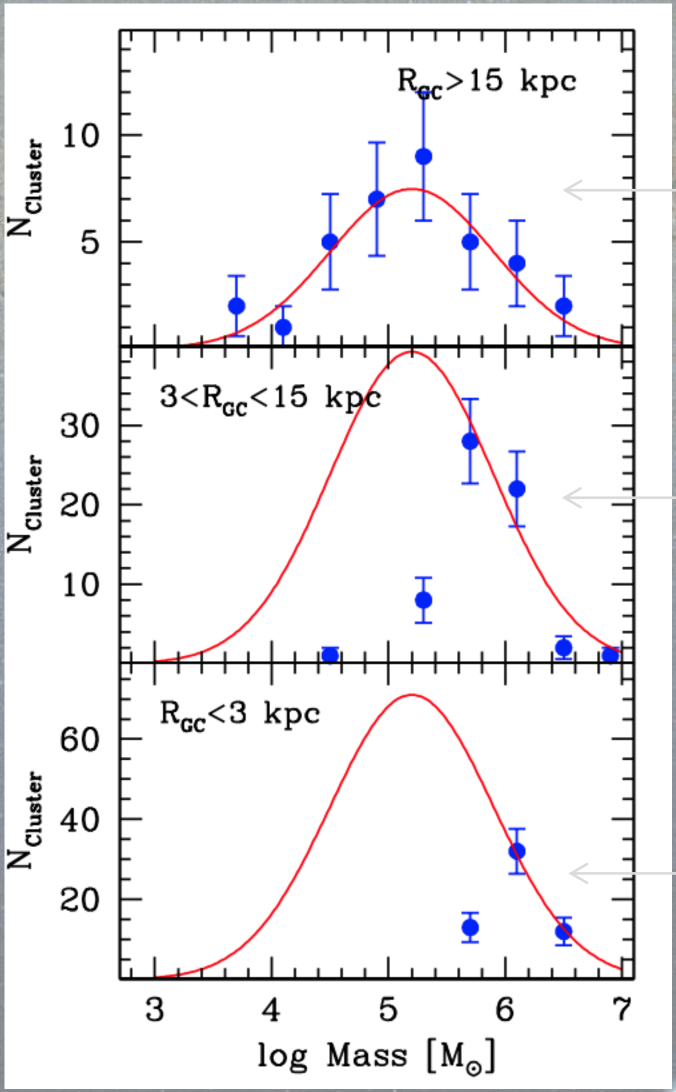
# Photometric searches of GCs

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



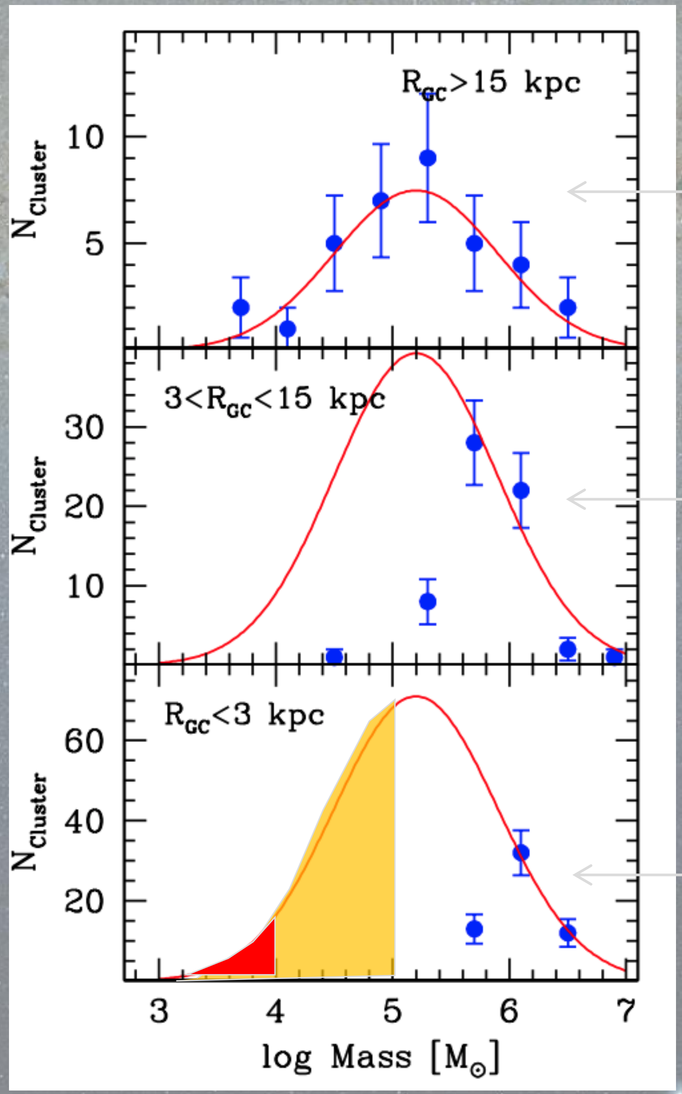

Baumgardt et al. 2018

~Halo GCs

~Disk GCs

~Bulge GCs

# Initial mass distribution of GCs in the MW




Baumgardt et al. 2018

~Halo GCs

~Disk GCs

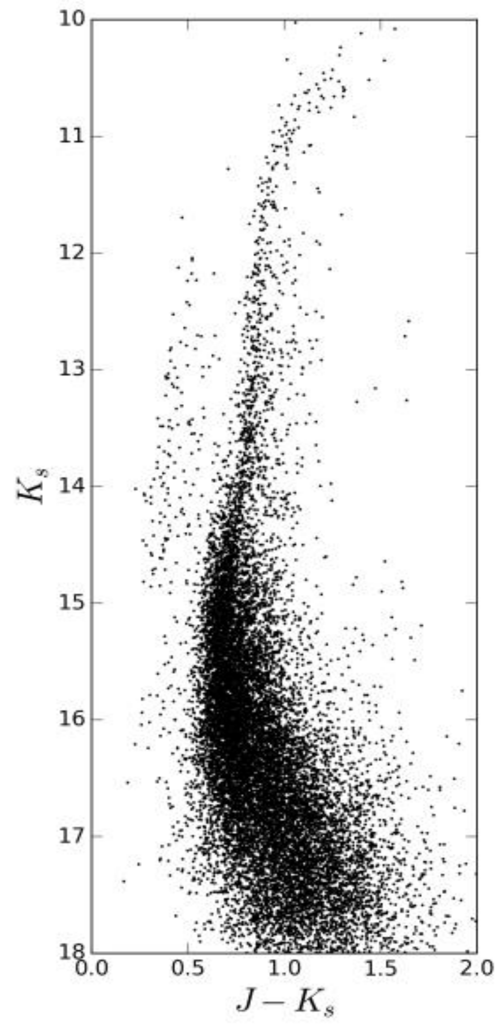
~Bulge GCs

# VVV proper motion catalog

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

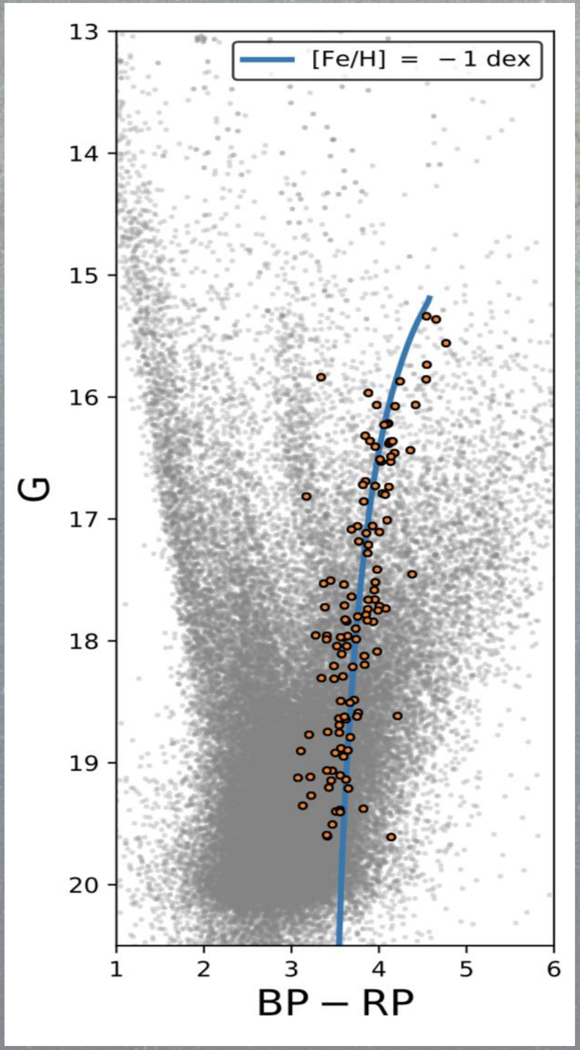
~100+ $K_s$ epochs

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




Minniti et al 2010, Contreras Ramos et al. 2017

# Gaia DR2 proper motion catalog




**Gran et al. 2019**


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

Valid for $|b| \geq 2^{o}$

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

Gaia Collaboration 2018

# Clustering on a 5-D phase-space

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

**+**

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

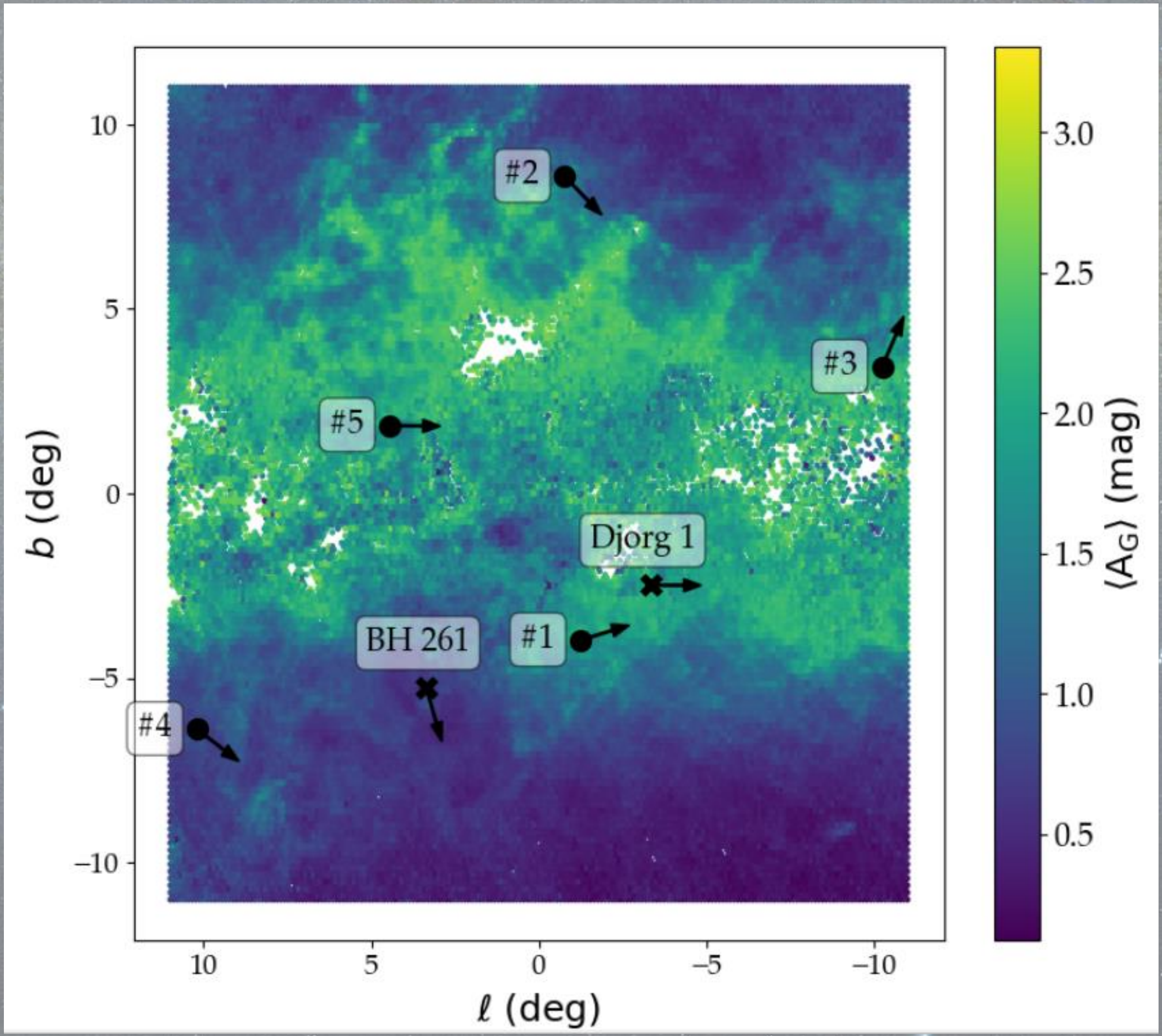
**+**

scikit learn: KDTree and DBScan

Pedragosa et al 2011

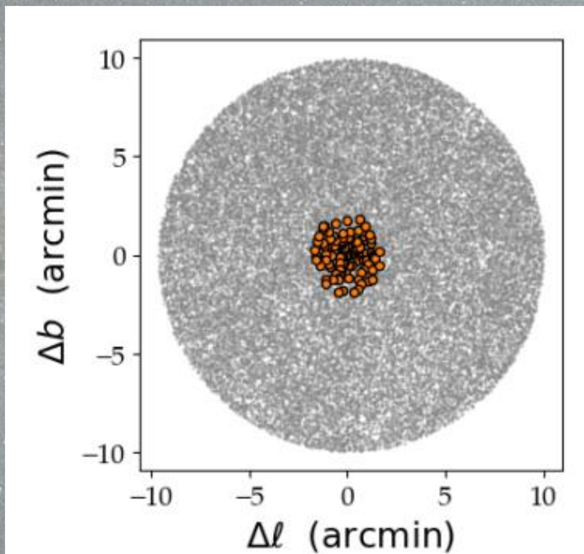
¡Candidate clusters in the 5-D phase space!

# Map of the new GCs




Gran et al. 2021

# New GCs: the case of Gran 3

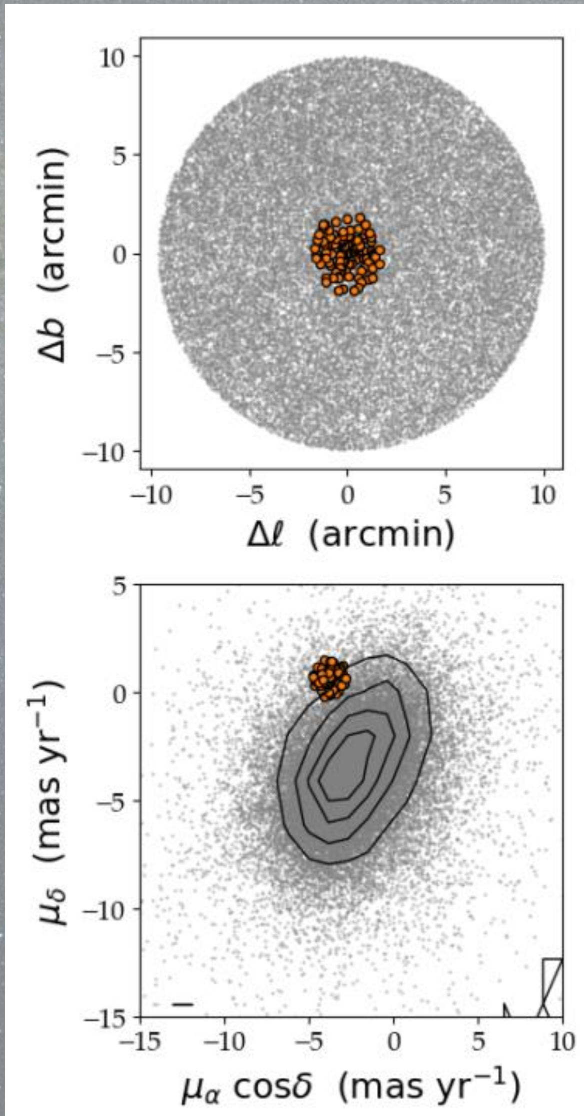



**Clustering requirements**:

- Grouped in space (ℓ,b)

Gran et al. 2021

# New GCs: the case of Gran 3



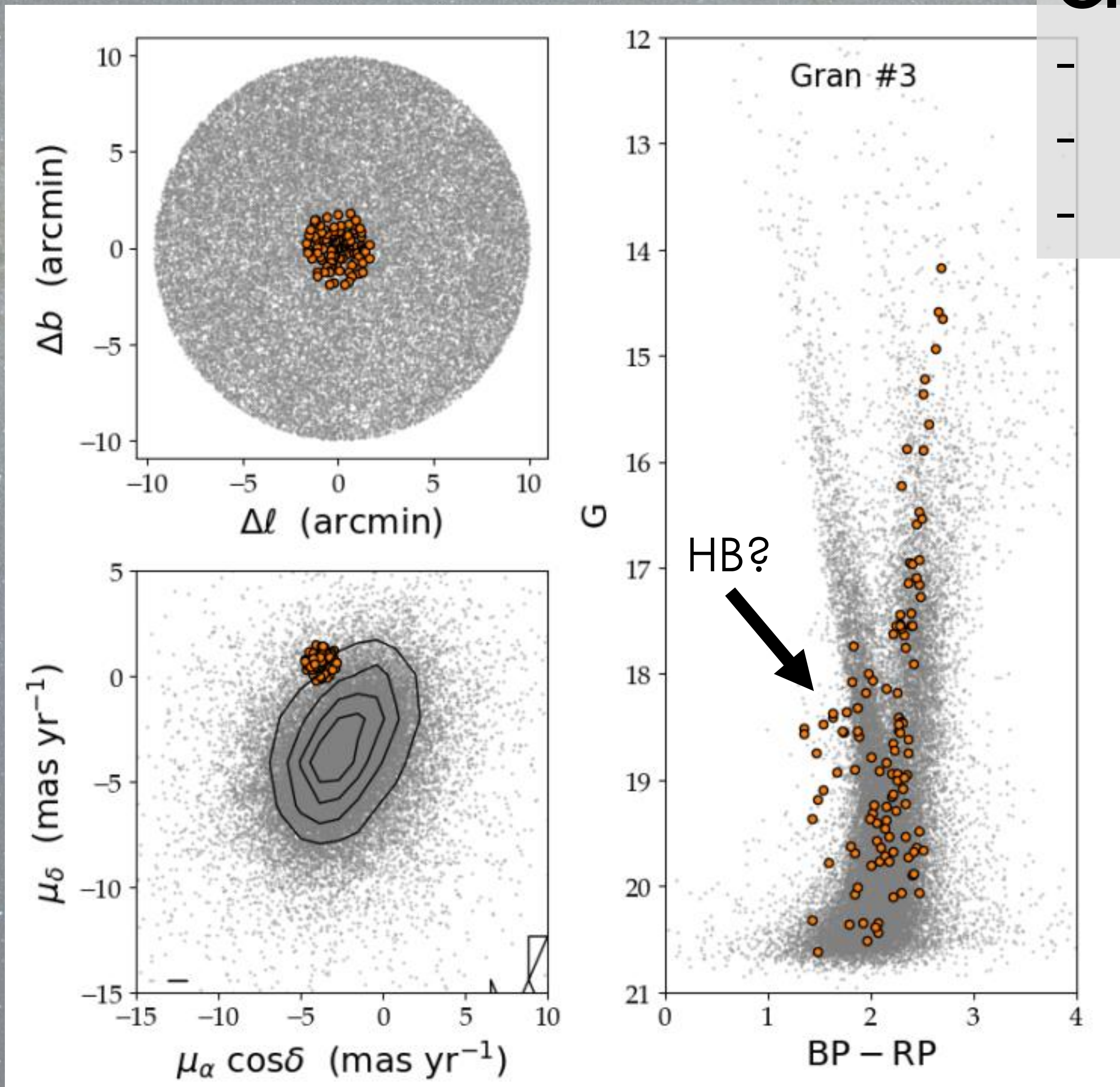

**Clustering requirements**:

- Grouped in space ($\ell$,b)
- Coherent motion (PMs)

**Gran et al. 2021**

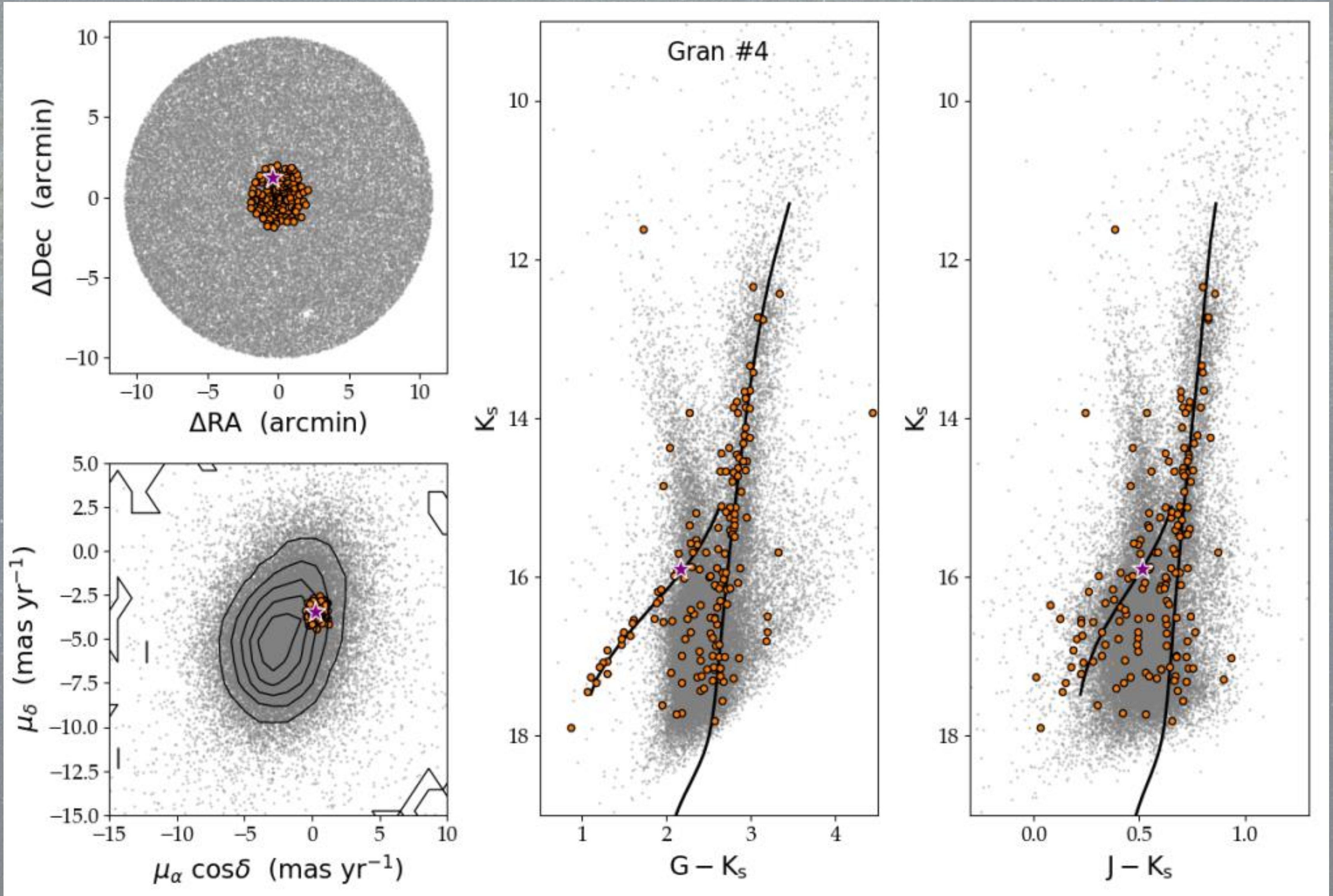
# New GCs: the case of Gran 3

**Clustering requirements**:
- Grouped in space ($\ell$,b)
- Coherent motion (PMs)
- Old stellar sequences



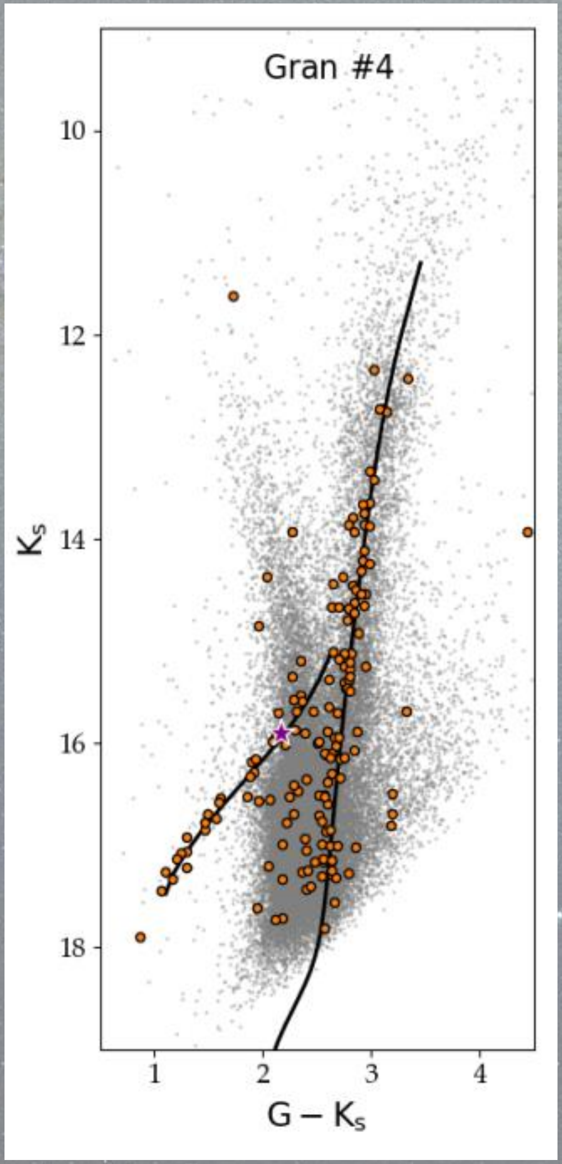

**Gran et al. 2021**

# New GCs: the case of Gran 4




Gran et al. 2021

# New GCs: the case of Gran 4




Gran et al. 2021

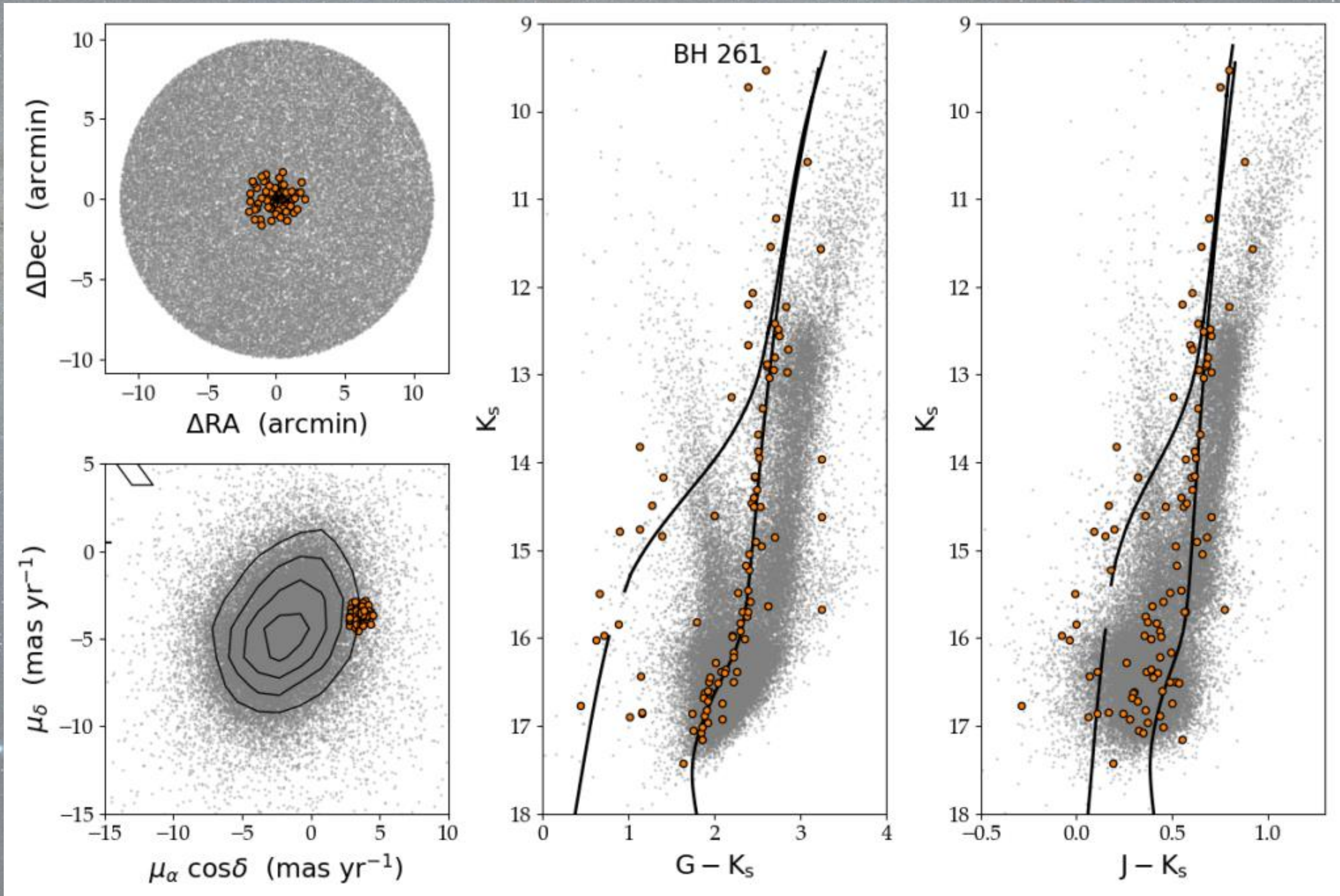
**Clustering requirements**:

- Grouped in space ($\ell$,b)
- Coherent motion (PMs)
- Old stellar sequences

**Cluster parameters:**

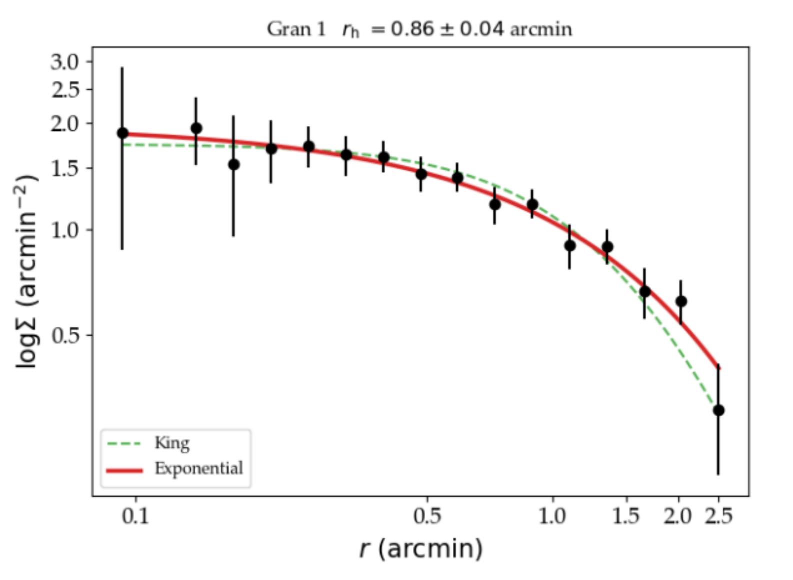
- Age ~12 Gyr
- Distance ~22 kpc
- [Fe/H] ~ -2.4 dex
- $r_h$ ~ 1.15 arcmin
- $M_{dyn} \sim 4 \times 10^5 M_\odot$

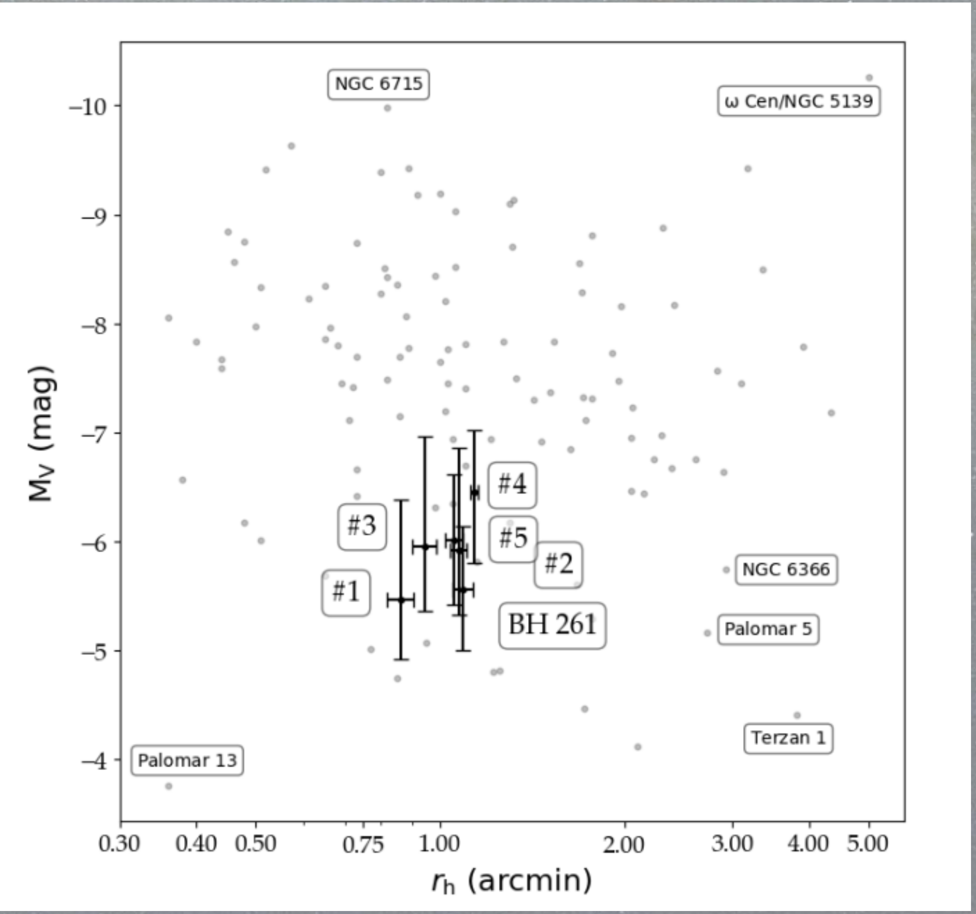
# New GCs: side products




Gran et al. 2021

# New GCs: full characterisation




**Gran et al. 2021**

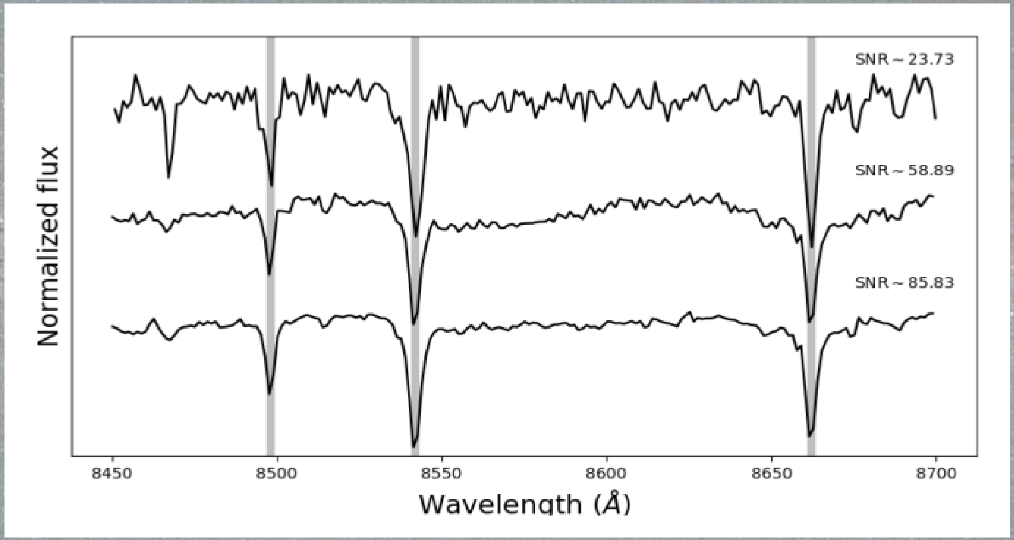
# New GCs: full characterisation

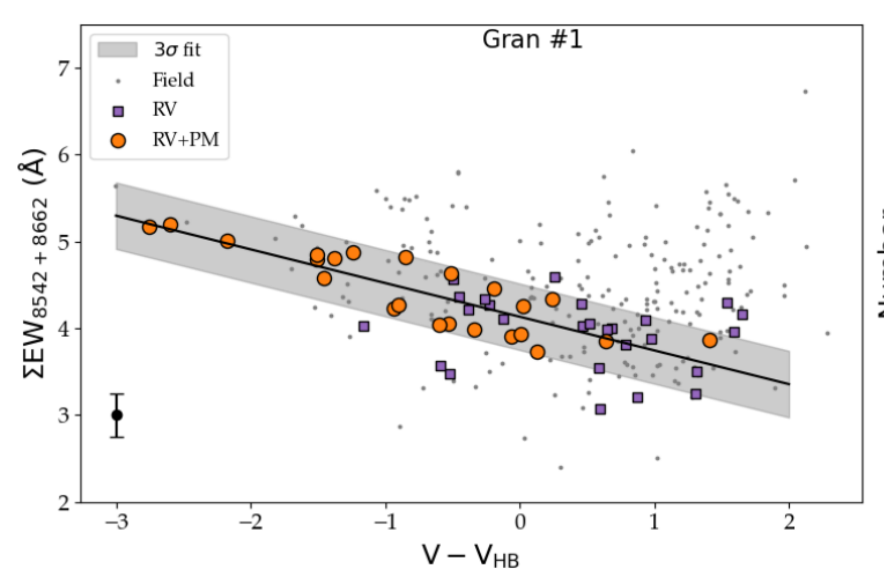
| GC | $\ell$ (deg) | $b$ (deg) | RA (deg) | Dec (deg) | $\mu_\alpha \cos(\delta)$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | $\mu_\ell \cos(b)$ (mas yr$^{-1}$) | $\mu_b$ (mas yr$^{-1}$) | $N_{\rm members}$ (number) |
|---|---|---|---|---|---|---|---|---|---|
| Gran 1 | -1.233 | -3.977 | 269.651 | -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 |

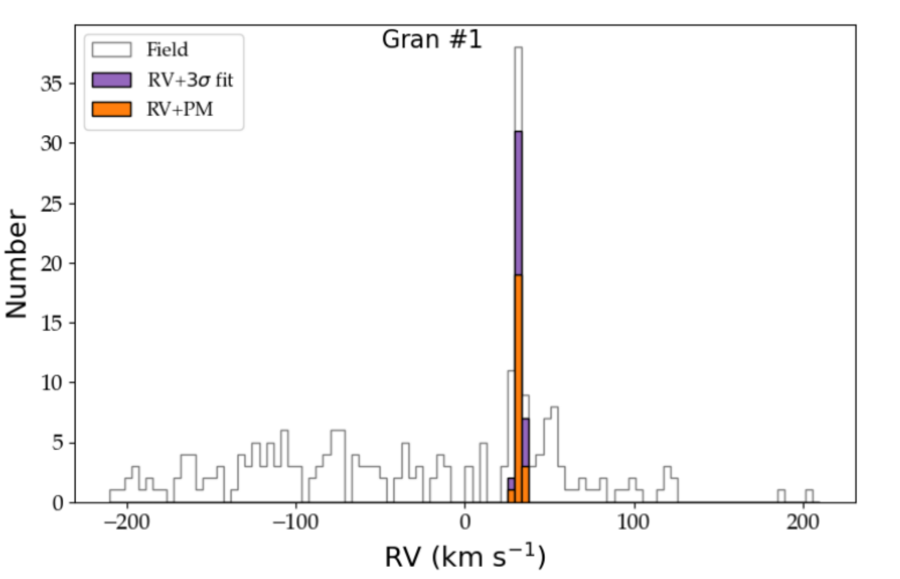
| GC | dm (mag) | Distance (kpc) | E(J – $K_s$) (mag) | $A_{K_s}$ (mag) | $A_G$ (mag) | $A_V$ (mag) | $V_t$ (mag) | $M_V$ (mag) | $r_h$ (arcmin) | [Fe/H] (dex) |
|---|---|---|---|---|---|---|---|---|---|---|
| Gran 1 | 14.60 | 7.94 | 0.45 | 0.24 | 2.70 | 3.38 | 12.41 | -5.46 | 0.86 | -1.19 |
| Gran 2 | 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. 2021**

# New GCs: MUSE observations

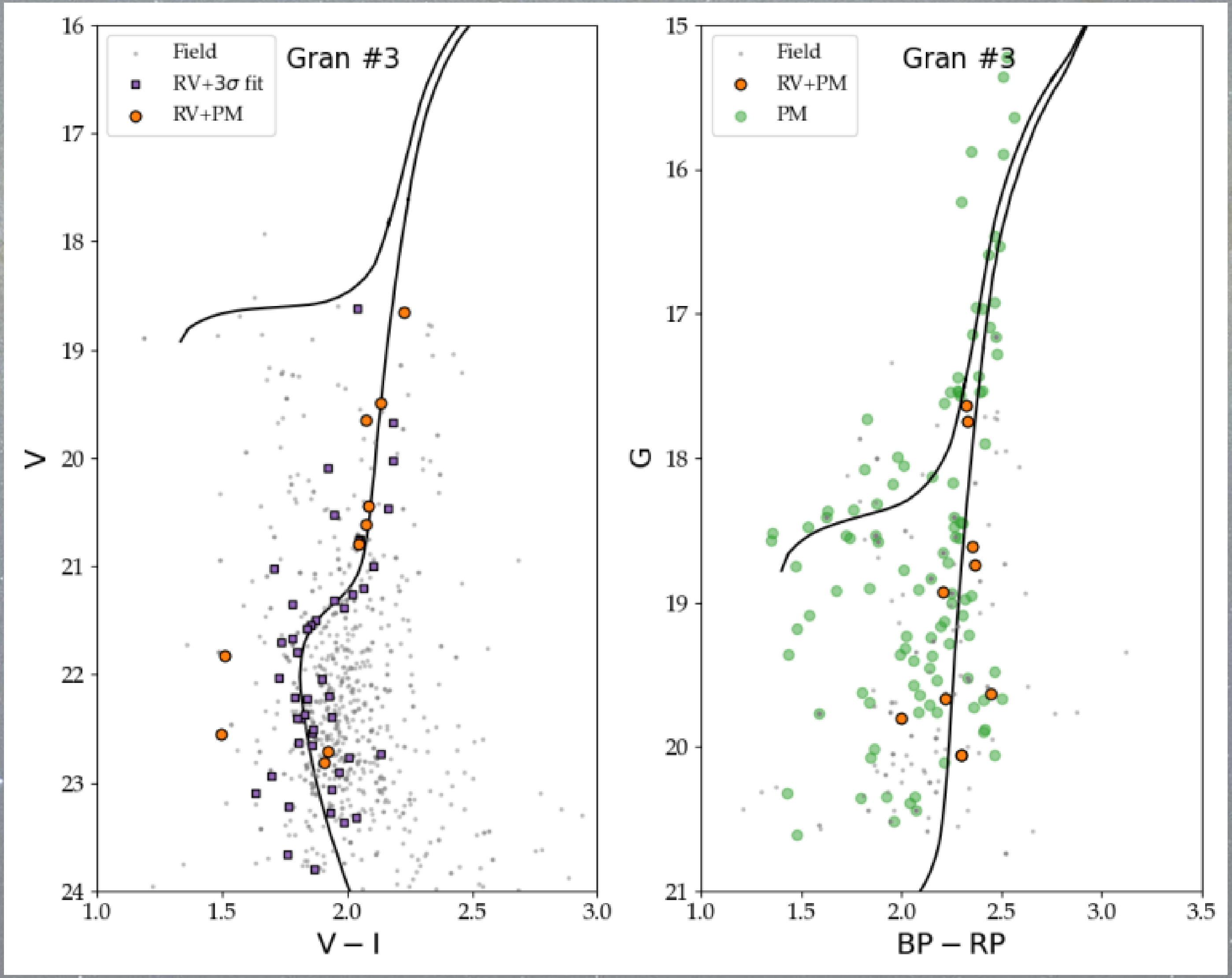


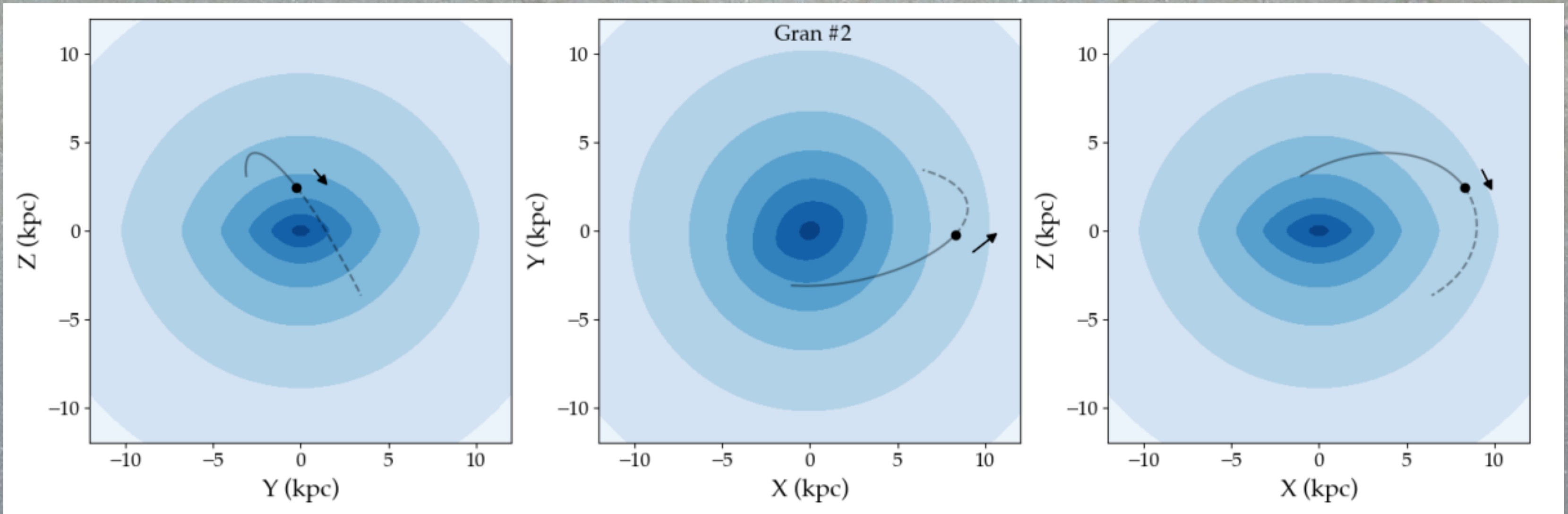

**Gran et al. 2021**

# New GCs: MUSE observations




Gran et al. 2021

# New GCs: MUSE observations




**Gran et al. 2021**

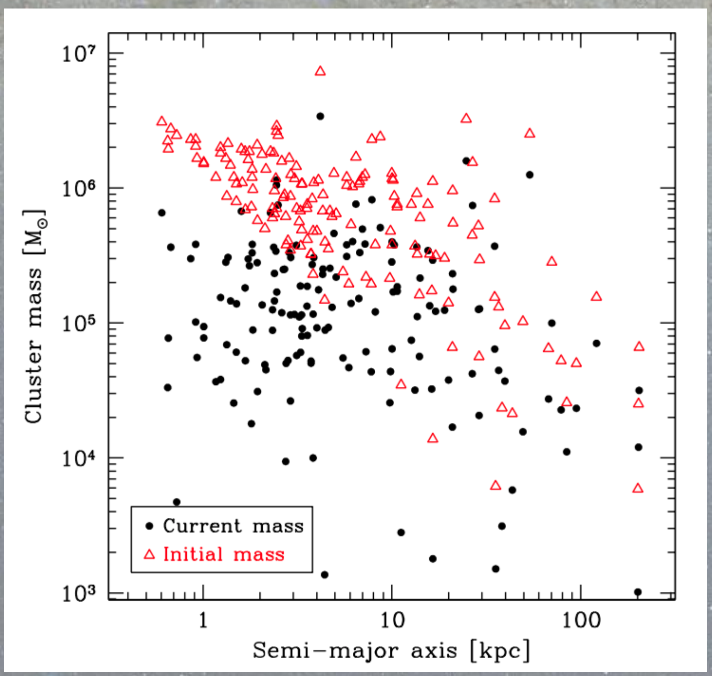
# New GCs: MUSE observations

| GC | $\sigma_0$ (km s$^{-1}$) | $M^{\rm dyn}(< 1.8r_{\rm h})$ ($10^5 M_\odot$) | $\Upsilon$ ($M_\odot L_\odot^{-1}$) |
|---|---|---|---|
| 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. 2021**

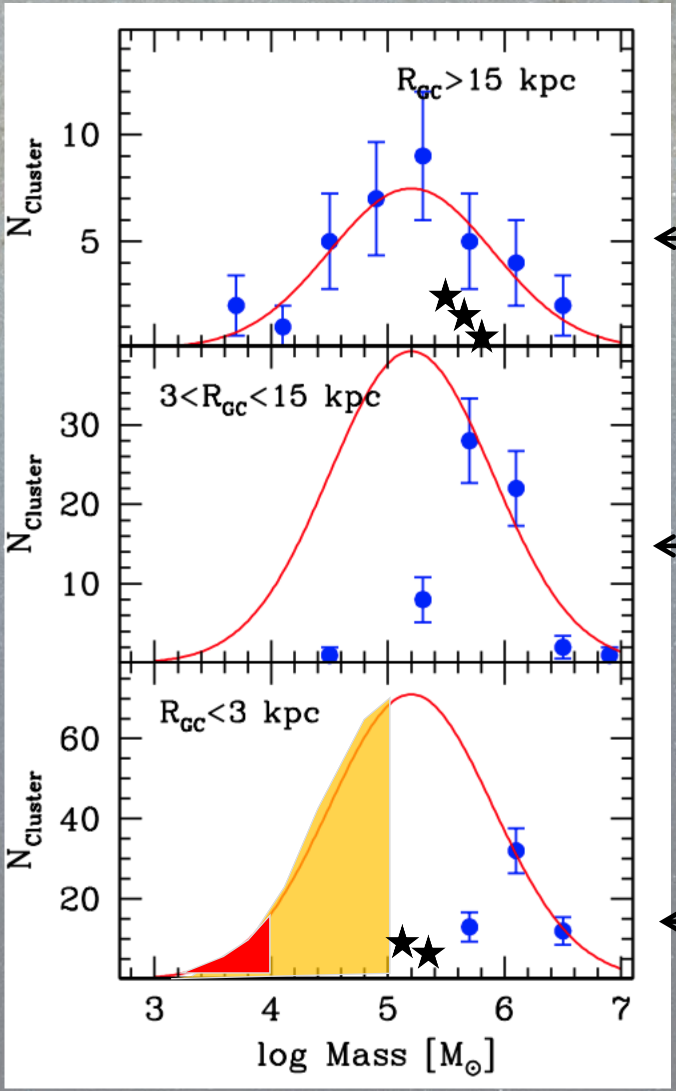
# New GCs: Galactic context
# Initial mass distribution




Baumgardt et al. 2018

Gran 2 + 3 + 4

Gran 1 + 5




← ~Halo GCs

← ~Disk GCs

← ~Bulge GCs

# Summary #2

★ Bulge GCs are tracers of the **MW formation and evolution**: *in situ* component (Myeong et al. 2018).

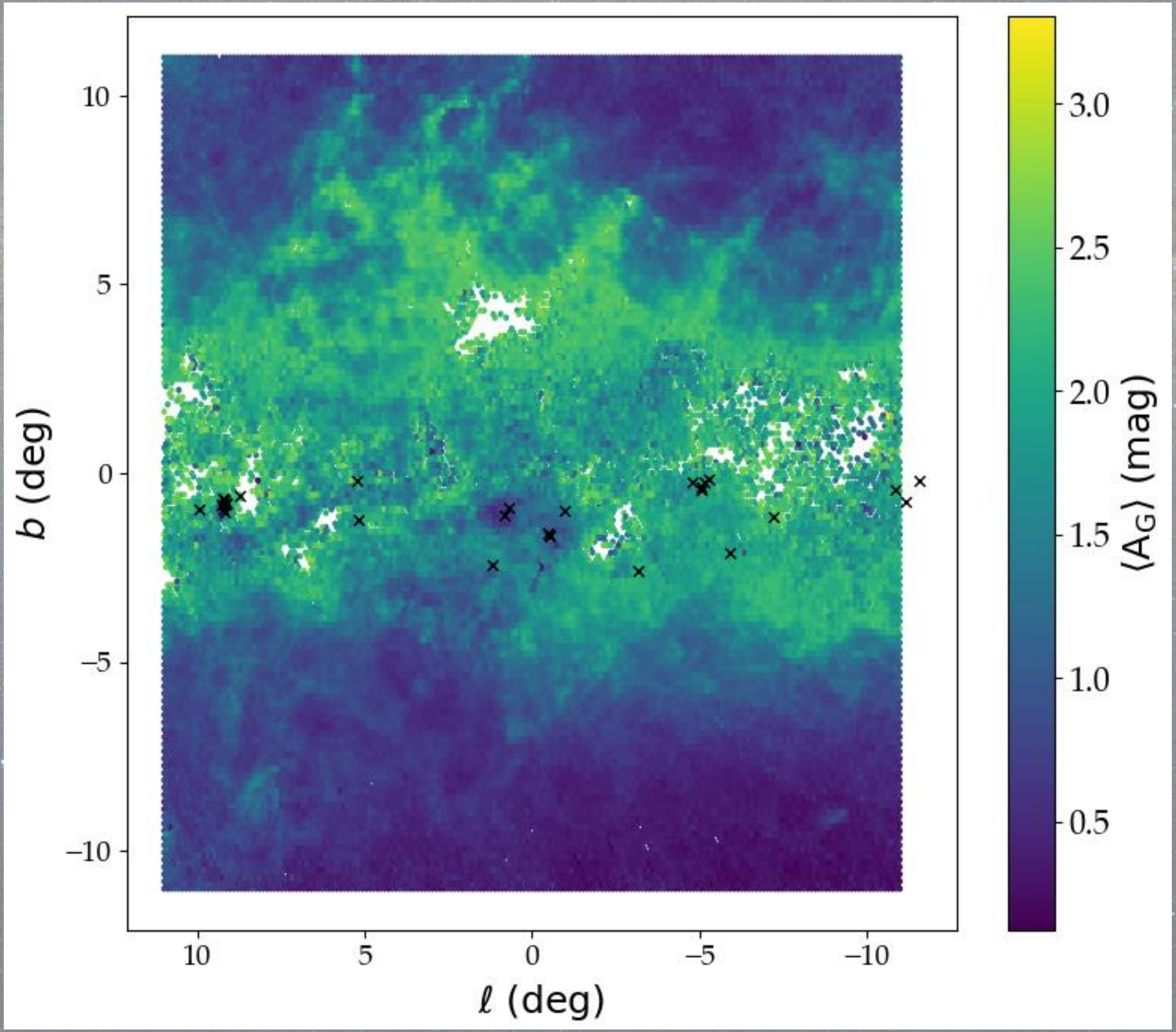
★ No consensus has been reached on the total number of **bulge GCs**.

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

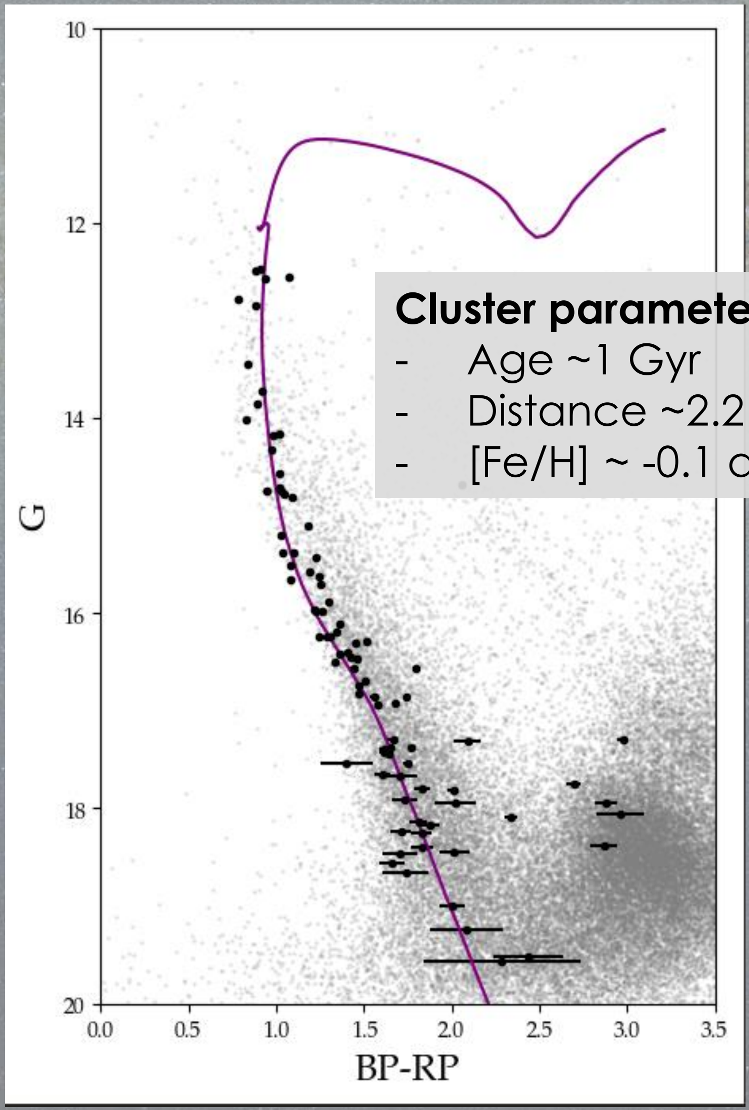
★ Orbital parameters and metallicities from the analysis of 5 **MUSE** cubes.

★ Key observable: **proper motions!**

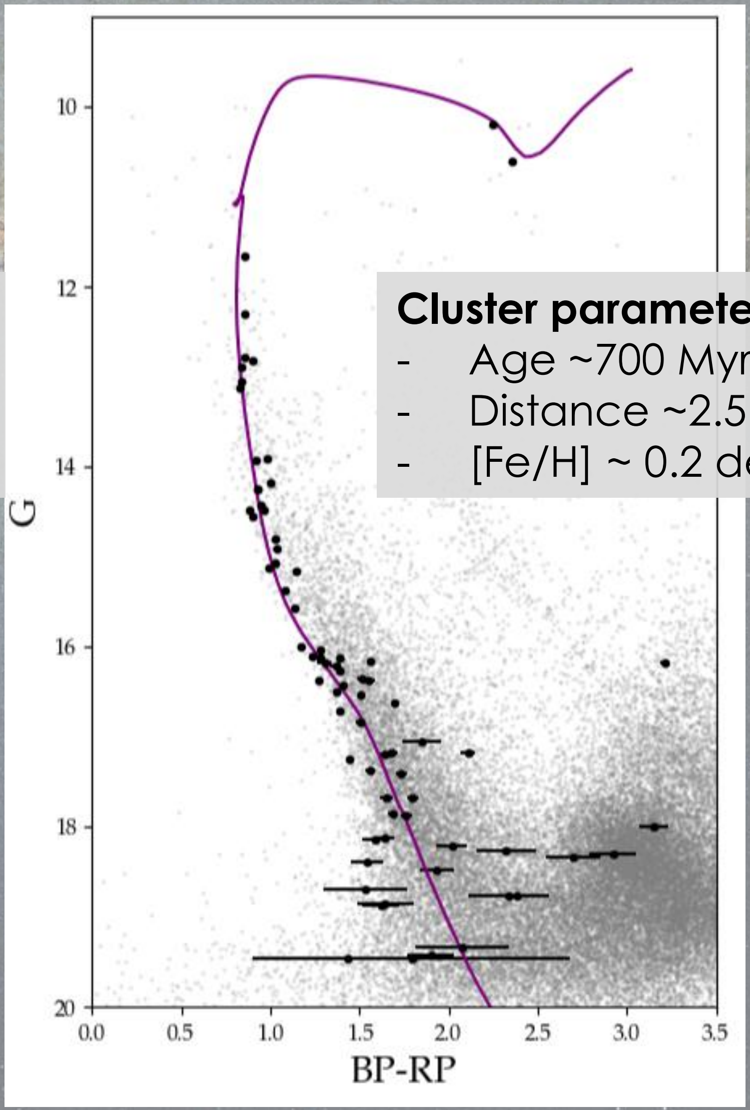
# Future work: new OCs



# Future work: new OCs




**Cluster parameters:**
- Age ~1 Gyr
- Distance ~2.2 kpc
- [Fe/H] ~ -0.1 dex




**Cluster parameters:**
- Age ~700 Myr
- Distance ~2.5 kpc
- [Fe/H] ~ 0.2 dex

# Thanks for your attention!

fegran@uc.cl

@fegranm fegran.github.io

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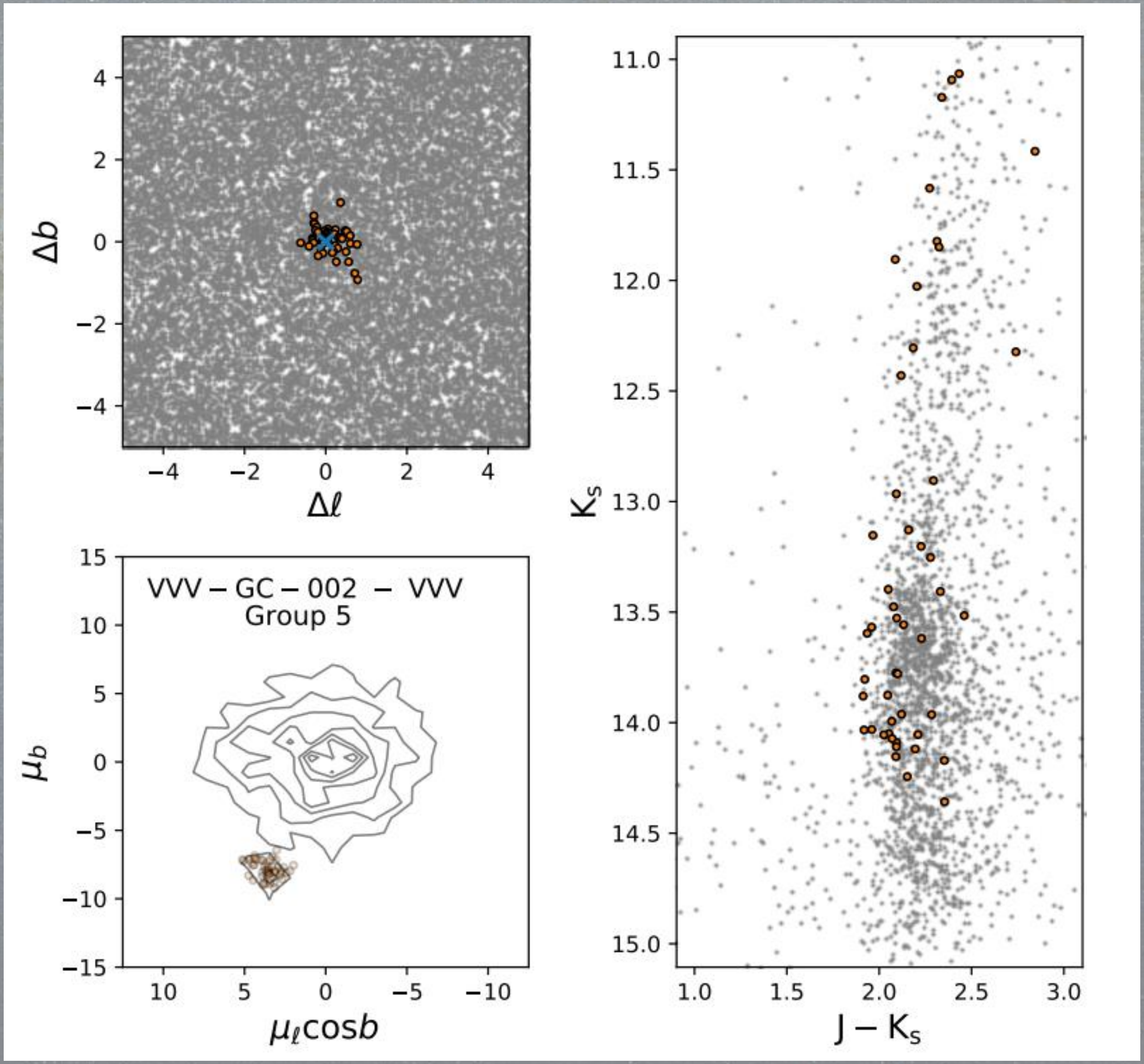
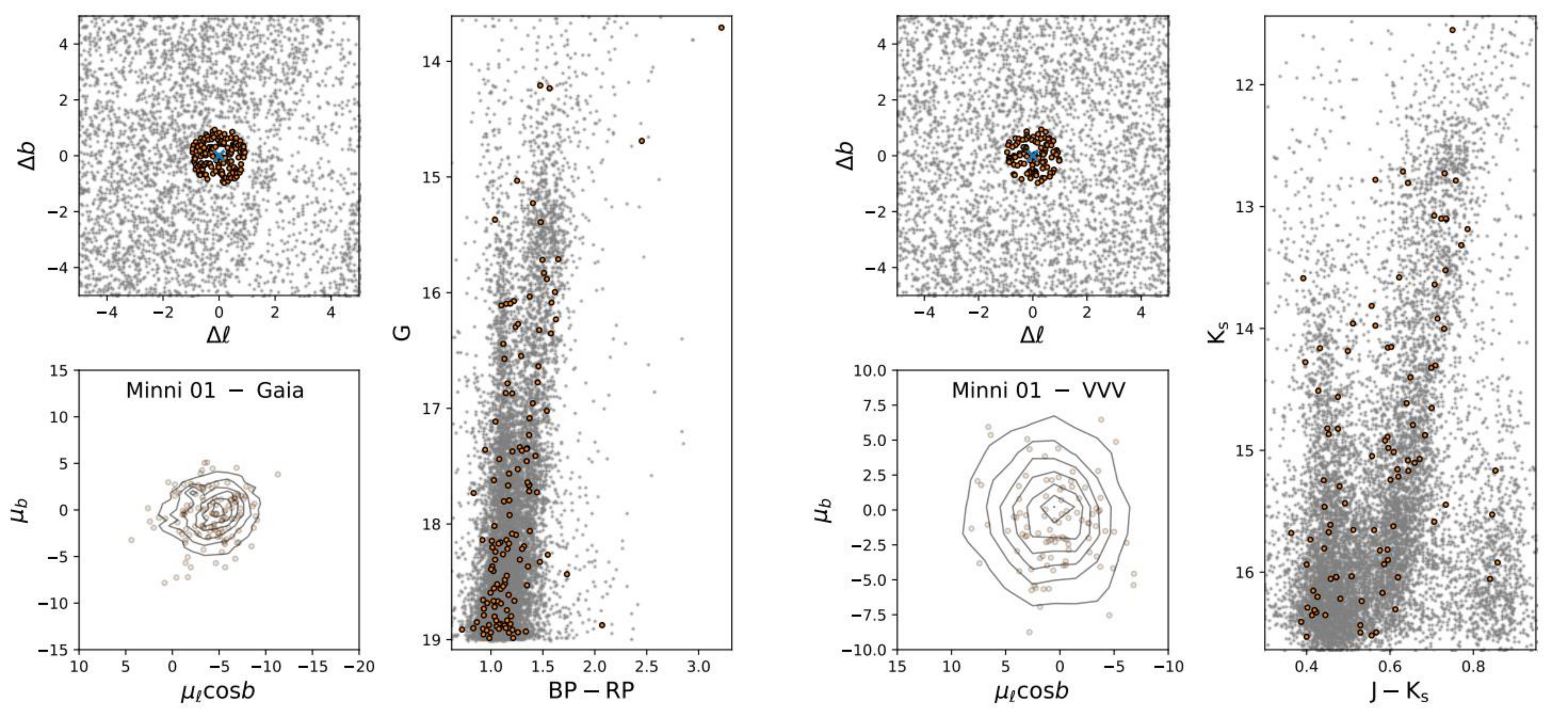
PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

ESO

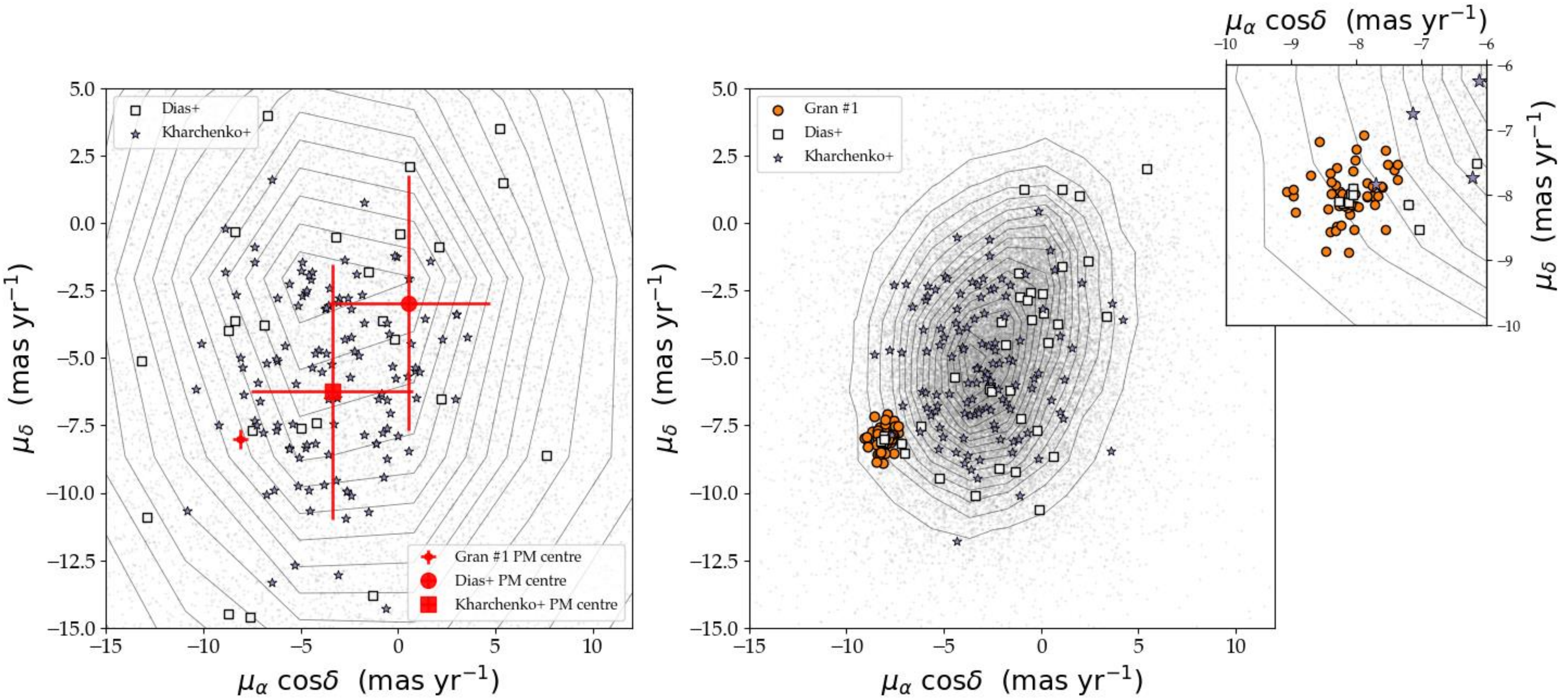
# Backup sludes :)



# Backup sludes :)



# Backup sludes :)



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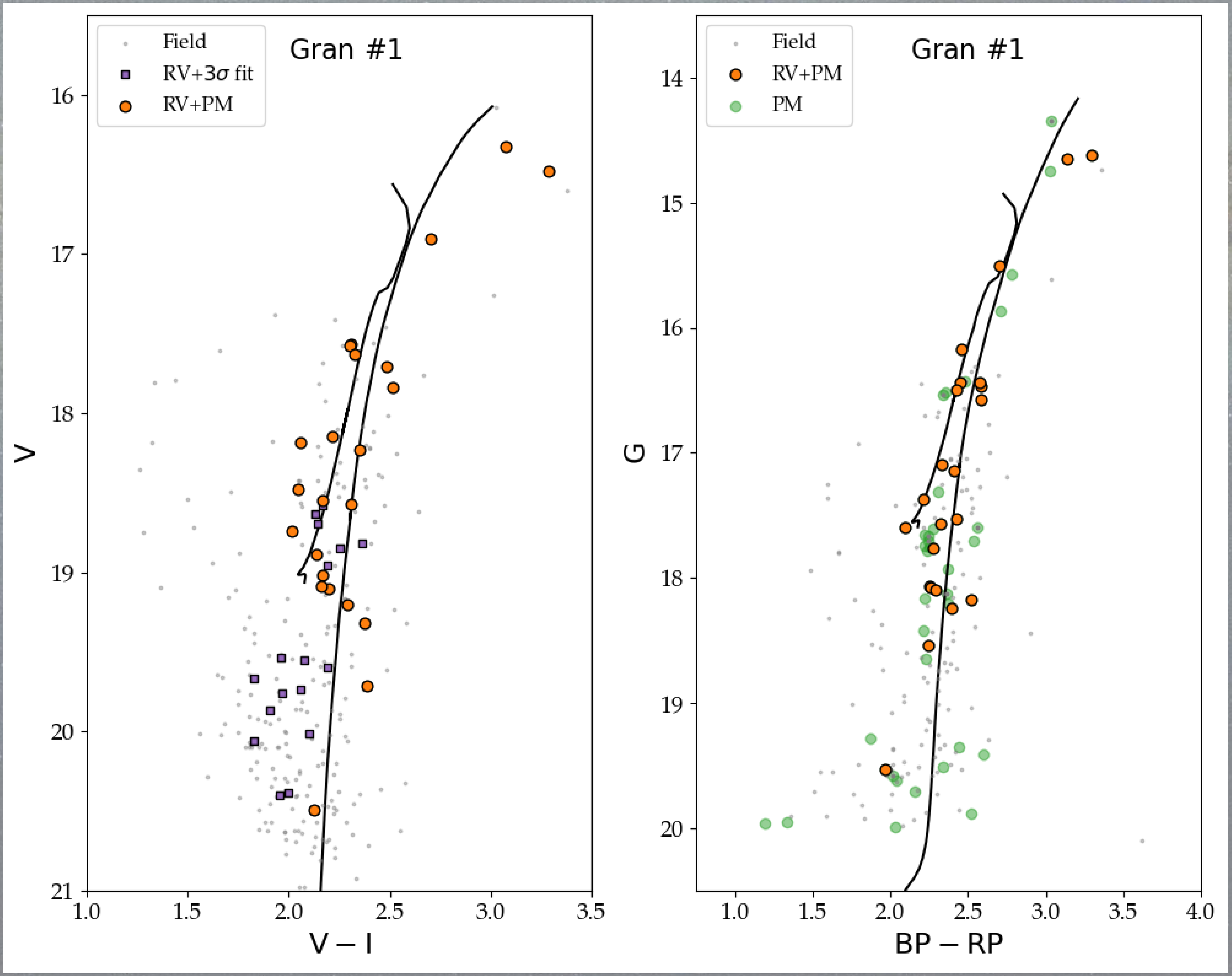

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