PhD Thesis defense – March 25, 2022

Unleashing the proper motions: revolution in the inner Galaxy

Felipe Gran Merino

Instituto de Astrofísica, PUC

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Advisors: Manuela Zoccali
Ivo Saviane (ESO Chile)

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

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This presentation is available at:
fegran.github.io/files/FGran_PhD_Defense.pdf
The thesis is available at:
fegran.github.io/files/FGran_PhD_Thesis.pdf

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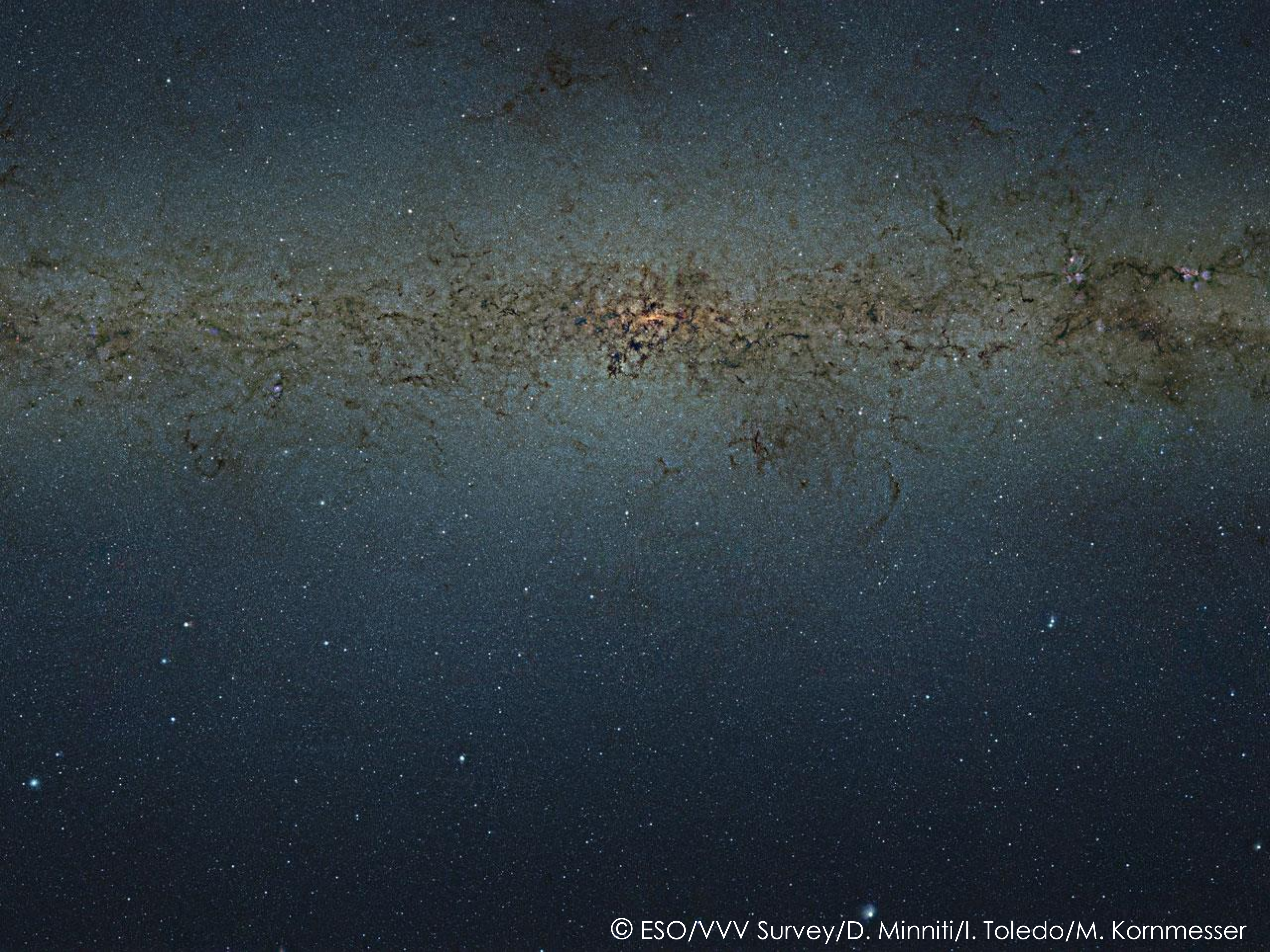
Unleashing the proper motions: revolution in the inner Galaxy

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

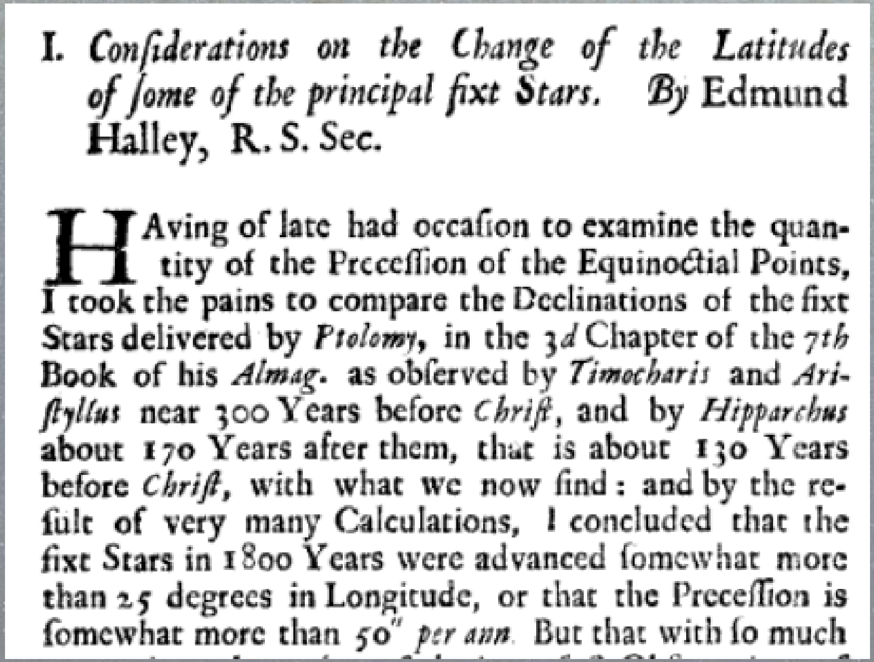
Steve Quirk, Wikipedia Commons

DSS/STScI

Key concept #1: stellar proper motions

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

★ Halley 1717: ~**few** stars


I. *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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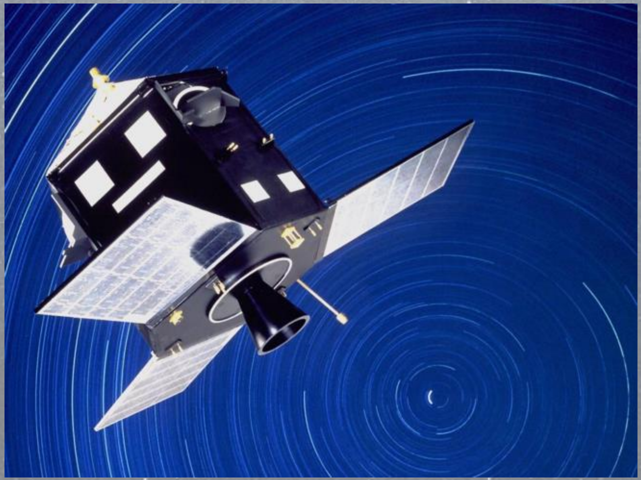
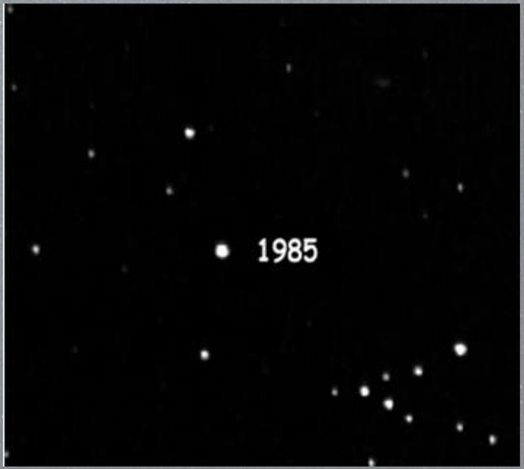


ESA, Hipparcos



Steve Quirk, Wikipedia Commons

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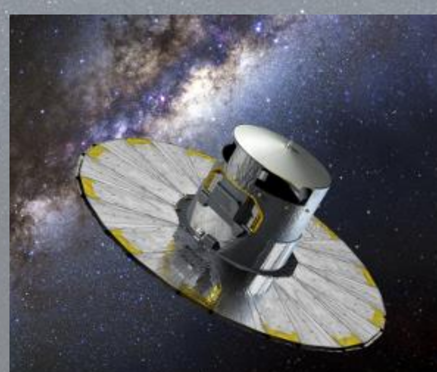
★ ESA Gaia space mission (active):
~**1.46 billion** stars
~**1.460.000.000** stars


POSS1, POSS2, DSS

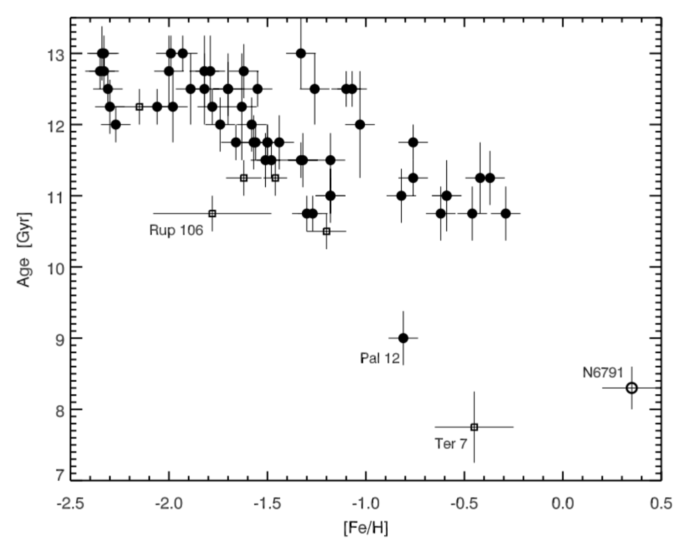
Steve Quirk, Wikipedia Commons


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

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

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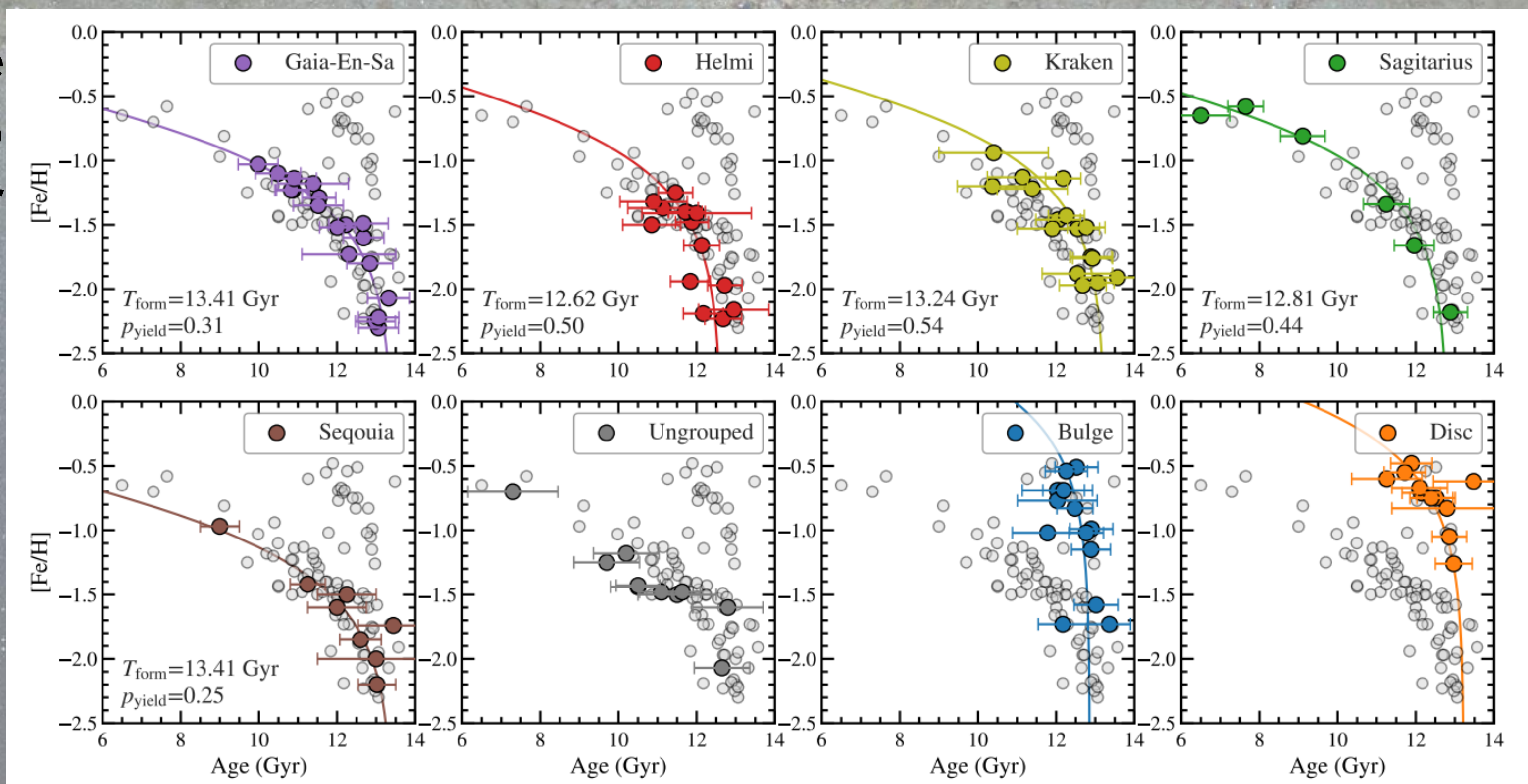
- We … ry
  lab
  enr



Callingham et al. 2022

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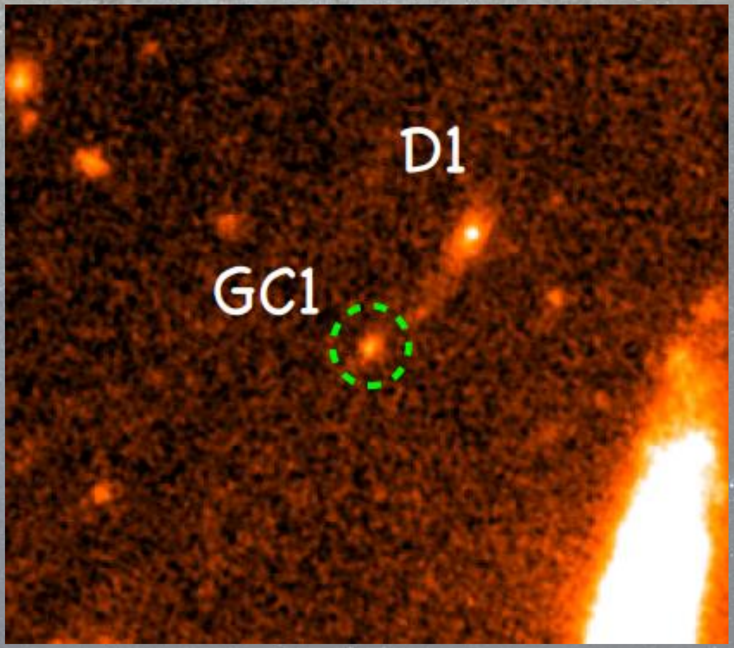
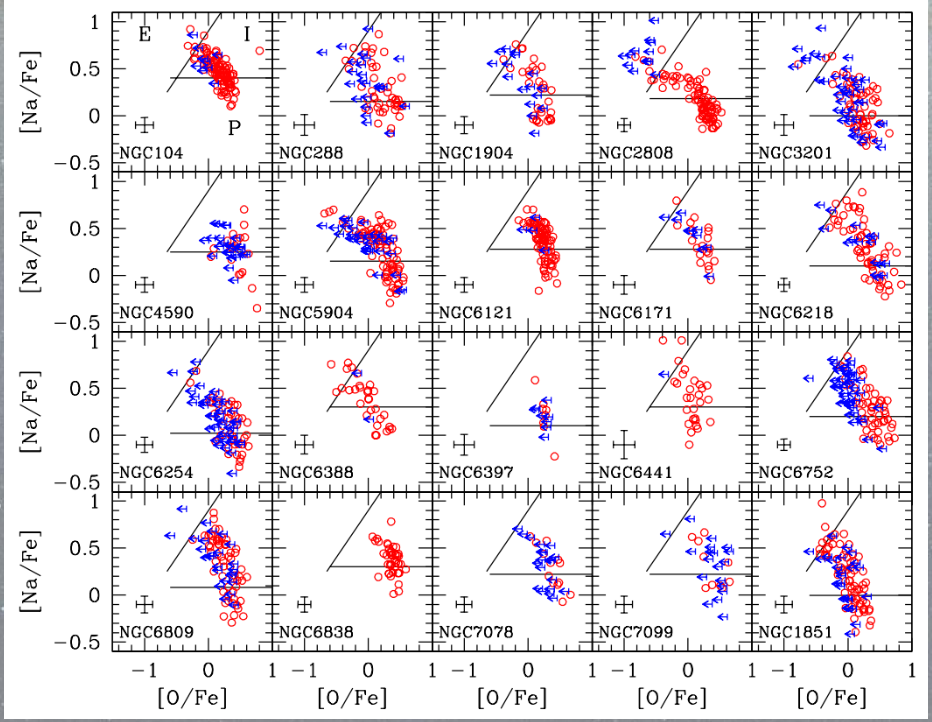
- ★ We can constrain **ages**, **masses**, and **distances**: the primary laboratory of stellar evolution including **chemical** and **enrichment processes**.
- ★ **Observations** and **simulations** can work together to account the different properties of **nowadays** clusters and the ones formed at **high redshift**.



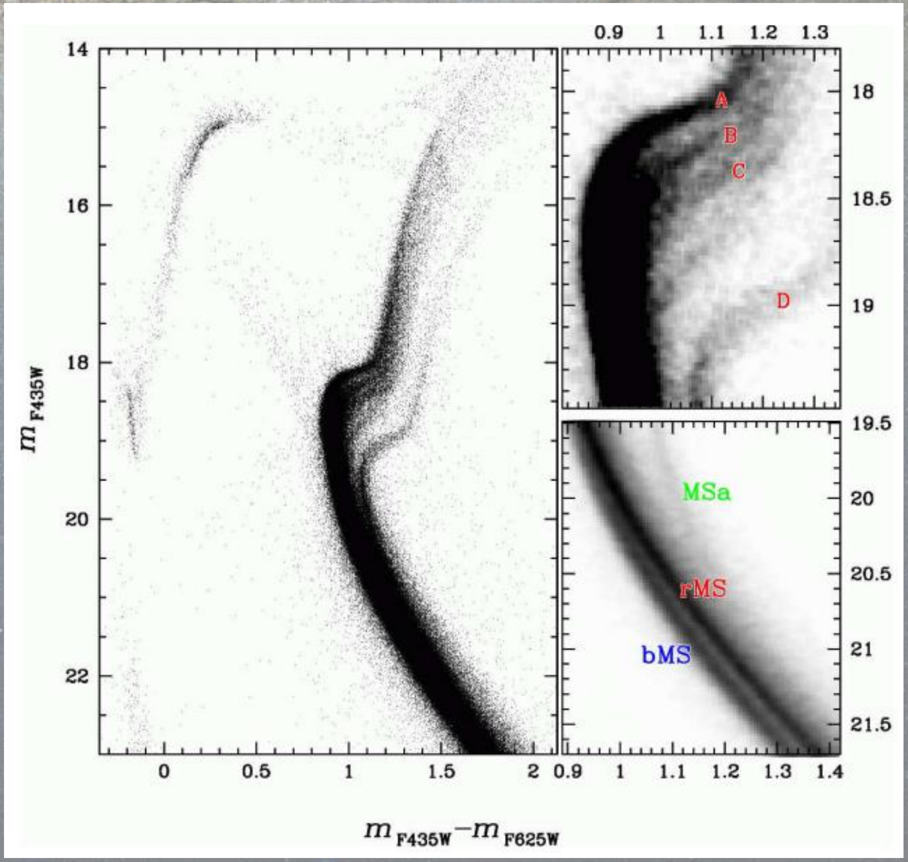
Vanzella et al. 2017

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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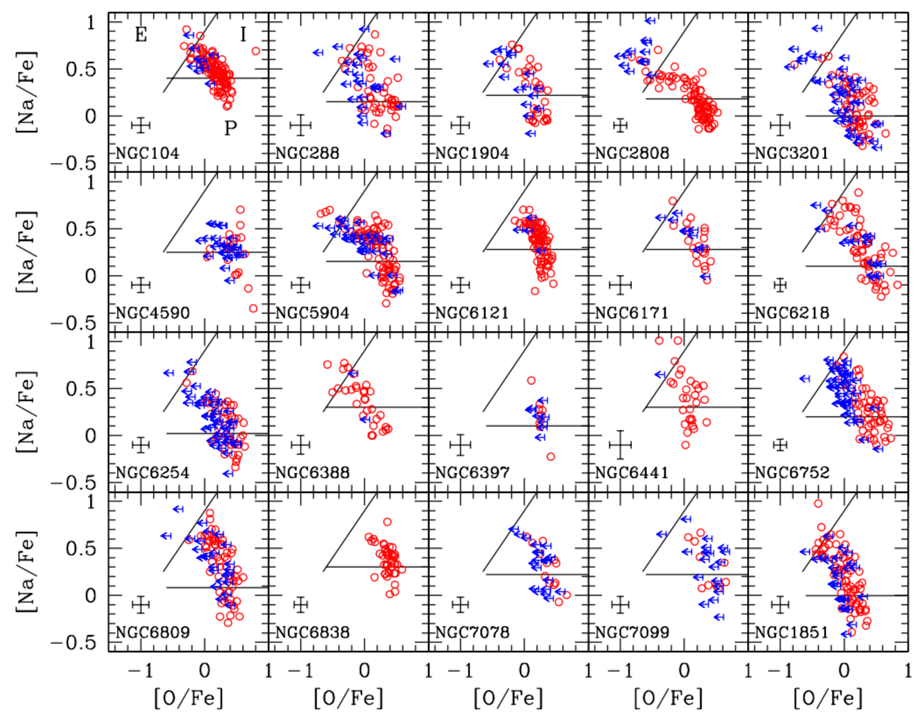


Carretta et al. 2009

★ [Fe/H] enrichment in only a limited cases: massive clusters

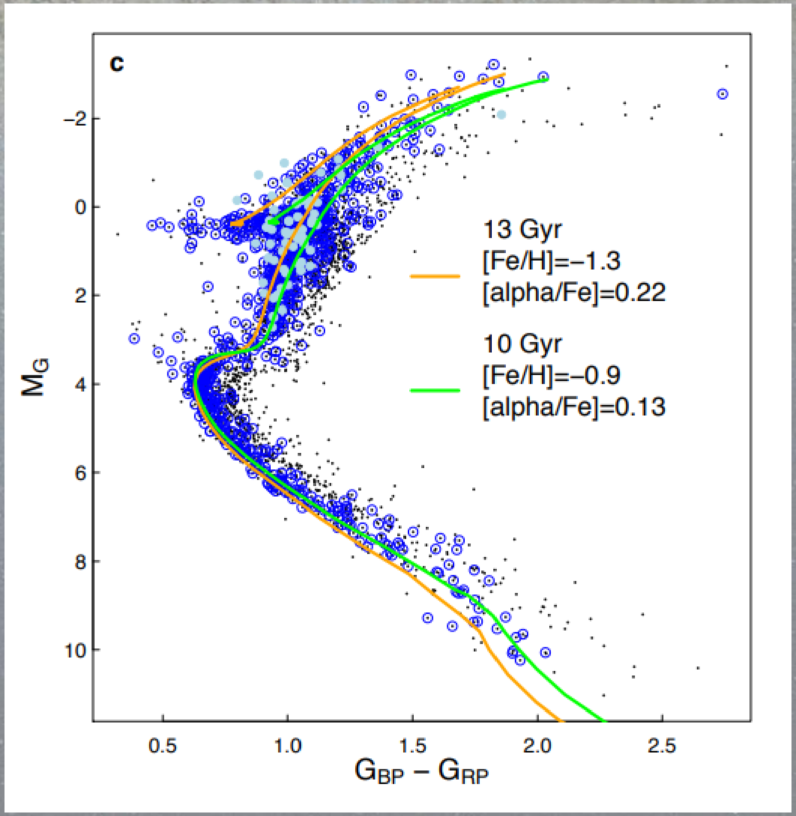
★ Light-element (proton capture) variations!
  - ★ C, N, O, Na, Mg, Al, Si, … among others!

★ AGB and massive fast rotators: most likely contributors

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

★ The Gaia satellite changes 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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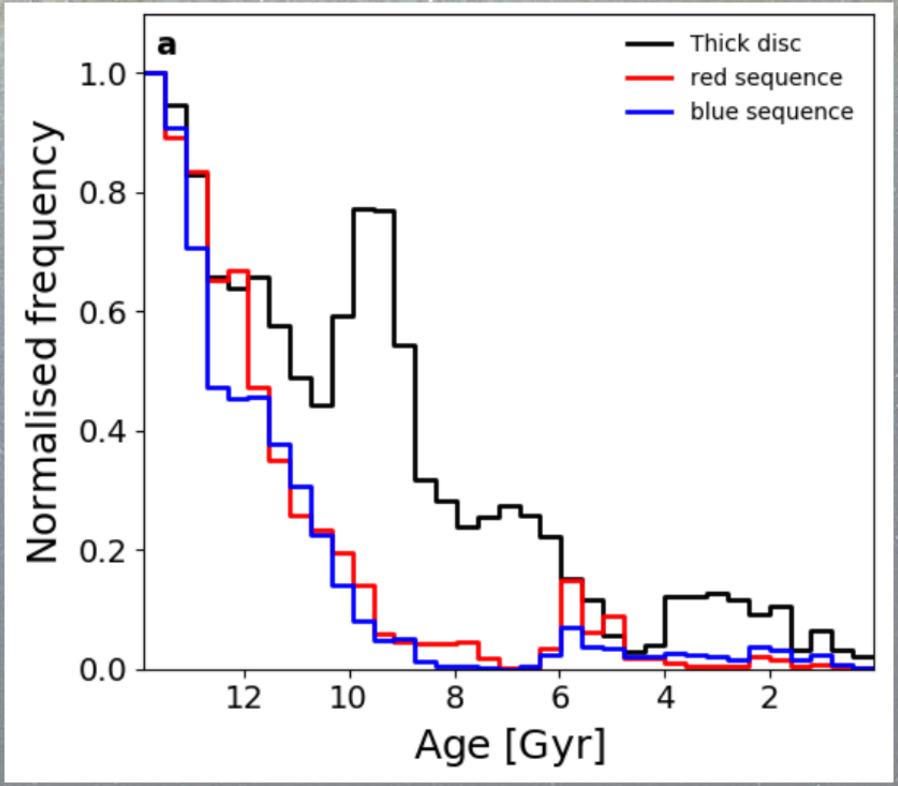

Gallart et al. 2019

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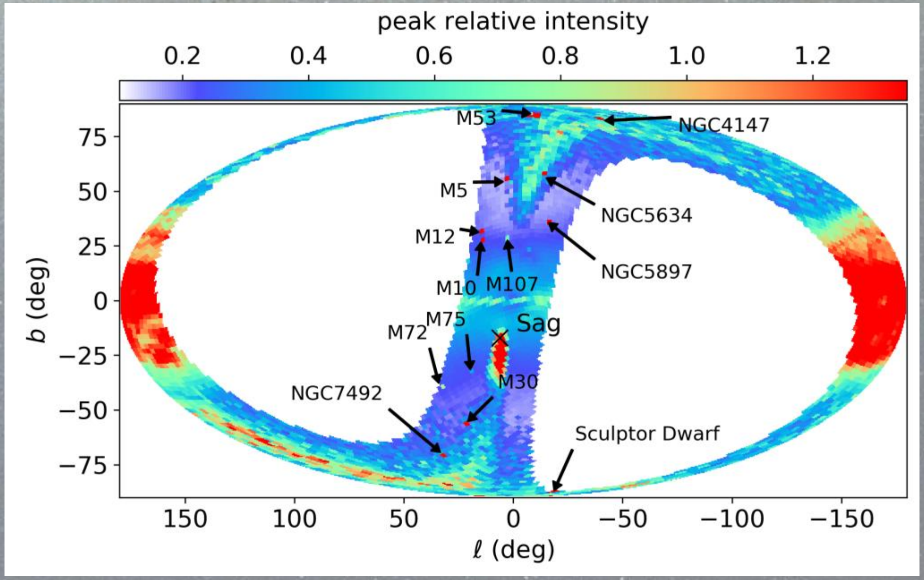

Antoja et al. 2020; Ramos et al. 2020

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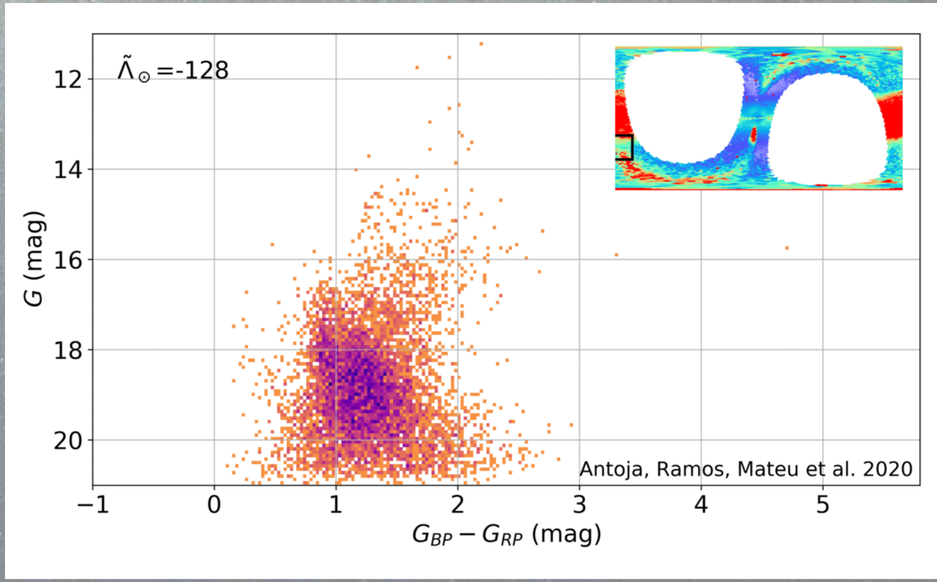

Antoja et al. 2020;
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Key concept 1+2+3 = #6: proper motions to isolate different stellar populations

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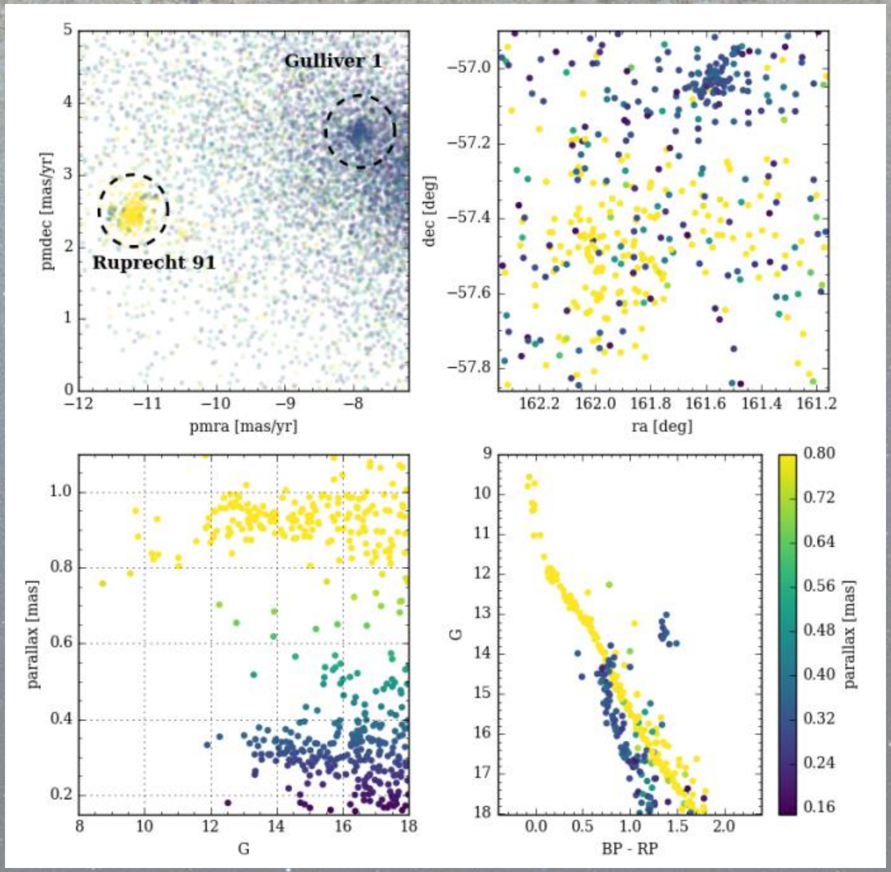
- ★ **CLUSTER SCIENCE!**



Cantat-Gaudin et al. 2018

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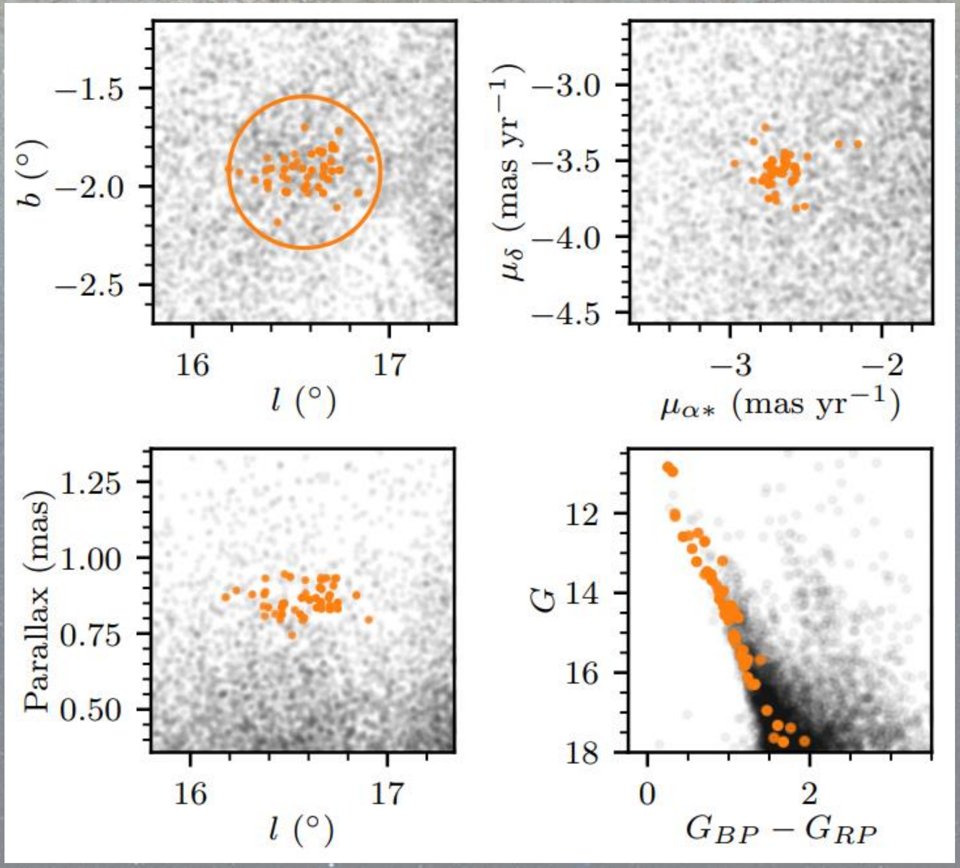

Hunt & Reffert 2021

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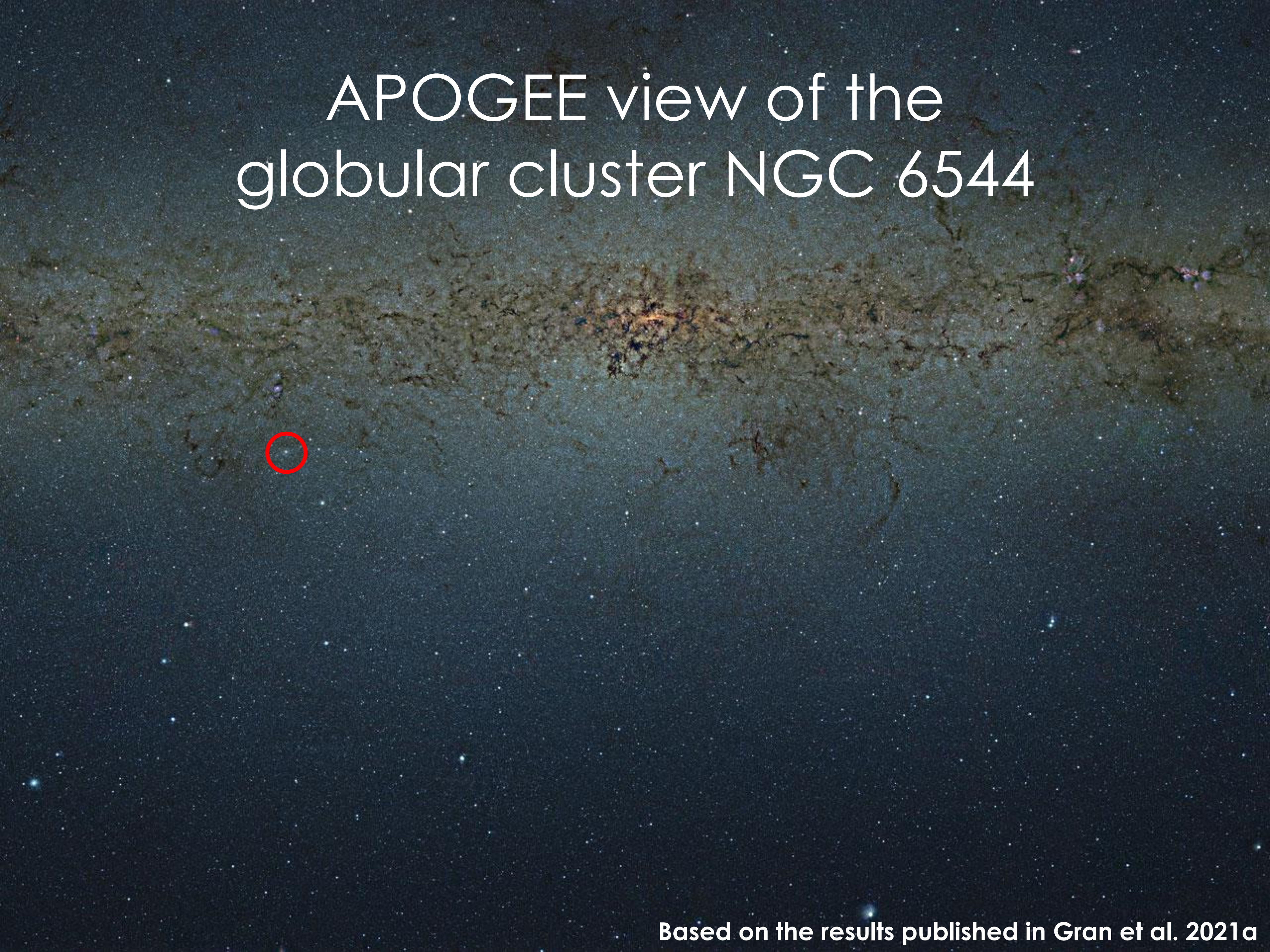
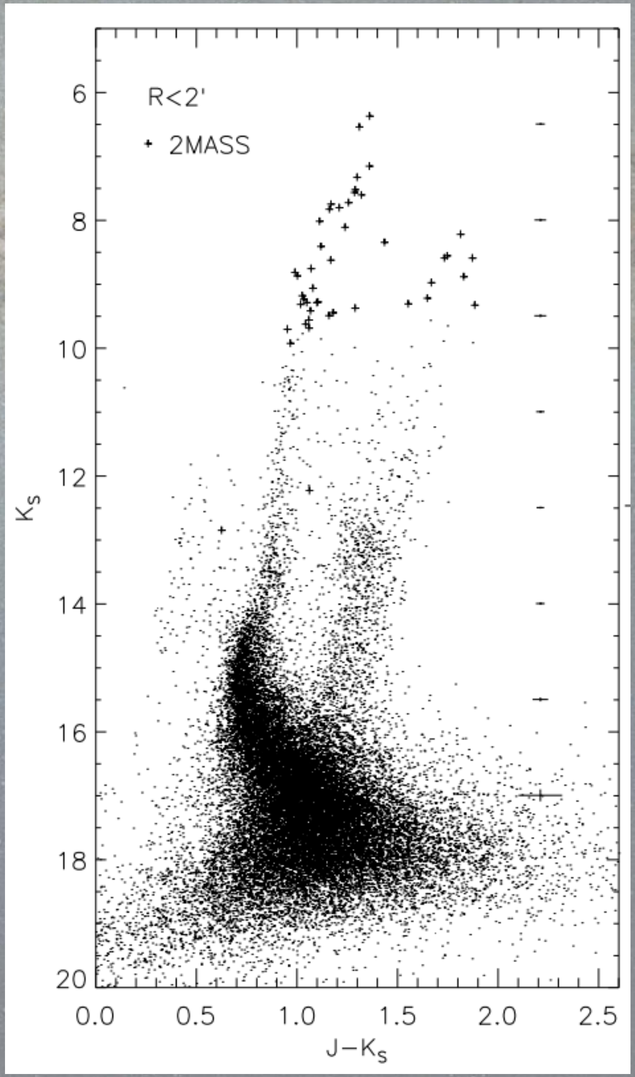

APOGEE view of the globular cluster NGC 6544
Based on the results published in Gran et al. 2021a

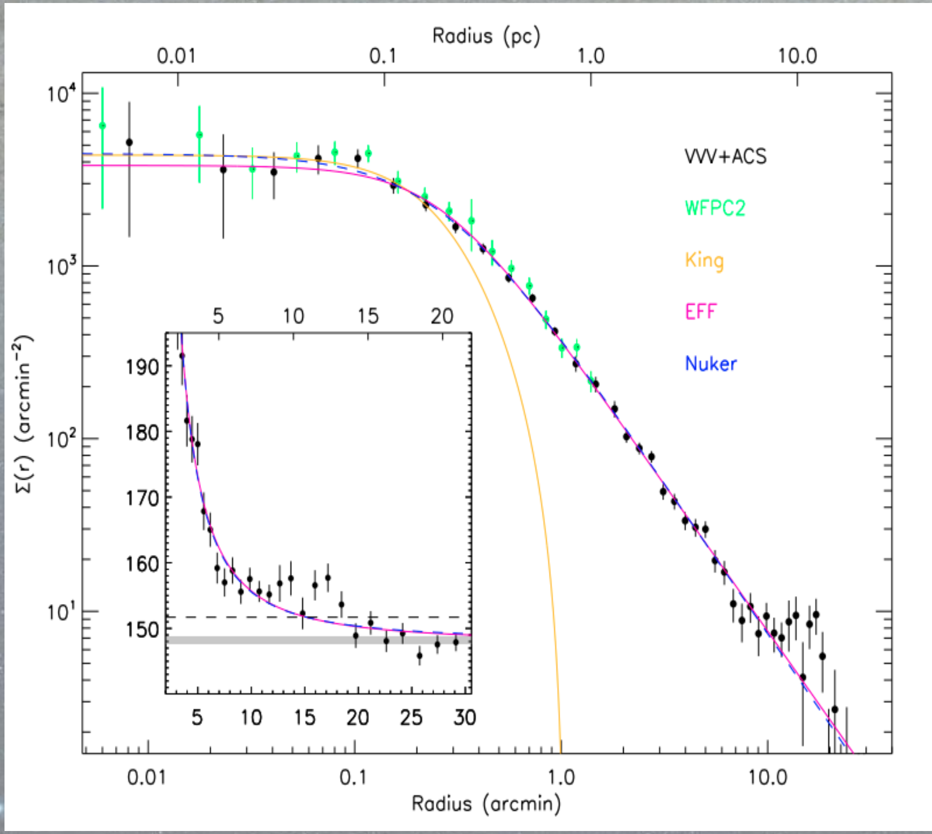
Context and history of NGC 6544

- 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 mag



Cohen et al. 2014

Context and history of NGC 6544



Cohen et al. 2014

★ 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**

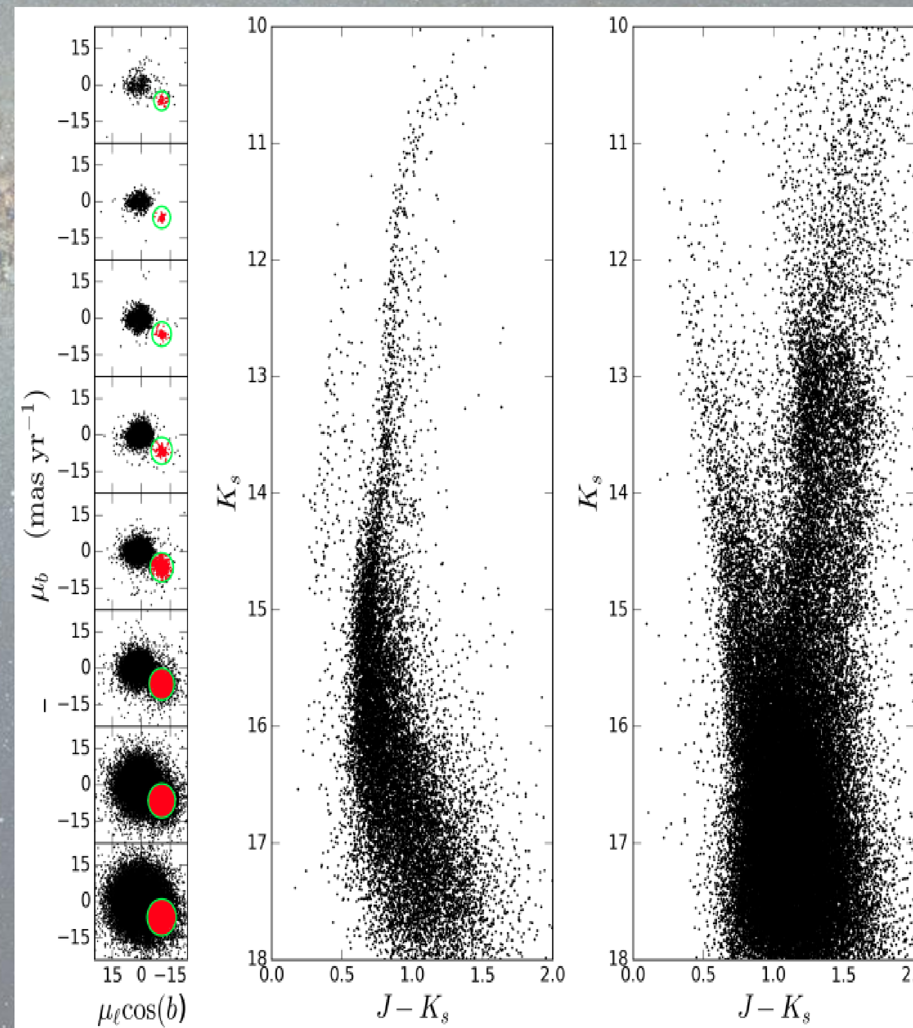
NGC 6544 in VVV/x survey

VVVX 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

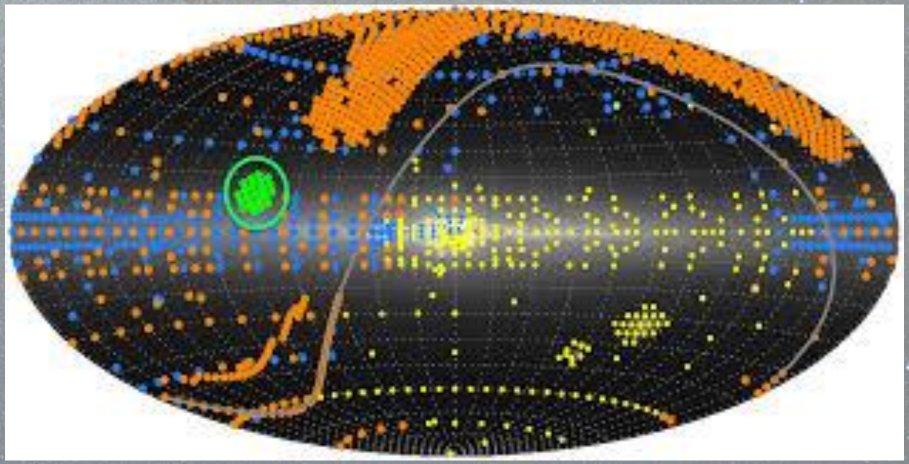
NGC 6544 in APOGEE survey

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

~2.660.000 spectra
~ 657.000 stars

DR17 publicly available

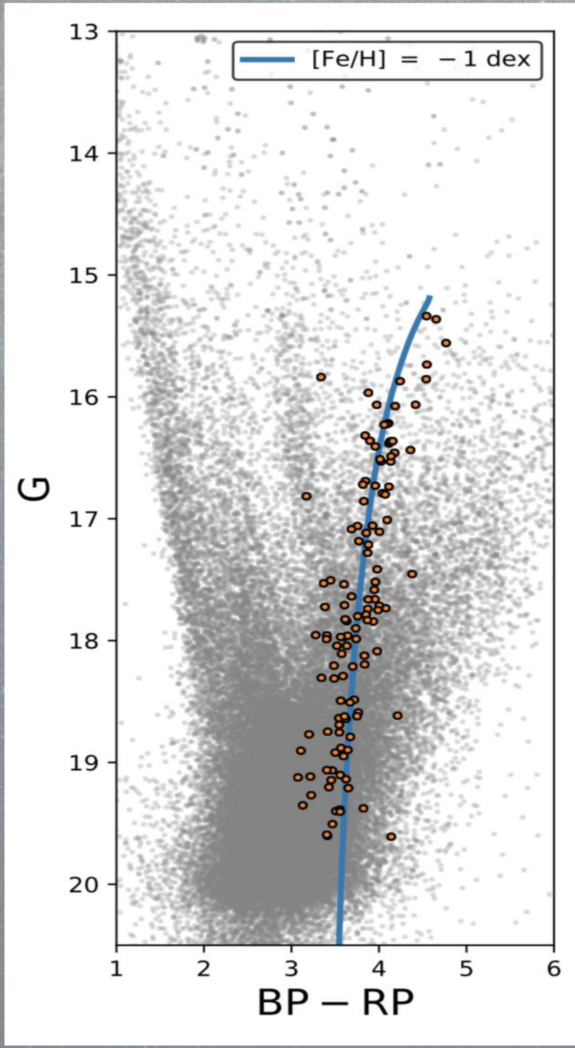
- ★ Part of the SDSS collaboration (SDSS-III and SDSS-IV)
- ★ **Chilean Participation Group**: access to proprietary data



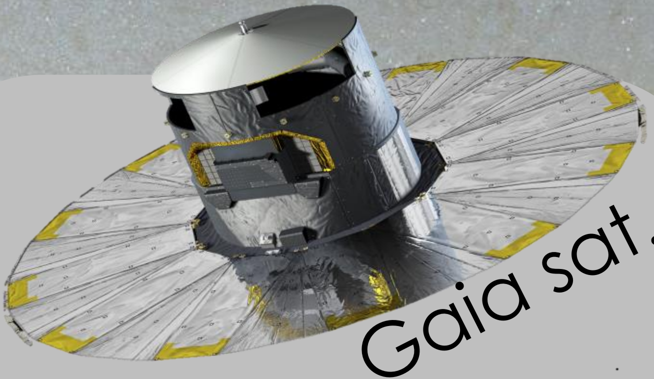
All-sky observations from APO and LCO.

Beaton et al. 2021, Santana et al. 2021 & Masters et al. 2021

Gaia DR2/EDR3 proper motion catalog



Gran et al. 2019



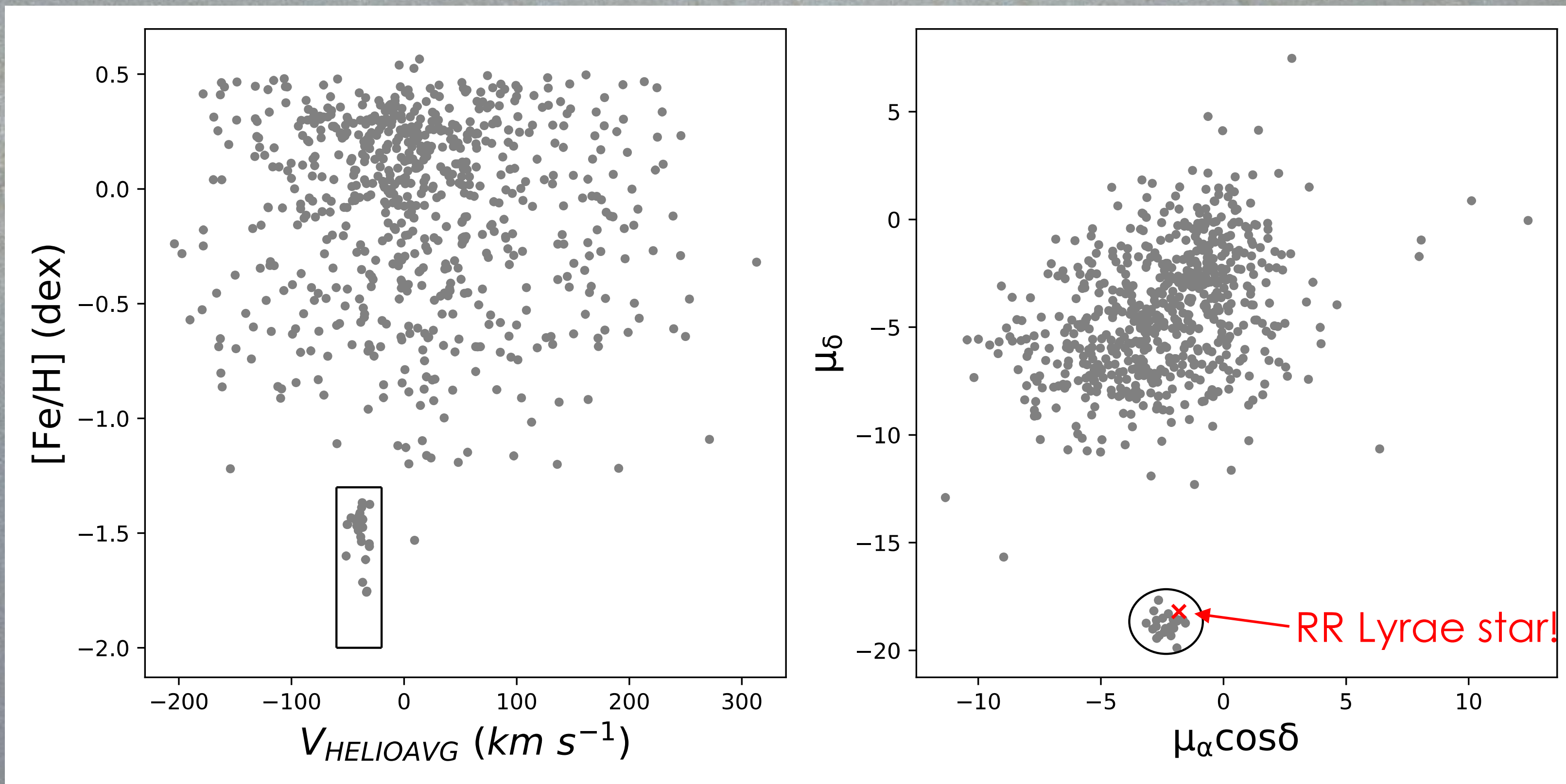
Optical survey (G, G_{BP}, G_{RP})

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

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

Gaia Collaboration 2018

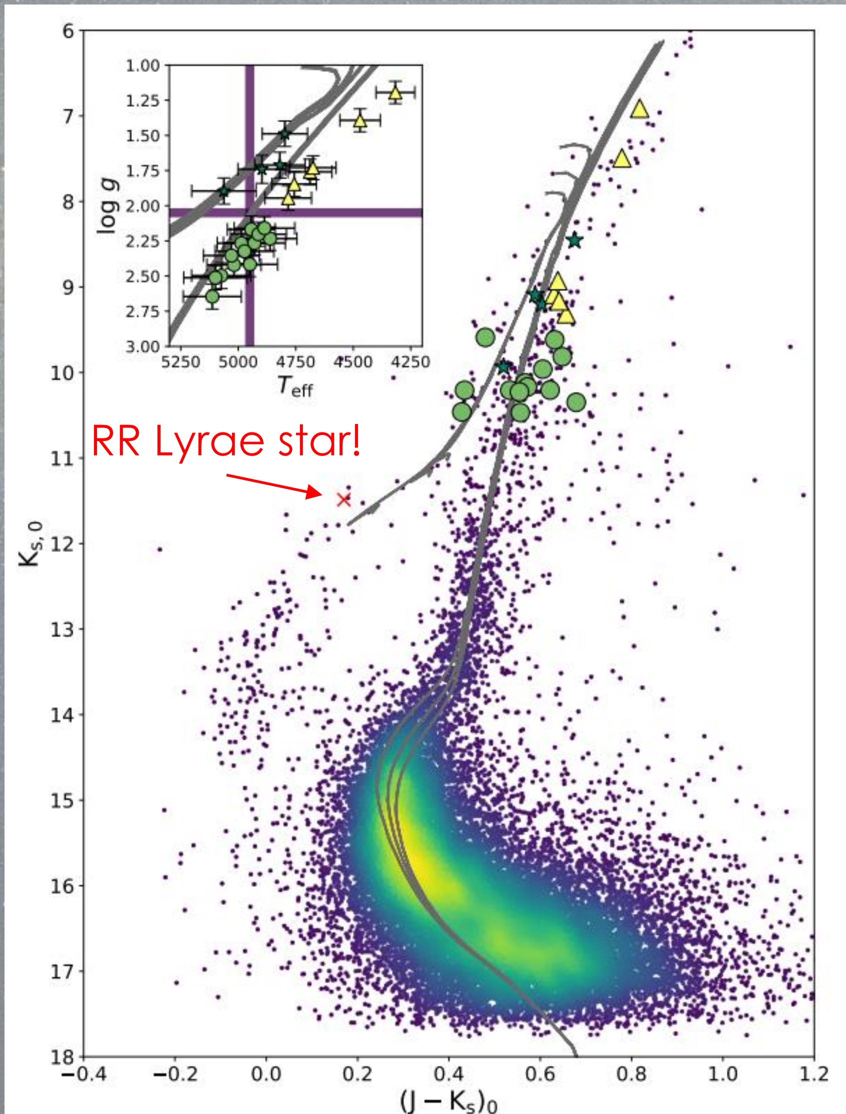
Selection of NGC 6544 members



Gran et al. 2021

(**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



Gran et al. 2021

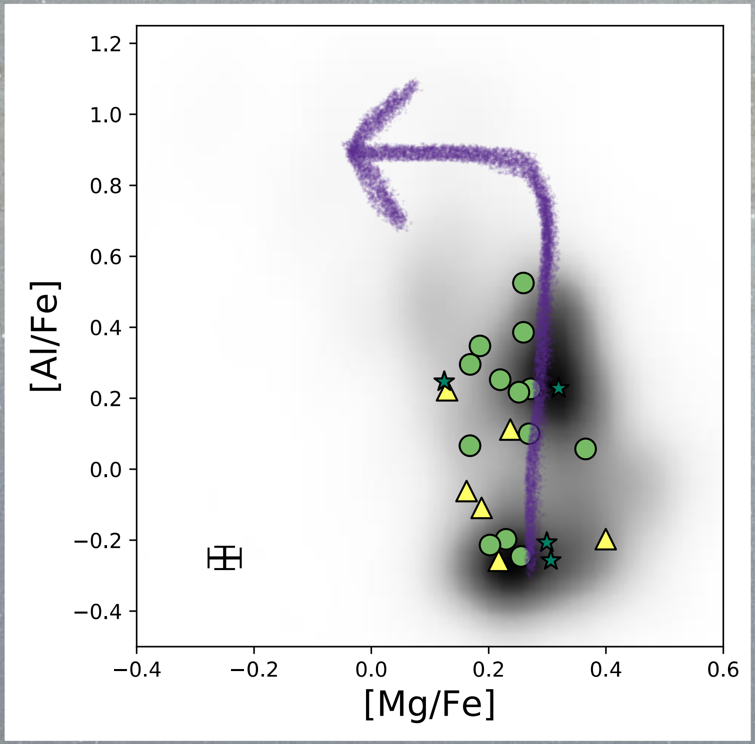
A total of 23 members were located:

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

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

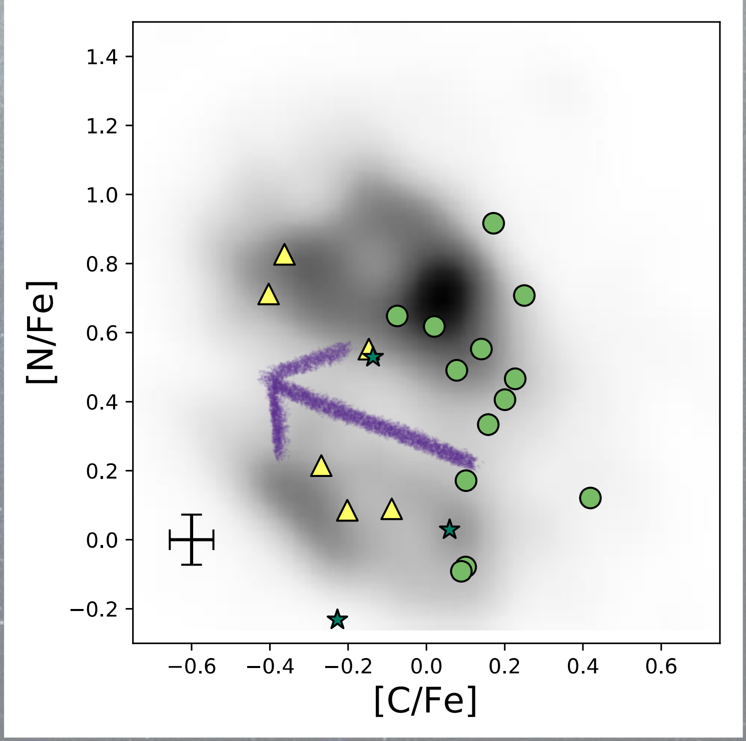
Dereddened VVV-2MASS CMD of NGC 6544

Known anticorrelations in NGC 6544



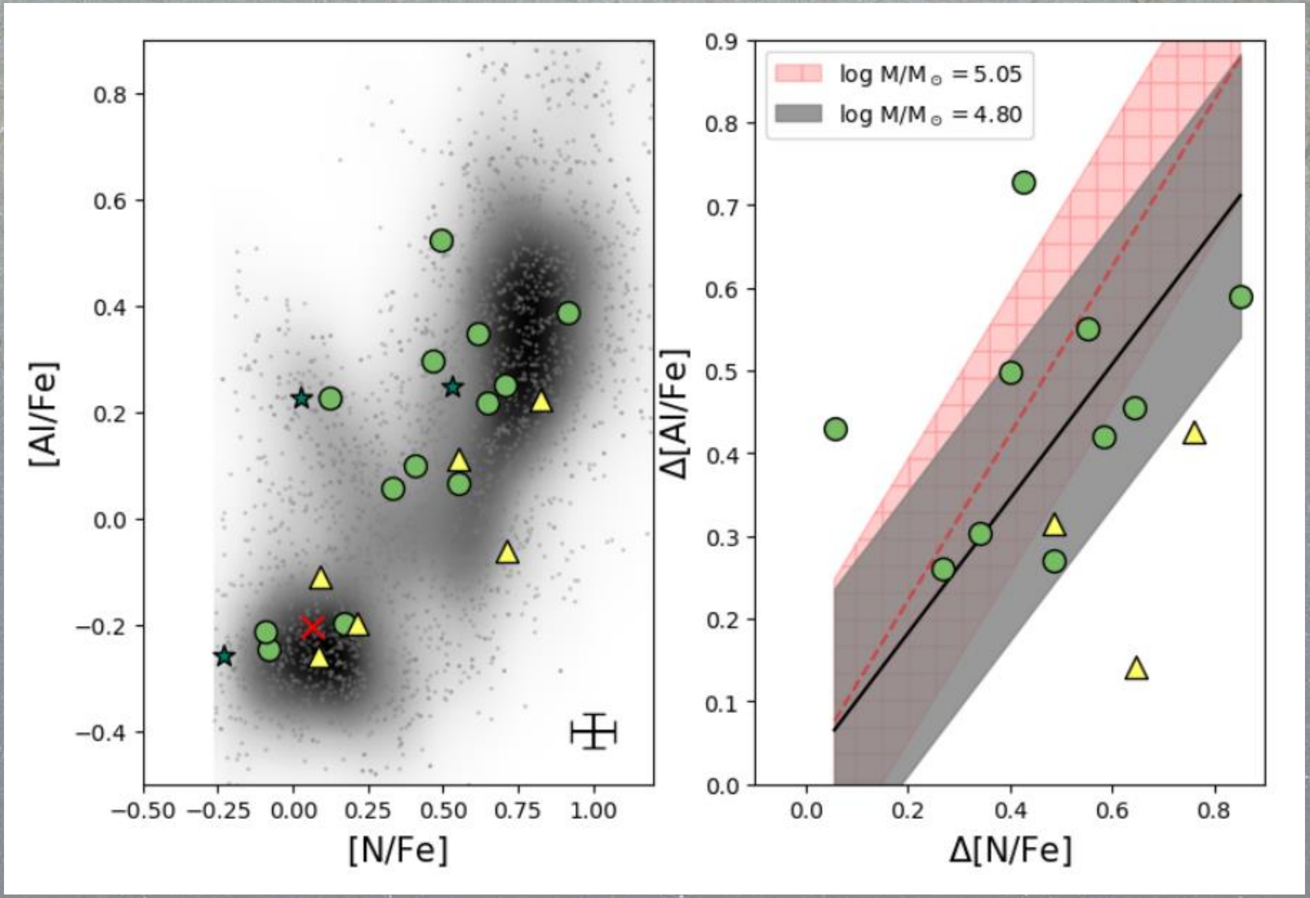
Gran et al. 2021

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



Gran et al. 2021

Abundance patters and the mass of NGC 6544

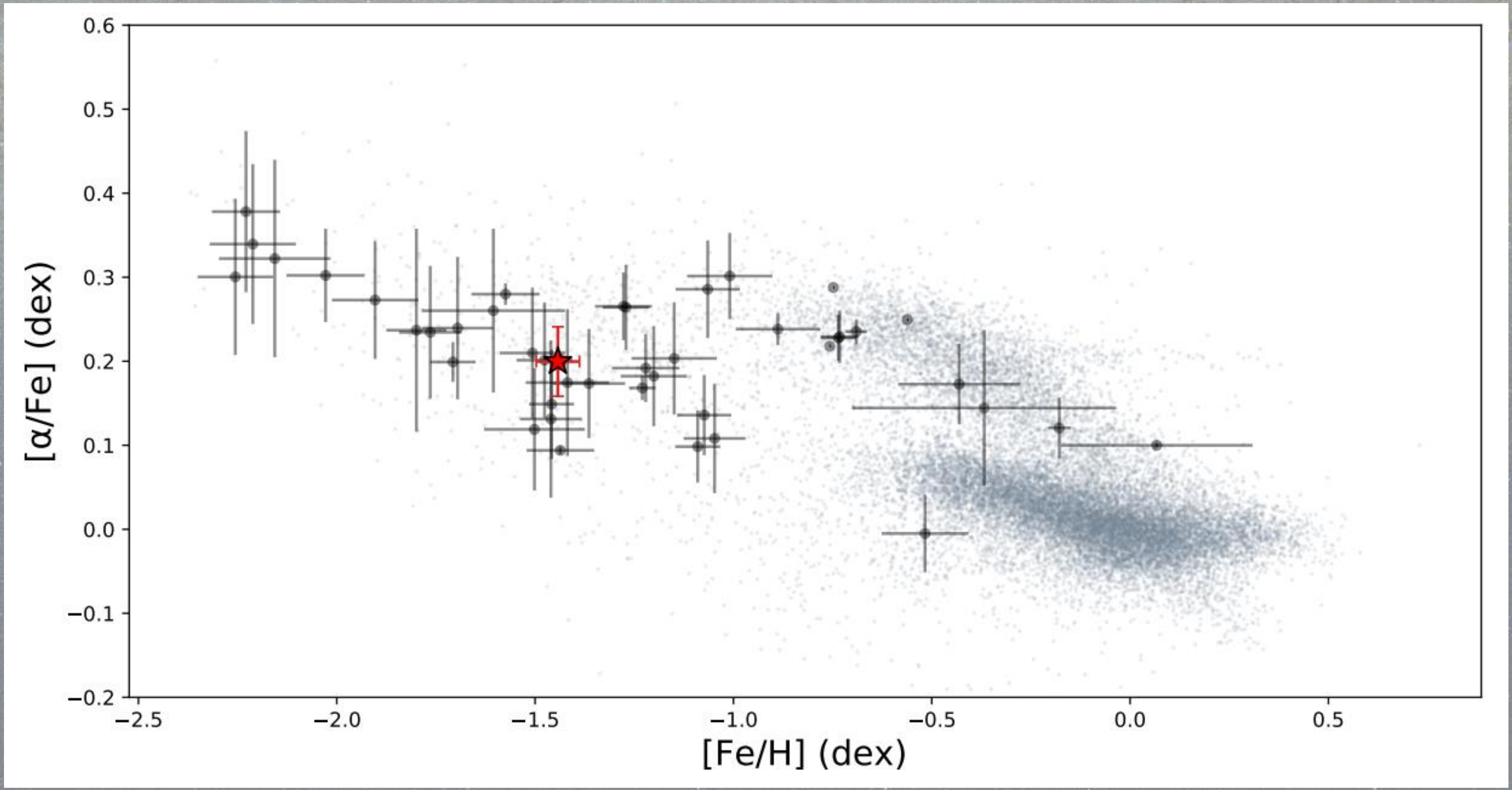


Gran et al. 2021

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



Gran et al. 2021

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

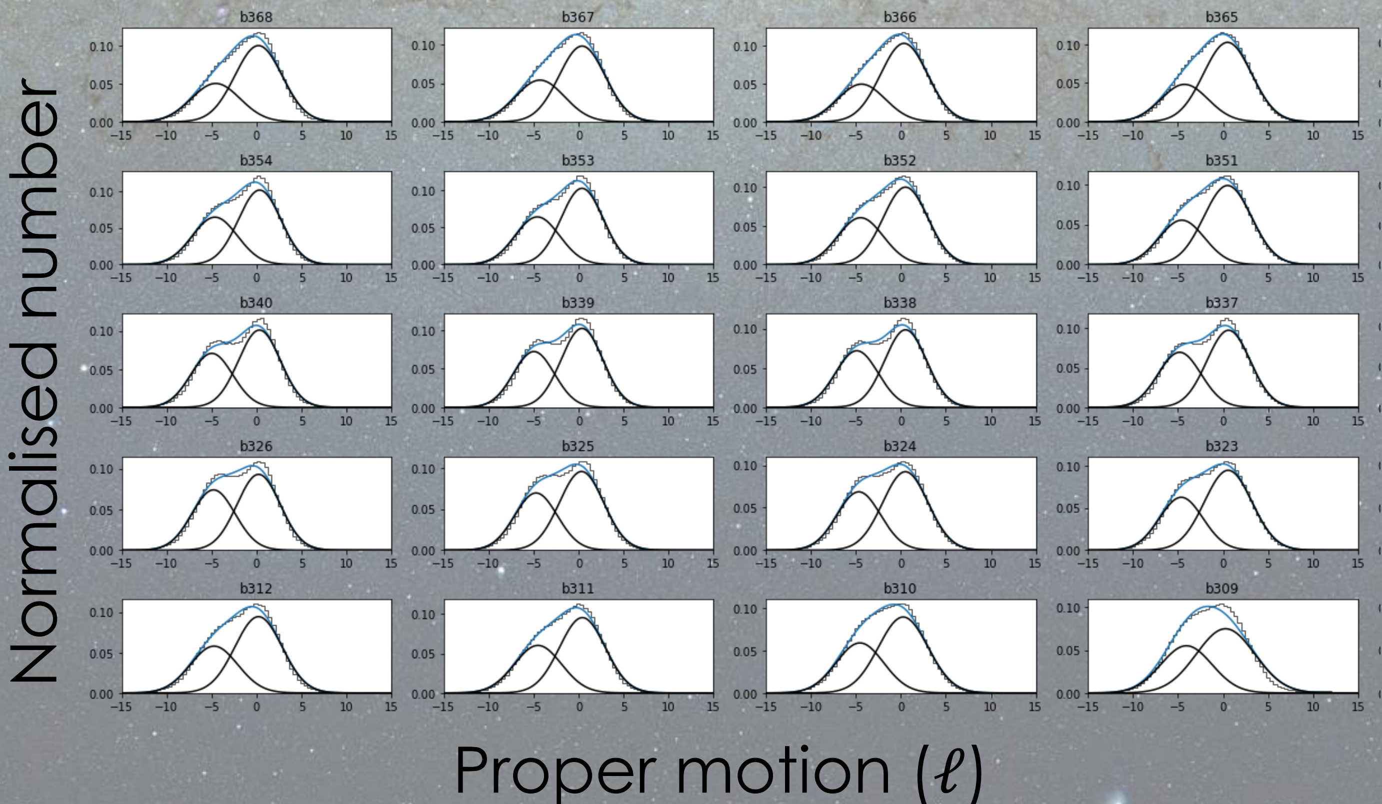
Summary #1

- ★ 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 stars
  - ★ **14** second generation stars
- ★ 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)

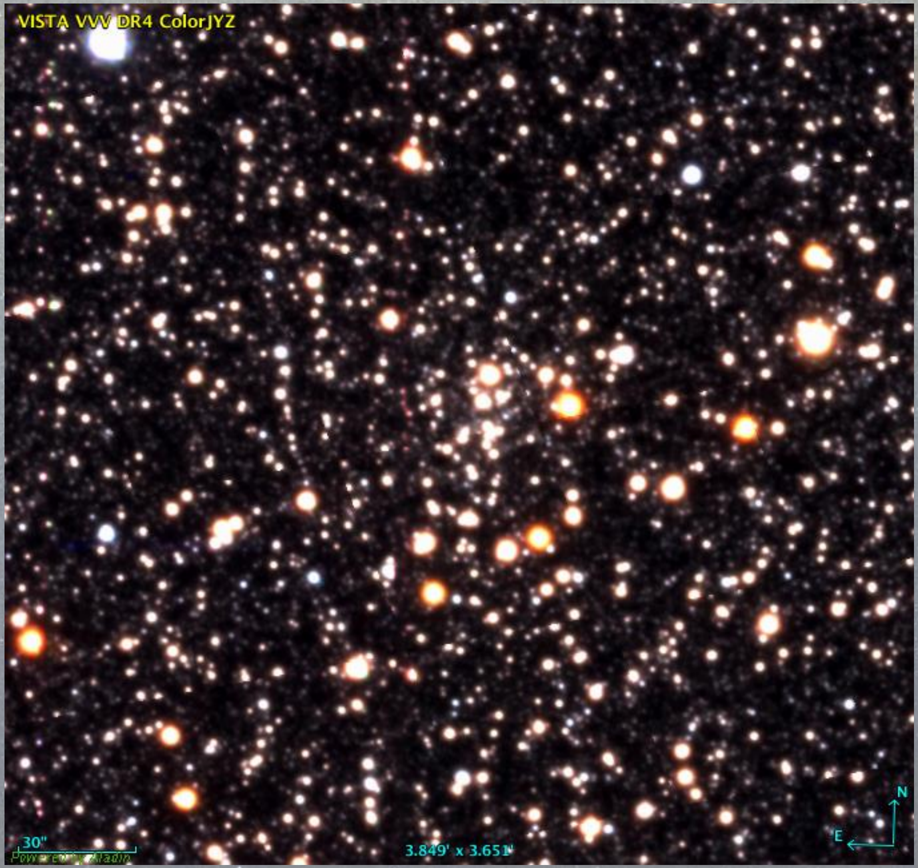
The *intermezzo*: GCs and PMs

- ★ 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



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



Gran et al. 2019

Based on the results published in Gran et al. 2019, 2021b

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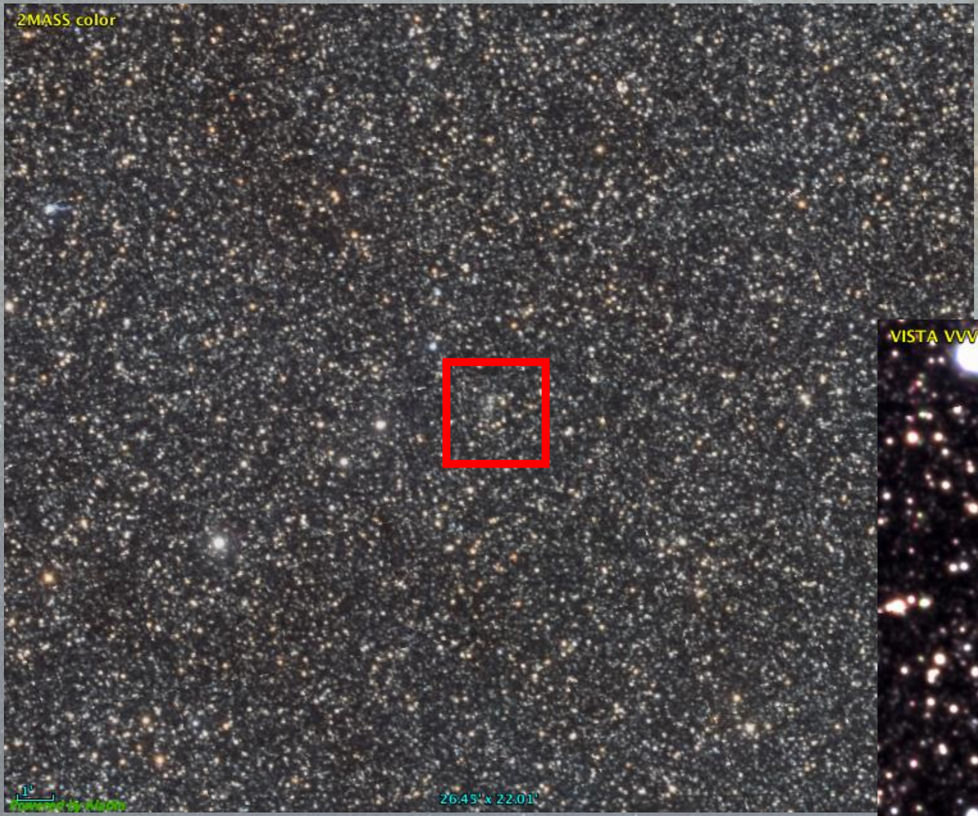

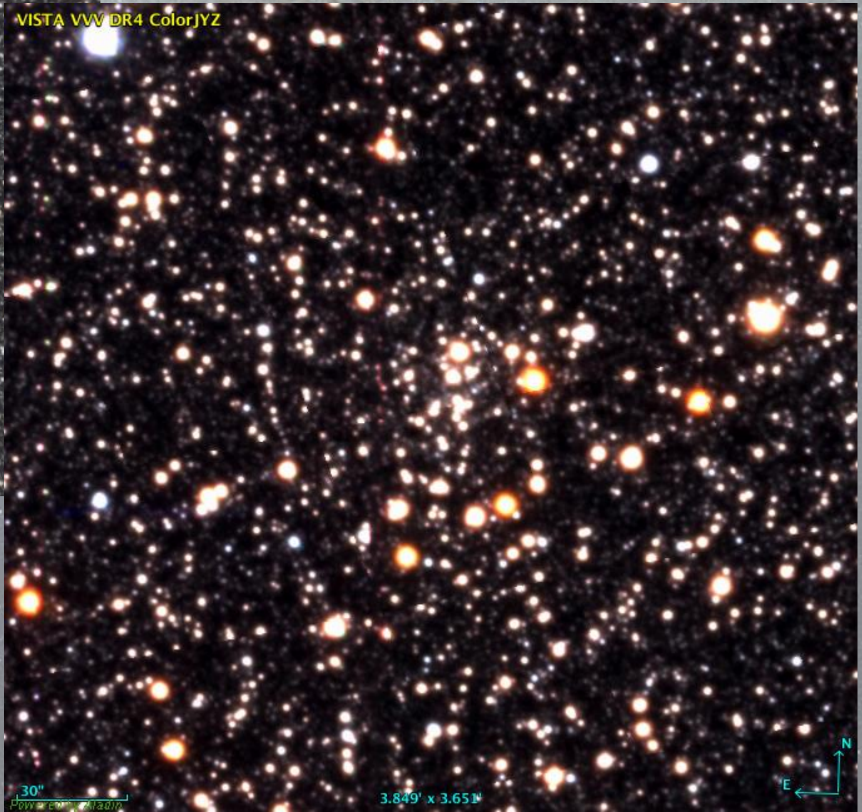

Hidden in the haystack:
New globular clusters towards the Milky Way bulge

- ★ 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 3π SURVEY

BENJAMIN P. M. LAEVENS[1,2], NICOLAS F. MARTIN[1,2], BRANIMIR SESAR[2], EDOUARD J. BERNARD[3], HANS-WALTER RIX[2], COLIN T. SLATER[4], ERIC F. BELL[4], ANNETTE M. N. FERGUSON[3], EDWARD F. SCHLAFLY[2], WILLIAM S. BURGETT[5], KENNETH C. CHAMBERS[5], LARRY DENNEAU[5], PETER W. DRAPER[6], NICHOLAS KAISER[5], ROLF-PETER KUDRITZKI[5], EUGENE A. MAGNIER[5], NIGEL METCALFE[6], JEFFREY S. MORGAN[5], PAUL A. PRICE[7], WILLIAM E. SWEENEY[5], JOHN L. TONRY[5], RICHARD J. WAINSCOAT[5], AND CHRISTOPHER WATERS[5]

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

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

[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
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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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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, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

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

DONGWON KIM, HELMUT JERJEN, A... ...ND GARY S. DA COSTA
Research School of Astronomy and Astrophysics, The Australian Na... ...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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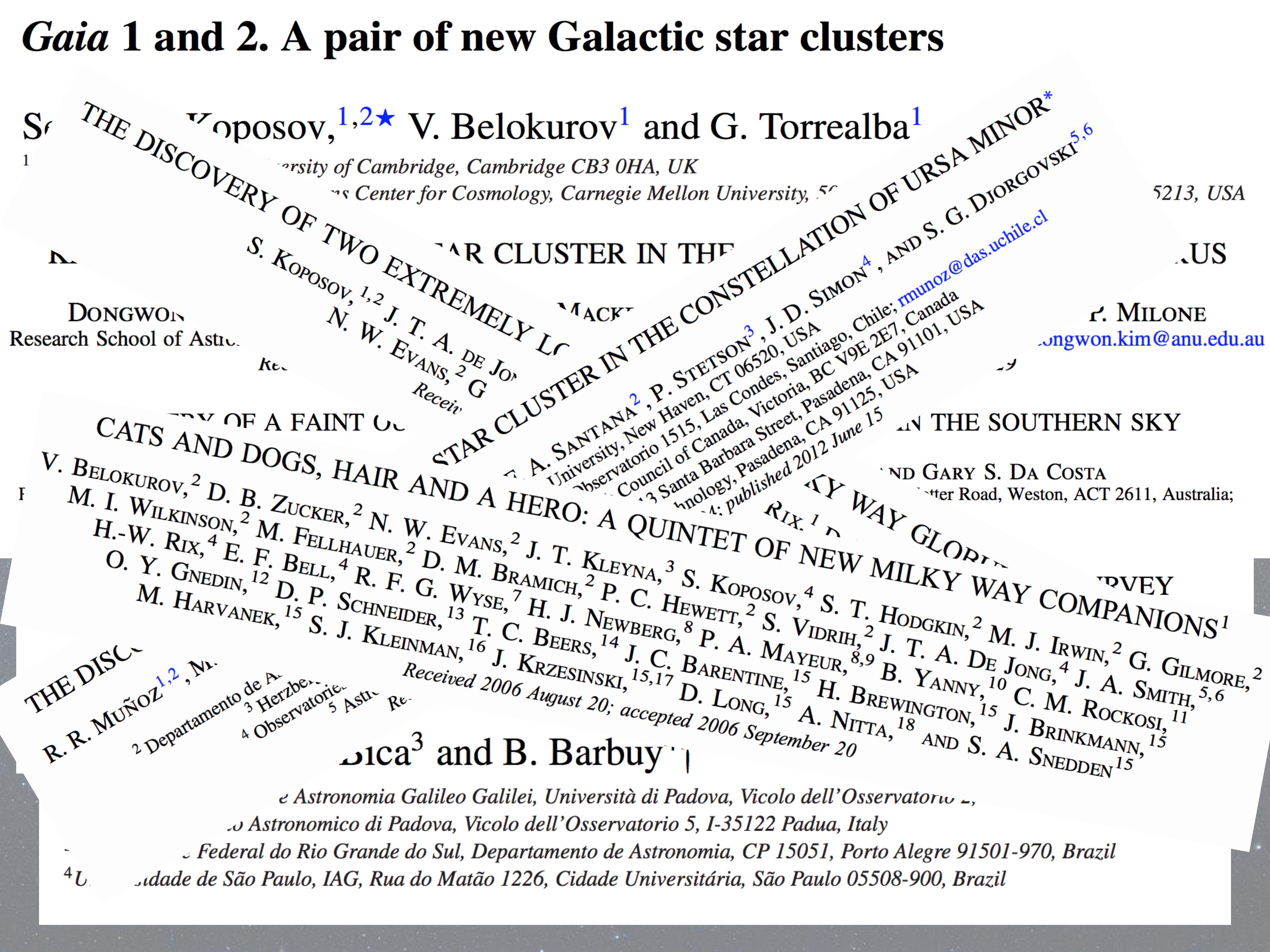
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S. Koposov,[1,2] J. T. A. de Jo
N. W. Evans,[2] G
STAR CLUSTER IN THE CONSTELLATION OF URSA MINOR*
A. Santana[2], P. Stetson[3], J. D. Simon[4], and S. G. Djorgovski[5,6]
rmunoz@das.uchile.cl
published 2012 June 15
THE SOUTHERN SKY
Gary S. Da Costa
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
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and B. Barbuy
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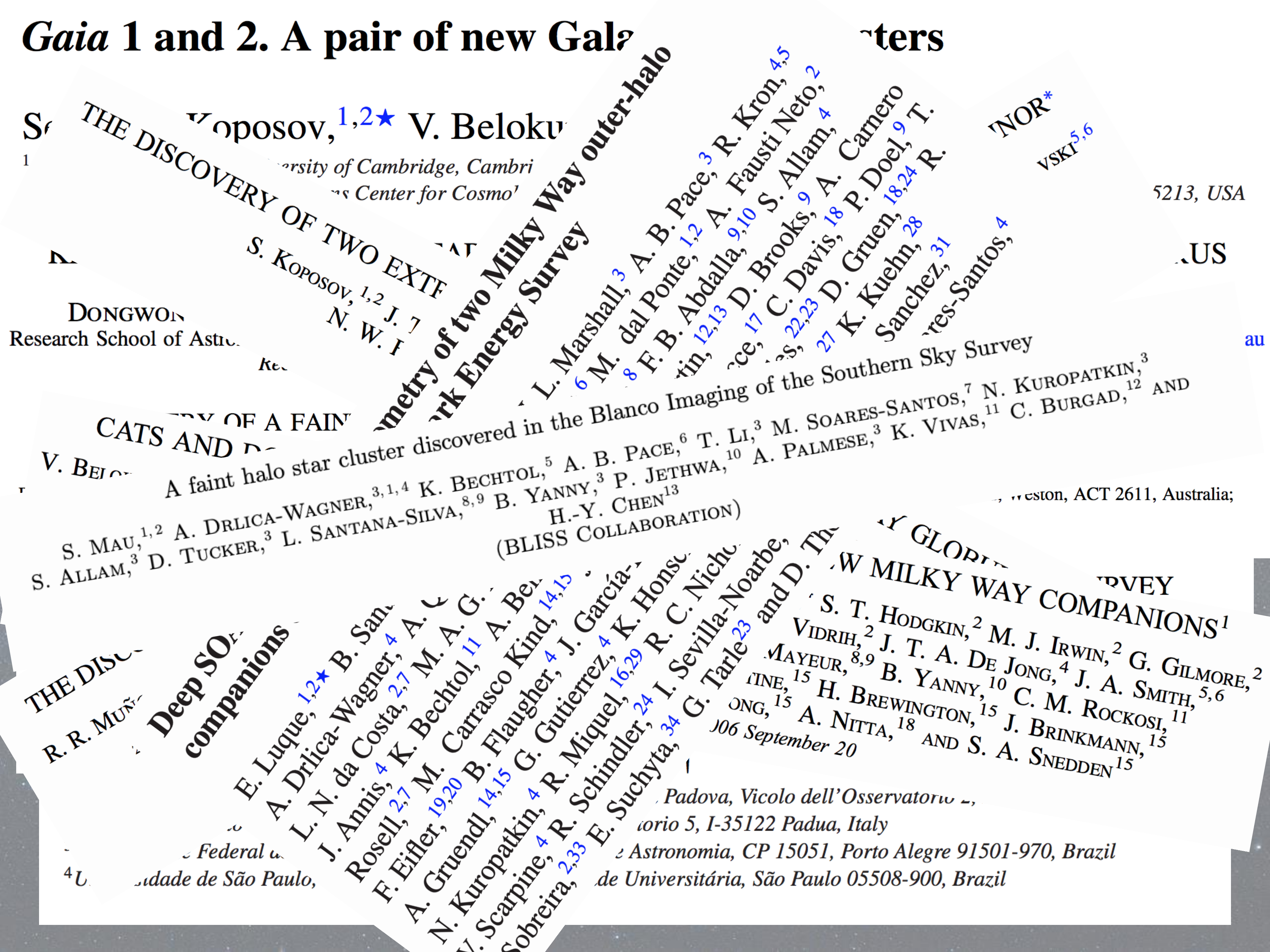
Universidade de São Paulo, IAG, Rua do Matão 1226, Cidade Universitária, São Paulo 05508-900, Brazil


Gaia 1 and 2. A pair of new Gala
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5213, USA
THE DISCOVERY OF TWO EXTR
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N. W.
metry of two Milky Way outer-halo
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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]
NOR*
VSKI[5,6]
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Research School of Astr
au
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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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. Nich
Scarpine,[4] R. Schindler,[24] I. Sevilla-Noarbe,
Sobreira,[2,33] E. Suchyta,[34] G. Tarle[23] and D. Th
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idade de São Paulo,
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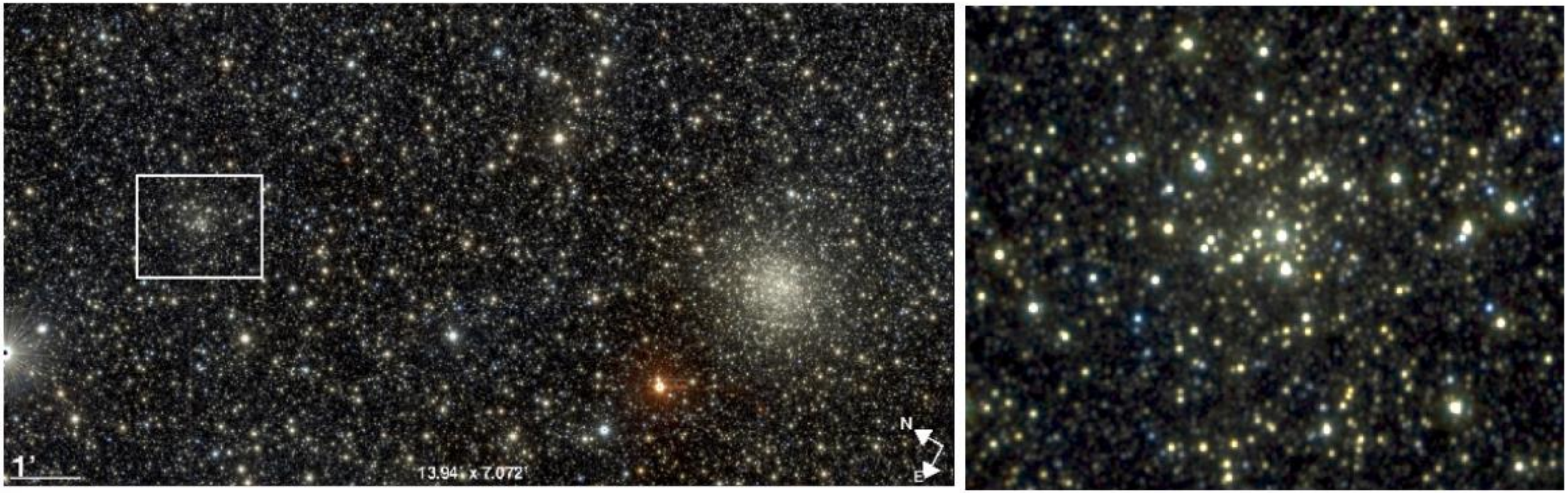
Photometric searches of GCs

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**.



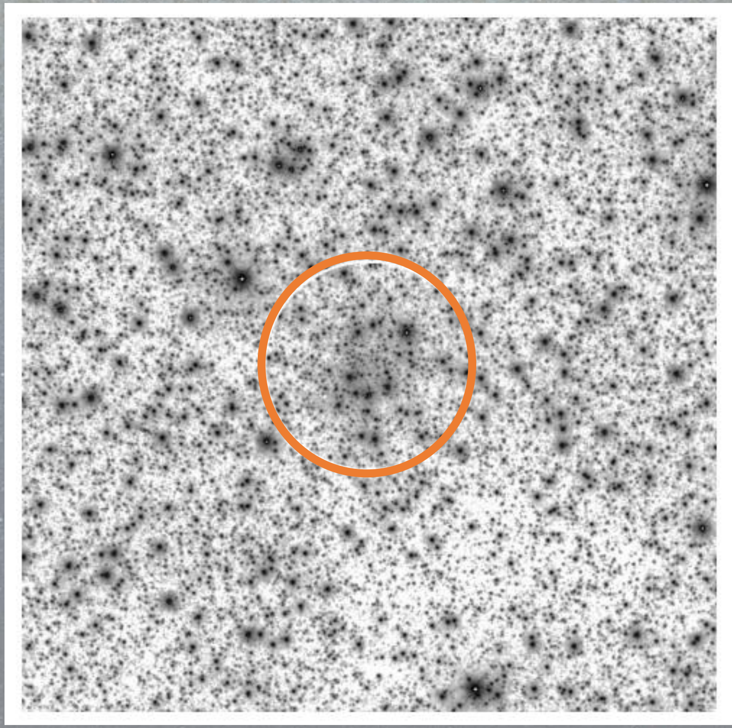
VVV CL 001

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

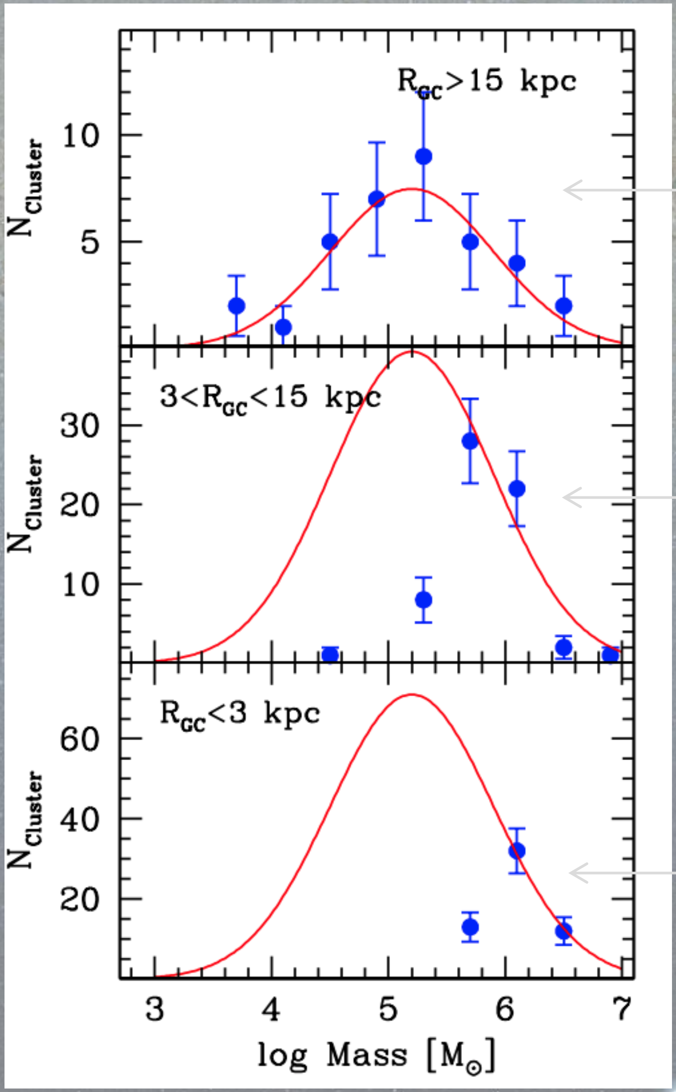
Photometric searches of GCs

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**):

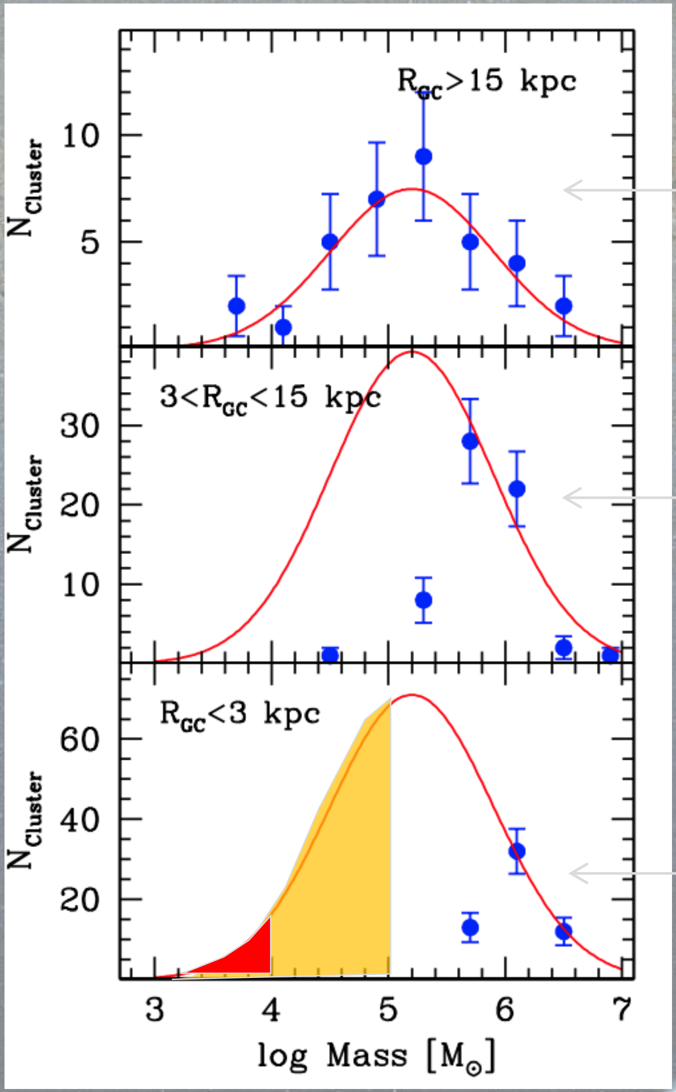
- ★ Spatial overdensities ☑
- ★ CMD different from field ⚠
- ★ Coherent space motion 🛑

Initial mass distribution of GCs in the MW



Baumgardt et al. 2018

Initial mass distribution of GCs in the MW



~Halo GCs

~Disk GCs

~Bulge GCs

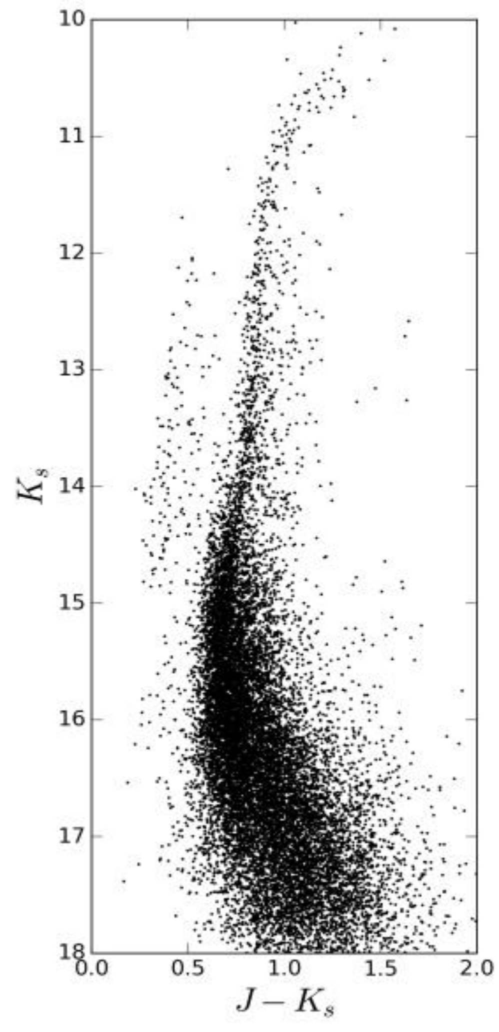
Baumgardt et al. 2018

VVV proper motion catalog

Near-IR survey
(ZYJH**K_s**)

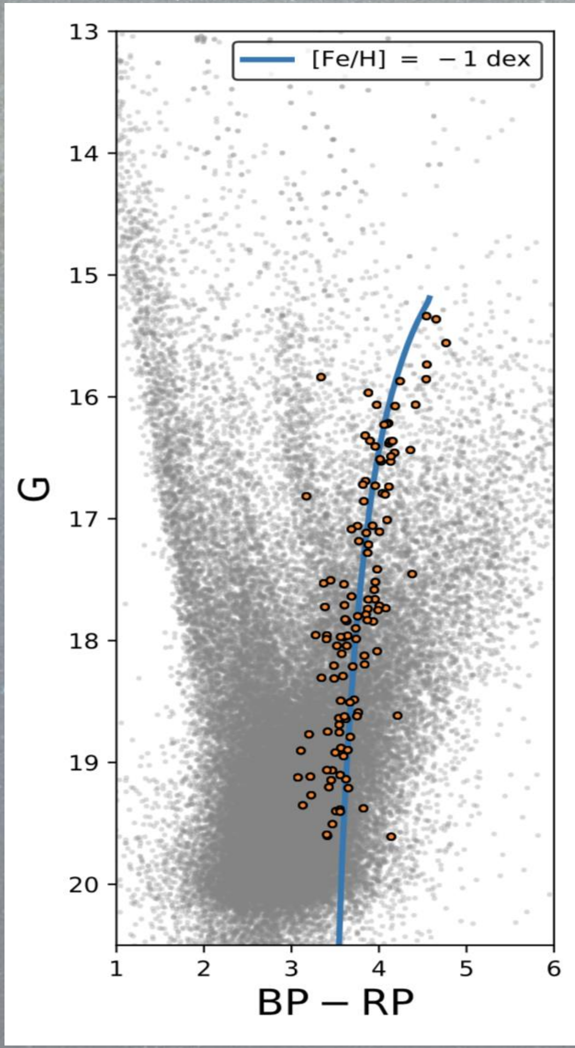
~100+ K_s epochs

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



Minniti et al 2010, Contreras Ramos et al. 2017

Gaia DR2/EDR3 proper motion catalog



Gran et al. 2019

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

Valid for |b| ≥ 2º

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

Gaia Collaboration 2018

Clustering on a 5-D phase-space

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

\+

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

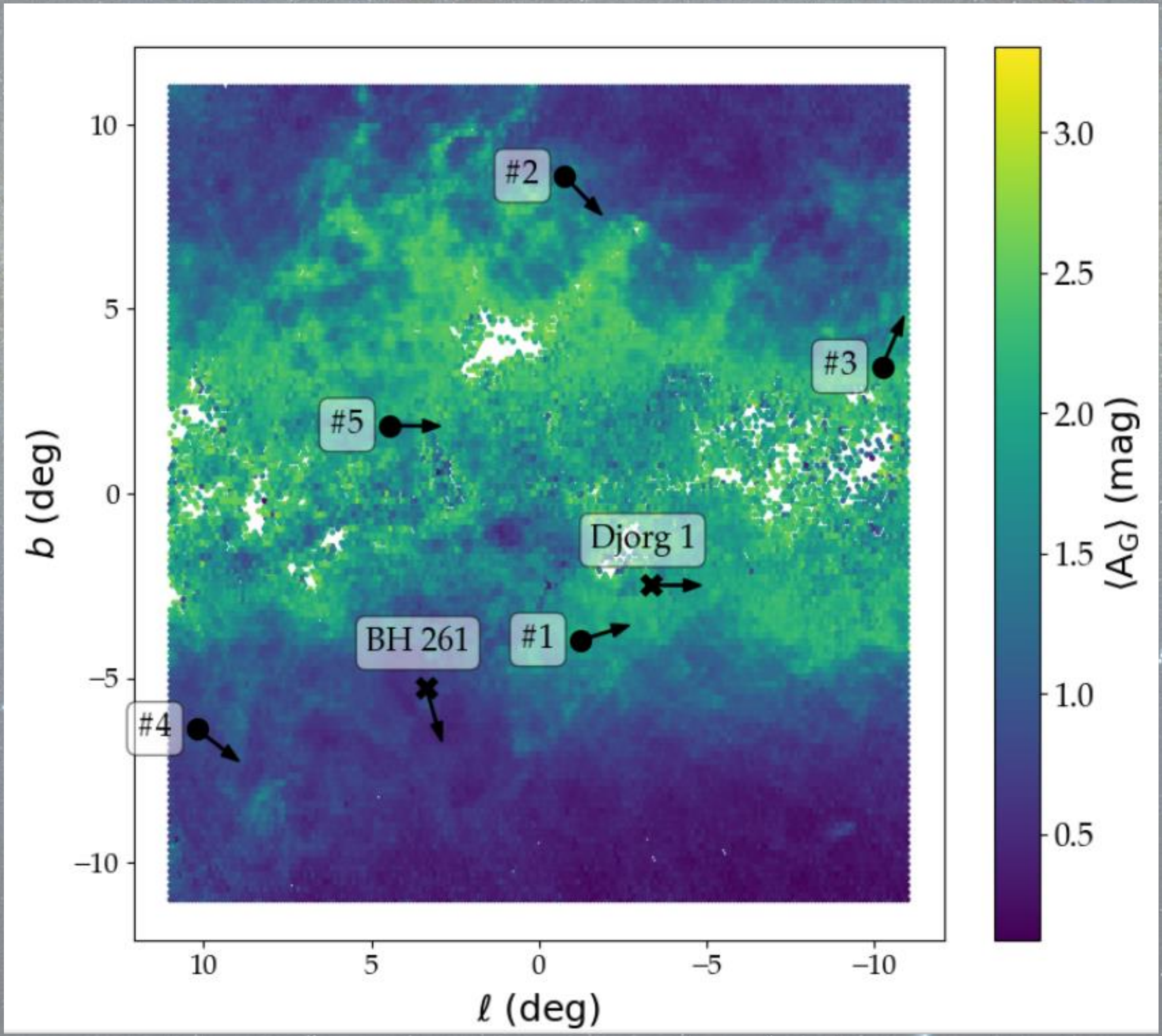
\+

scikit learn: KDTree
and DBScan

Pedragosa et al 2011

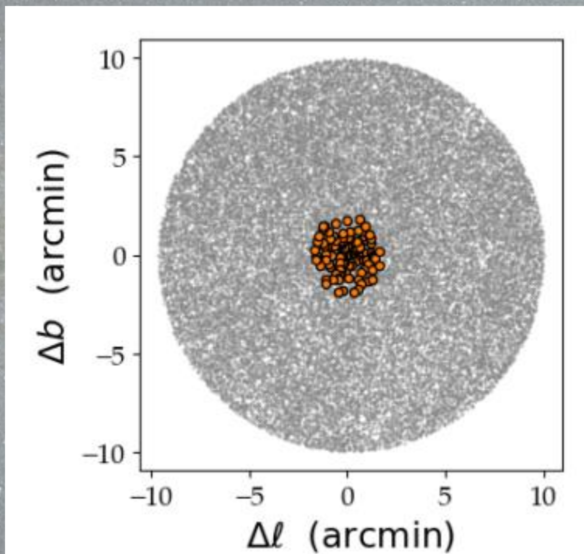
¡Candidate clusters in the 5-D phase space!

Map of the new GCs



Gran et al. 2021

New GCs: the case of Gran 3

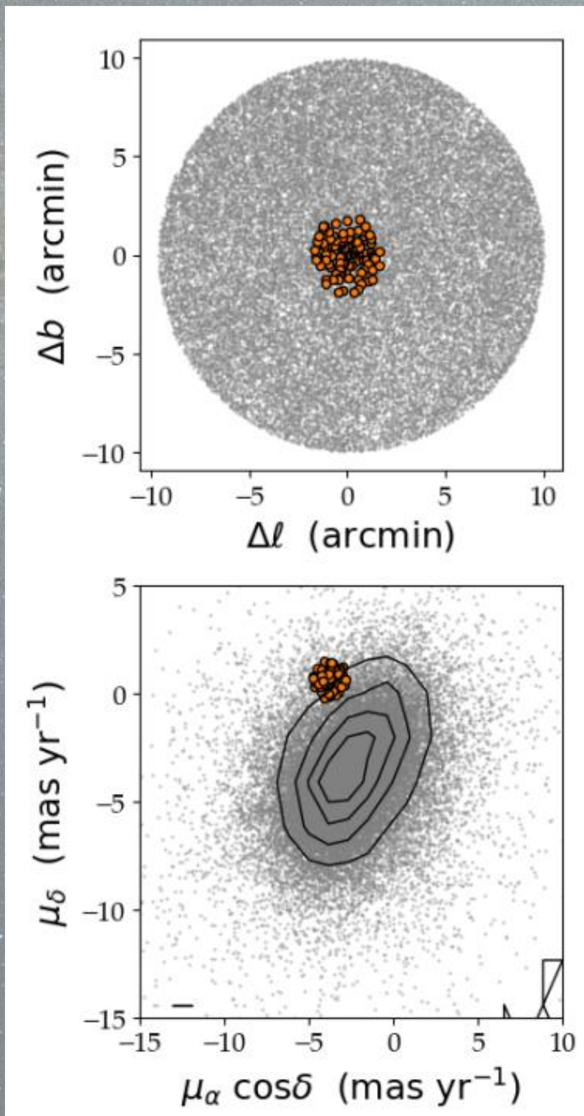


Clustering requirements:

- Grouped in space (ℓ,b)

Gran et al. 2021

New GCs: the case of Gran 3

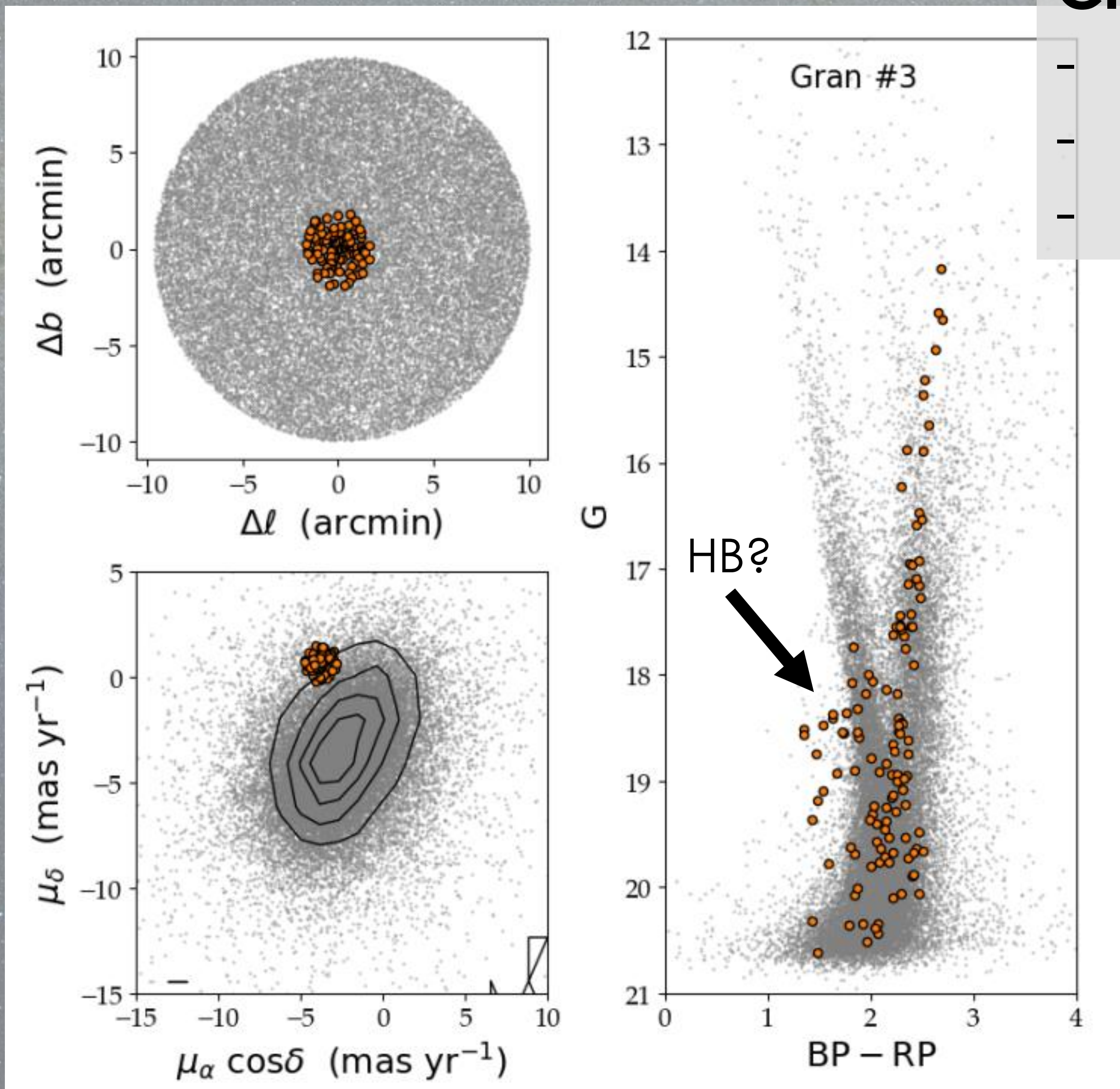


Clustering requirements:
- Grouped in space (ℓ,b)
- Coherent motion (PMs)

Gran et al. 2021

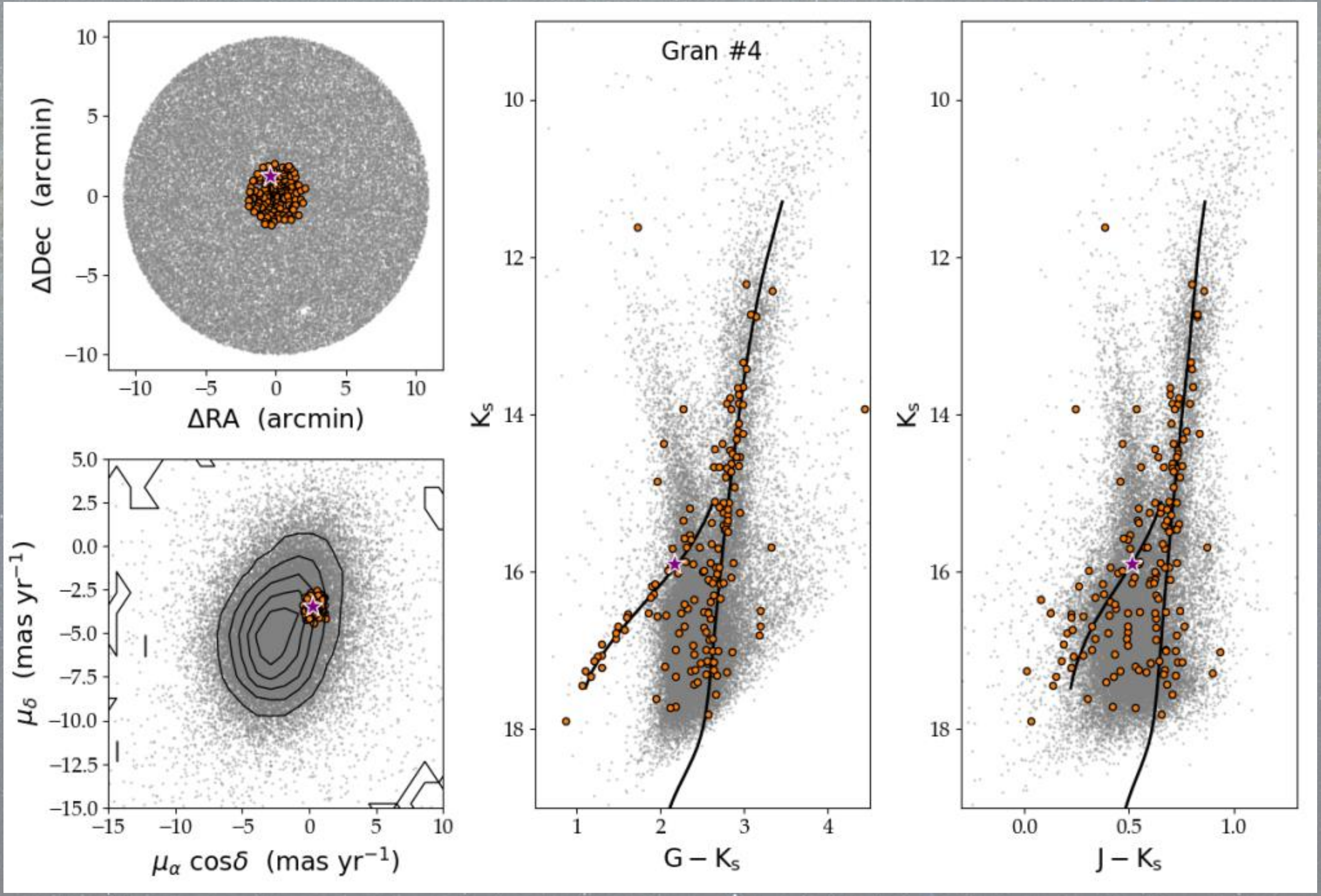
New GCs: the case of Gran 3

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



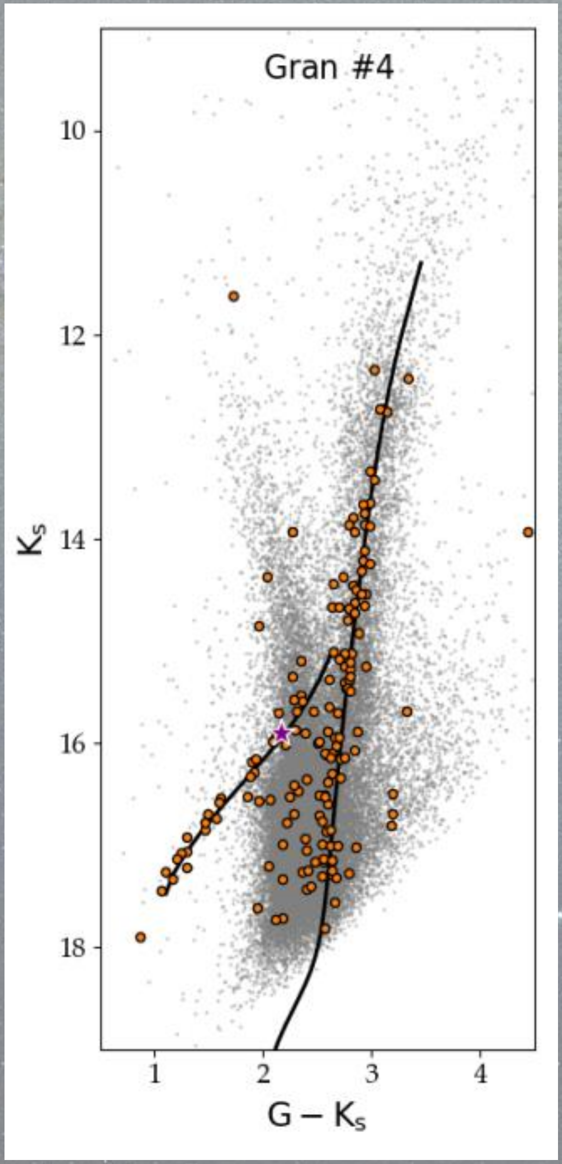
Gran et al. 2021

New GCs: the case of Gran 4



Gran et al. 2021

New GCs: the case of Gran 4

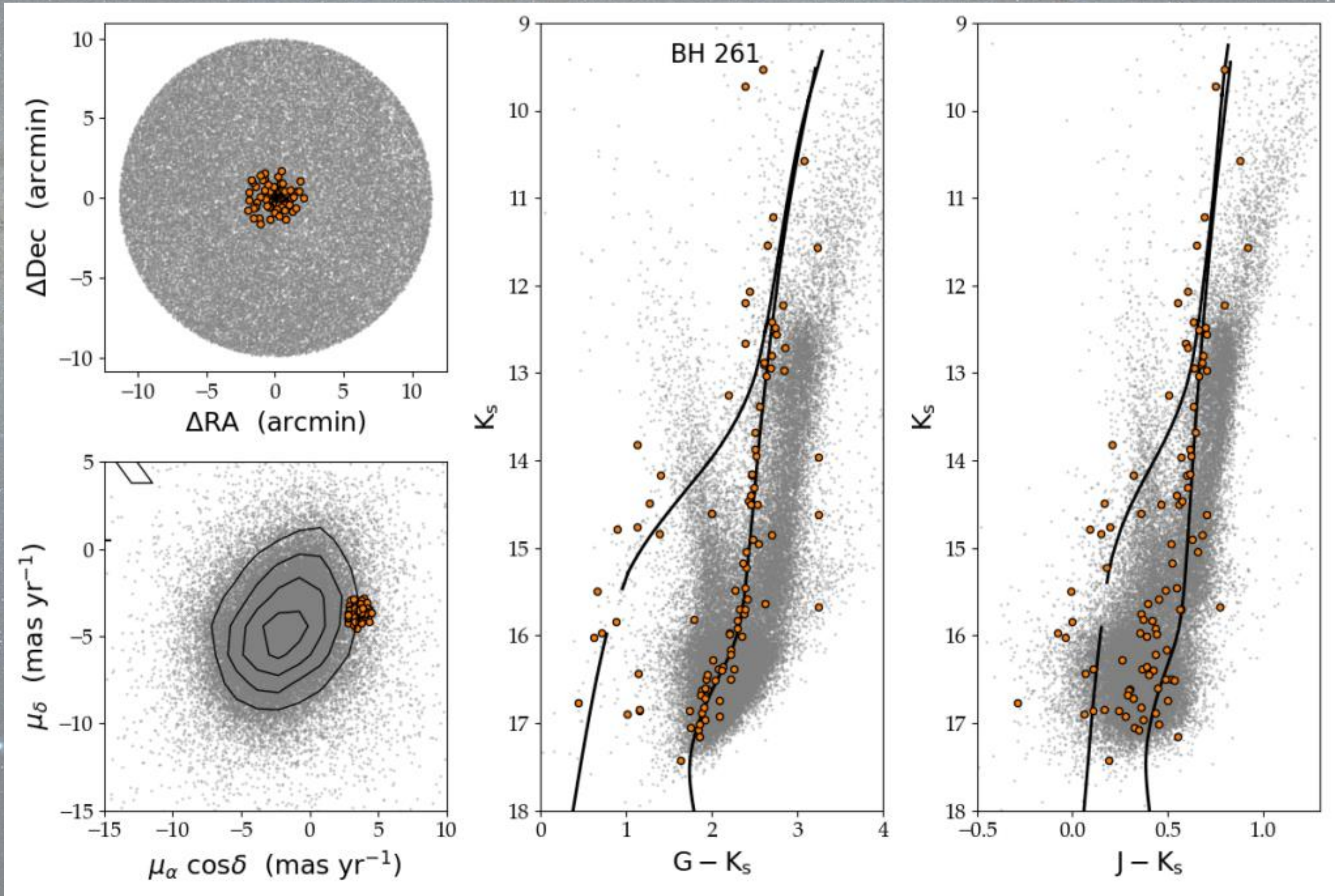


Gran et al. 2021

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

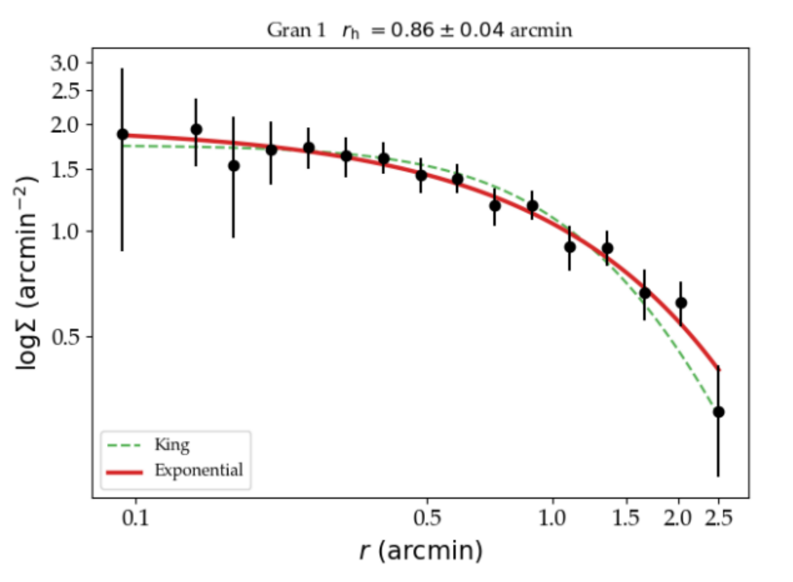
Cluster parameters:
- Age ~12 Gyr
- Distance ~22 kpc
- [Fe/H] ~ -2.4 dex
- r_h ~ 1.15 arcmin
- $M_{dyn} \sim 4 \times 10^5\ M_\odot$

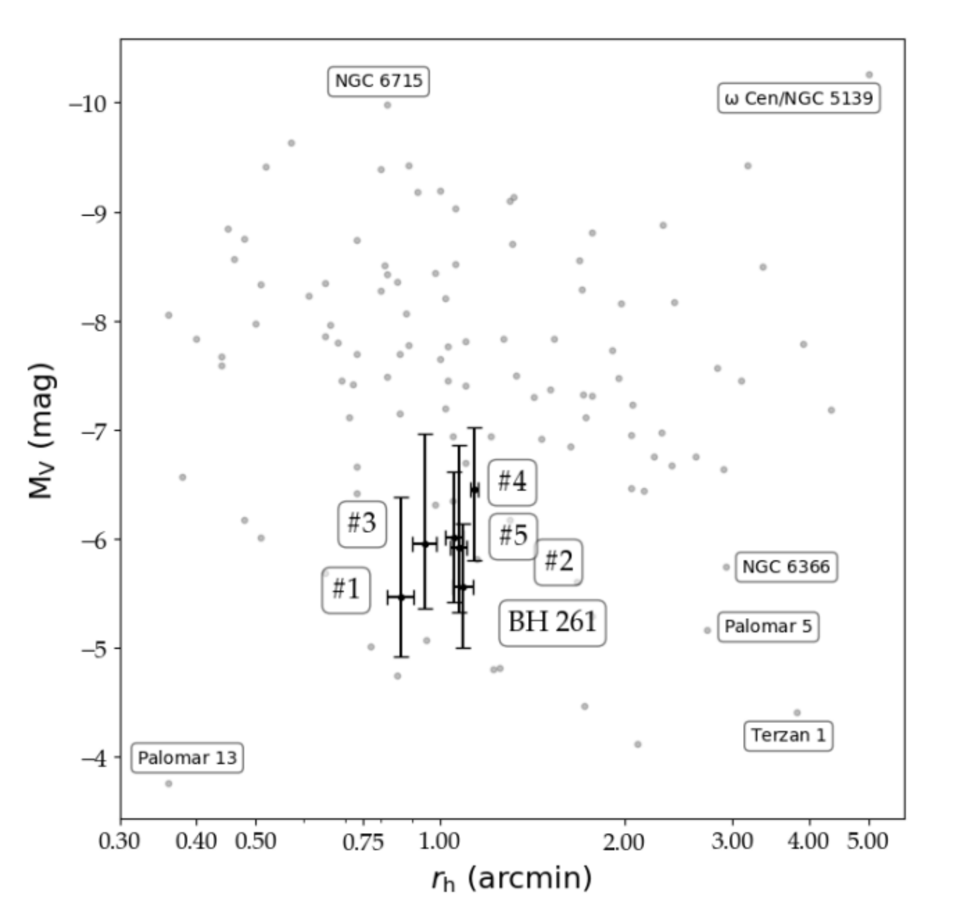
New GCs: side products



Gran et al. 2021

New GCs: full characterisation





Gran et al. 2021

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. 2021

New GCs: MUSE properties

muse

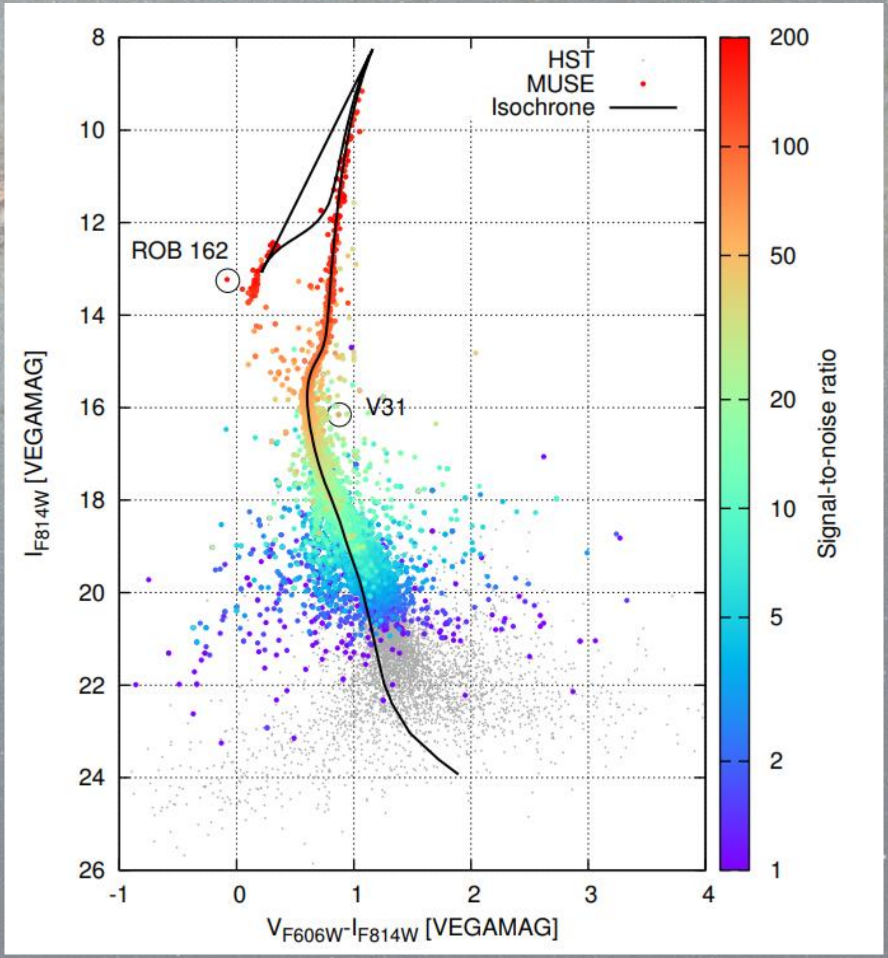
Optical IFU
(4600-9300 A)

R~2000-4000

Wide Field Mode

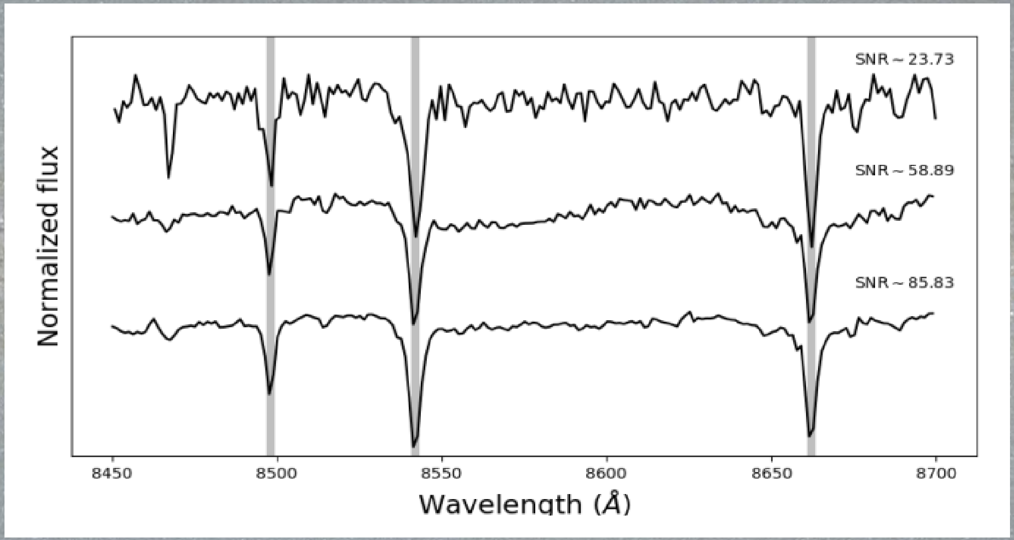
1x1 sq arcmin

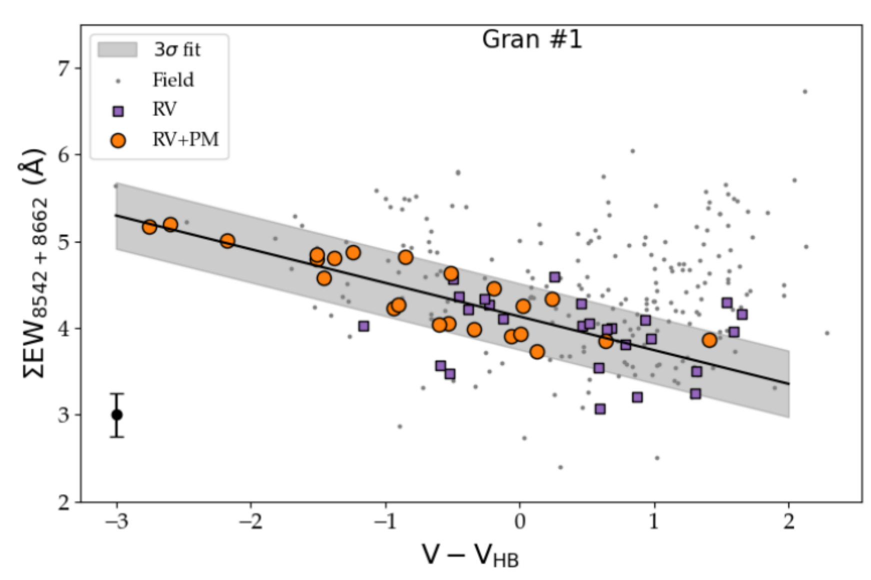
ESO Period 103 &105:
14 hours in Service MODE

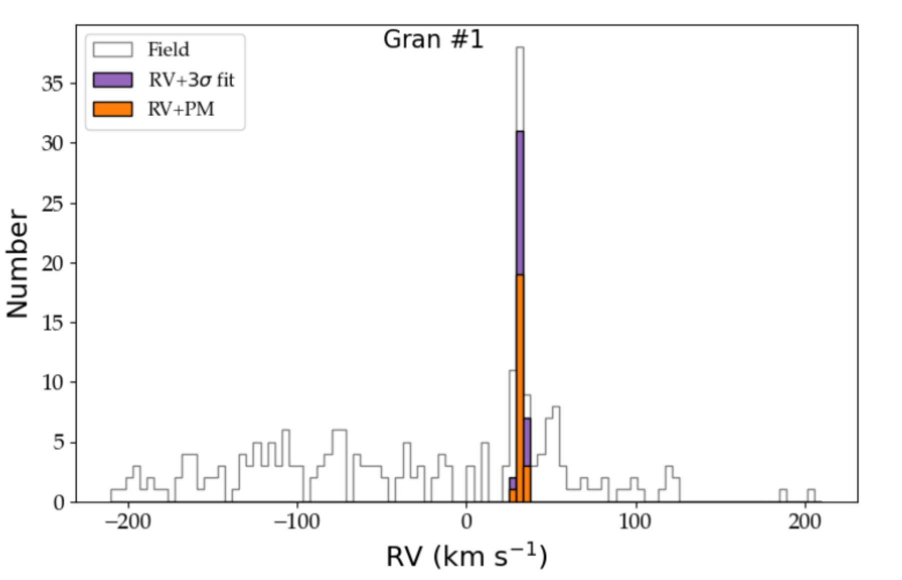


Bacon et al. 2010, Husser et al. 2021

New GCs: MUSE observations

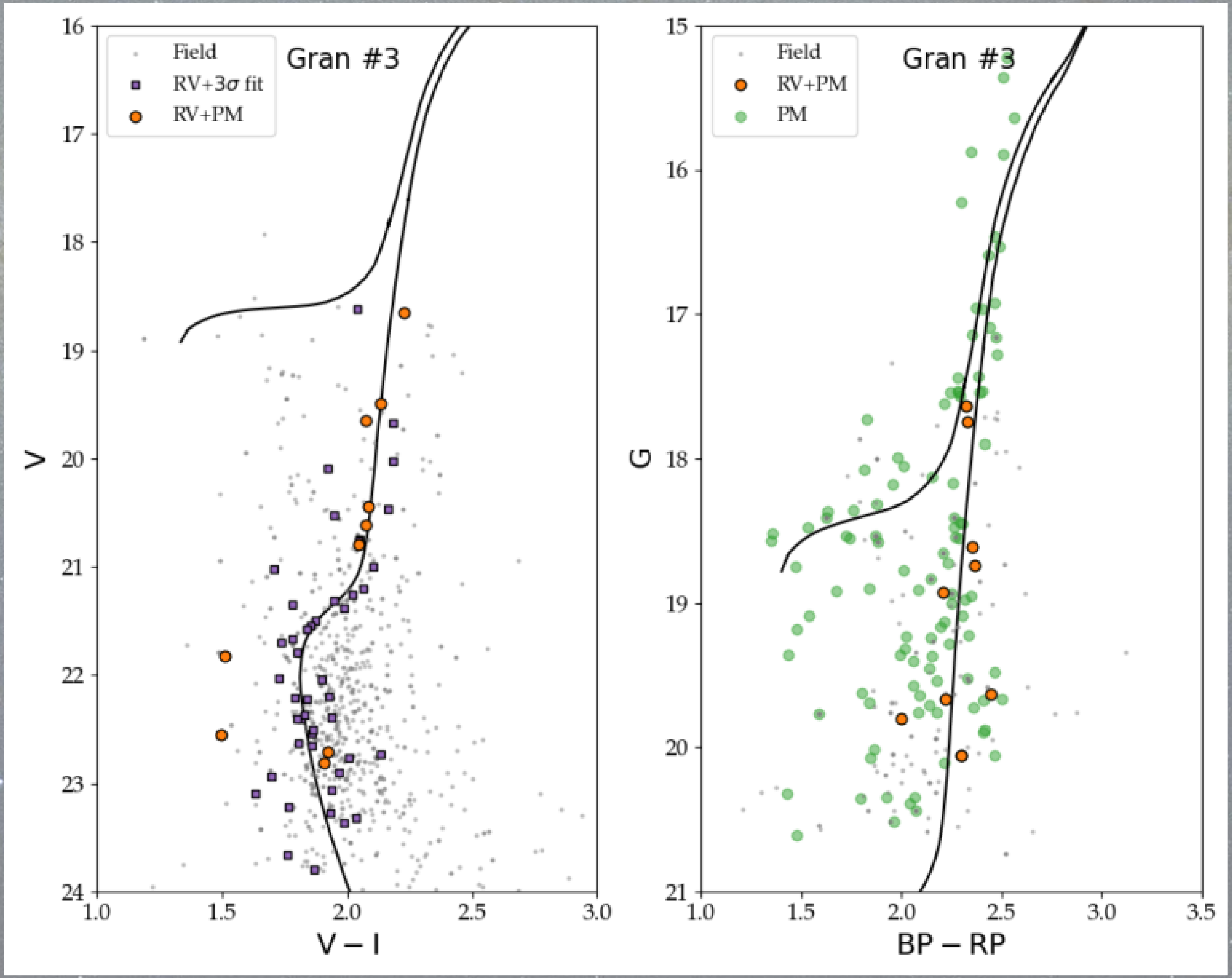






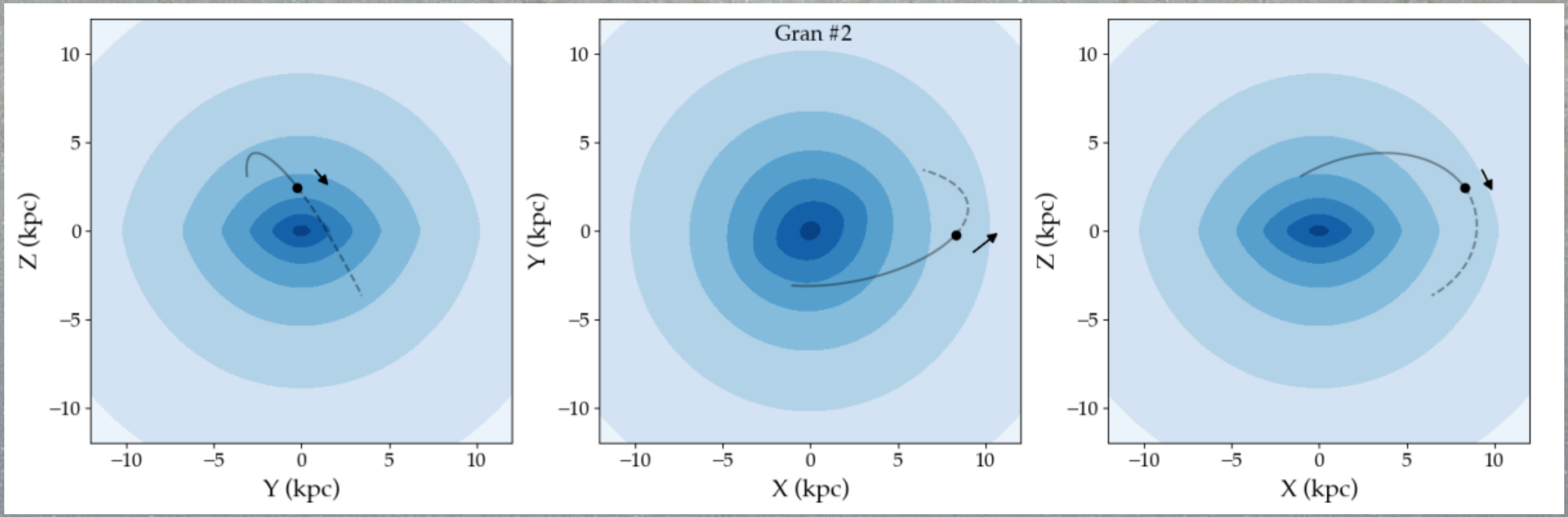
Gran et al. 2021

New GCs: MUSE observations



Gran et al. 2021

New GCs: MUSE observations



Gran et al. 2021

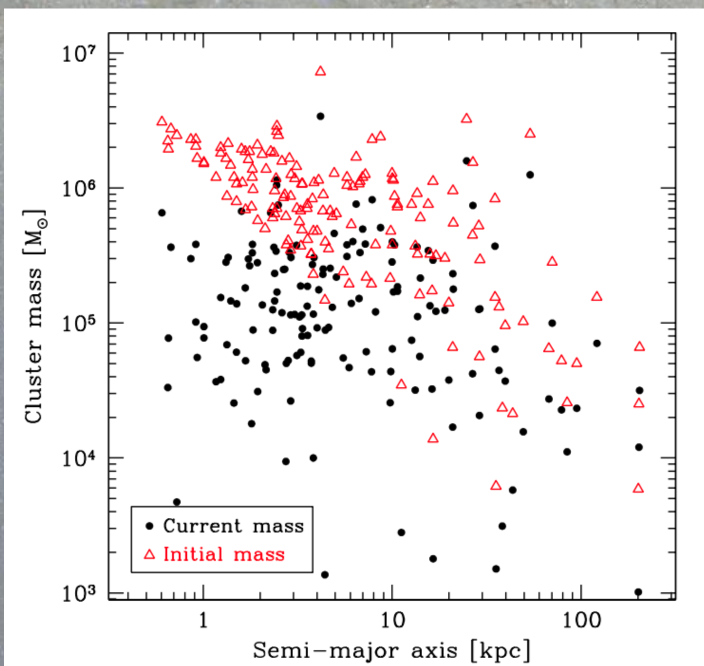
New GCs: MUSE observations

GC	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. 2021

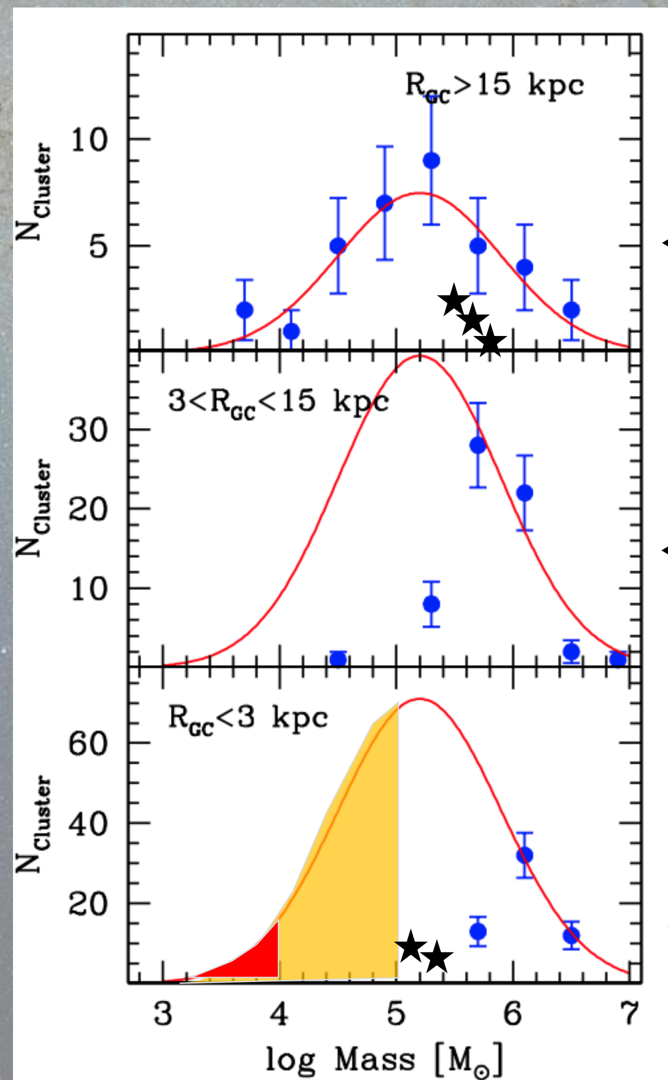
New GCs: Galactic context
Initial mass distribution



Baumgardt et al. 2018

Gran 2 + 3 + 4

Gran 1 + 5



← ~Halo GCs

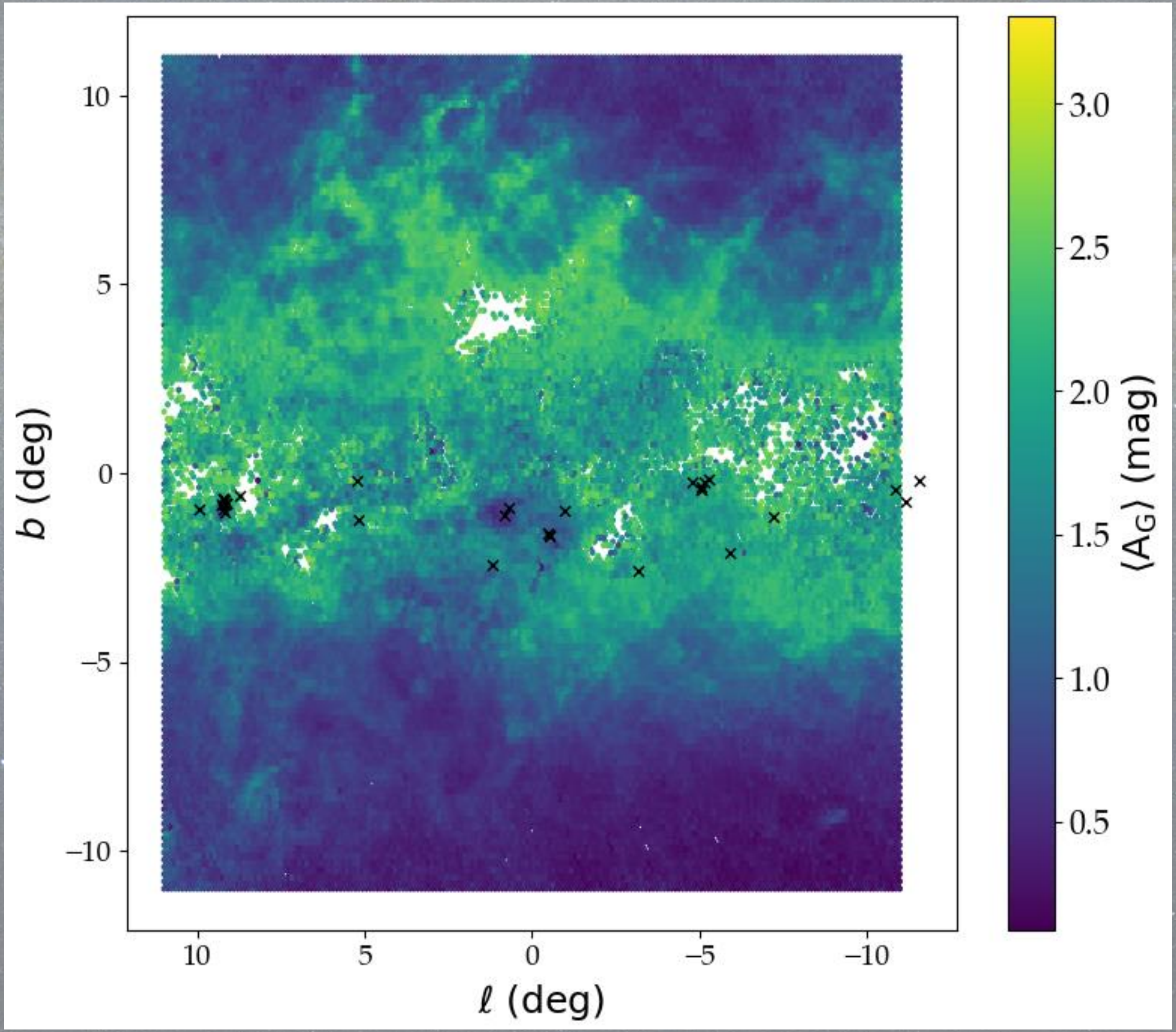
← ~Disk GCs

← ~Bulge GCs

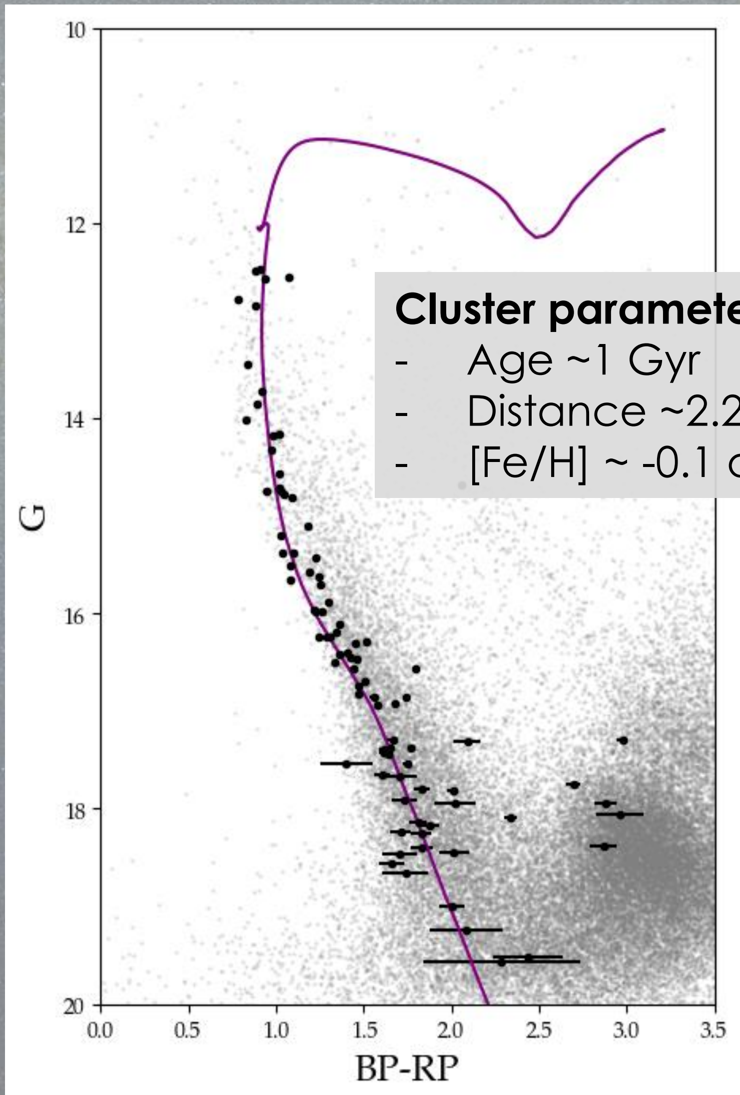
Summary #2

- ★ 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!**

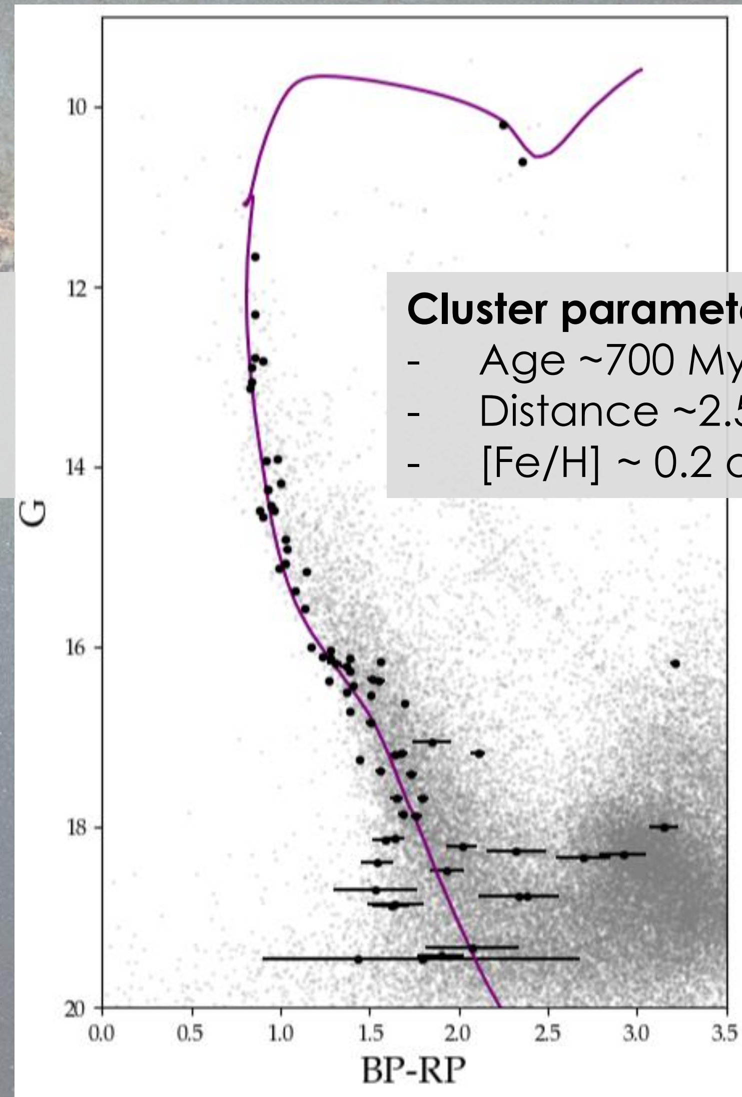
Future work: new OCs



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

Summary #3 (and final)

- ★ 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**.
- ★ Key observable: **proper motions!**
- ★ Impressive results and conclusions will be made with the new **Gaia DR3**!

Thanks for your attention!

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@fegranm fegran.github.io

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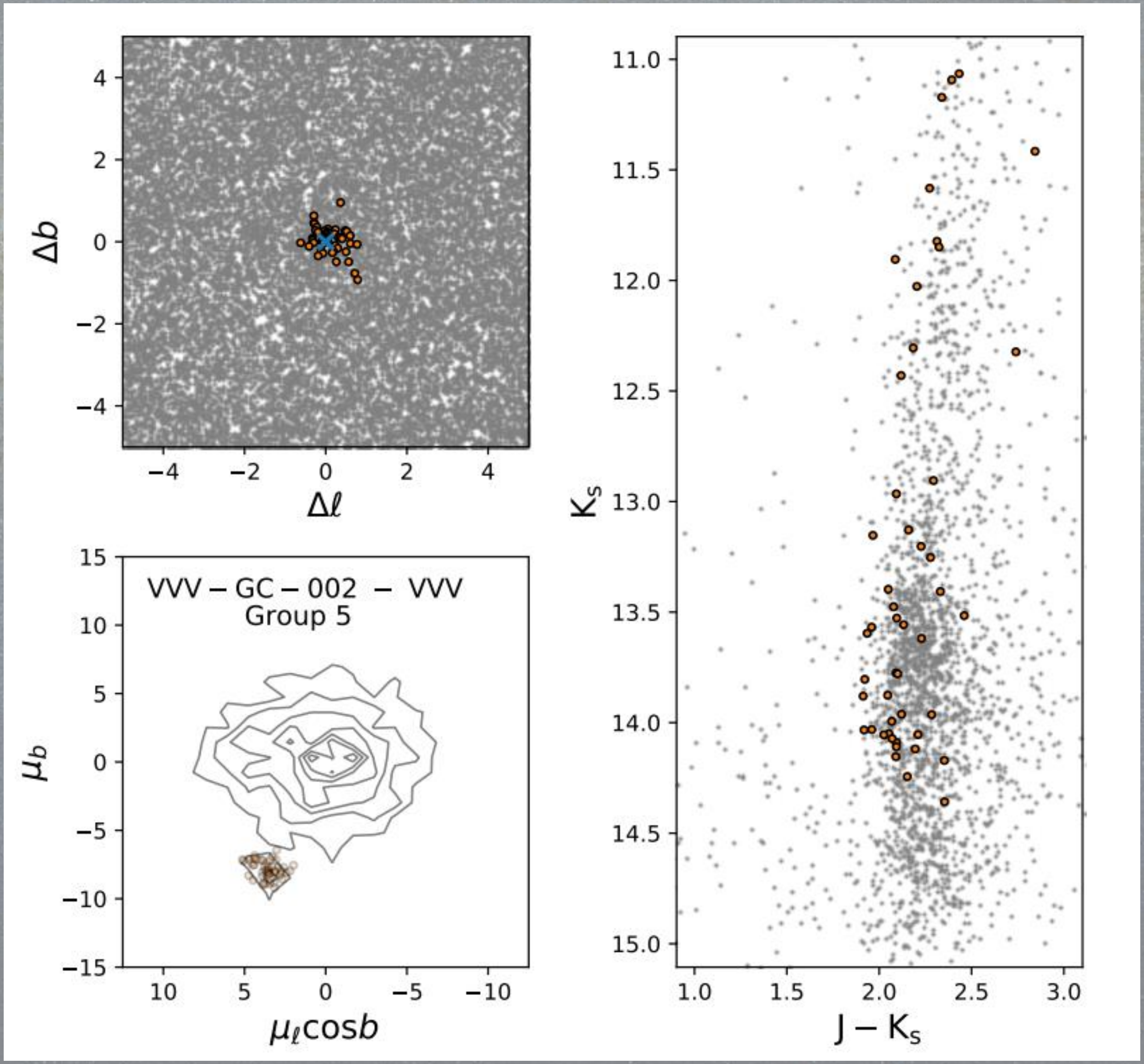
Ministerio de Educación
Gobierno de Chile

INSTITUTO MILENIO DE ASTROFÍSICA

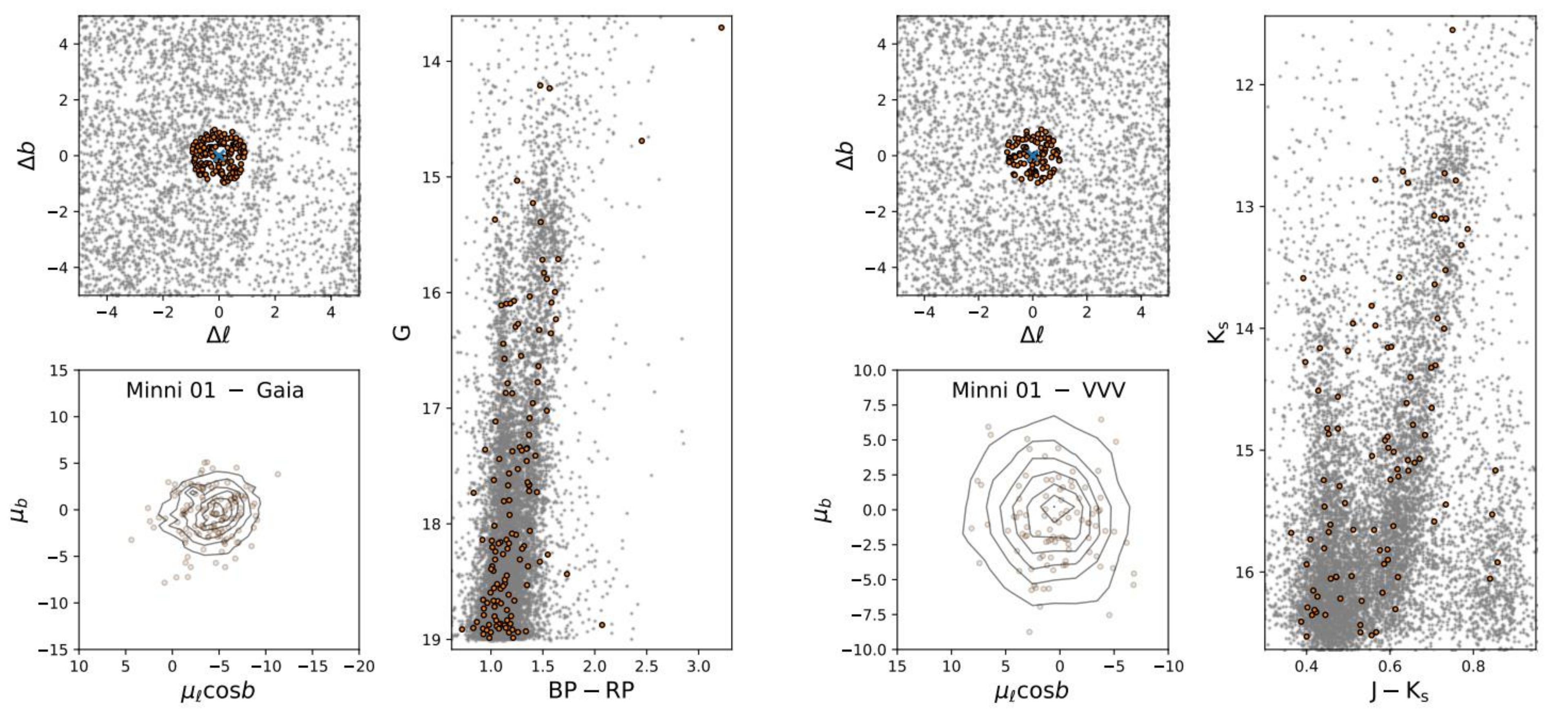
PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

ESO

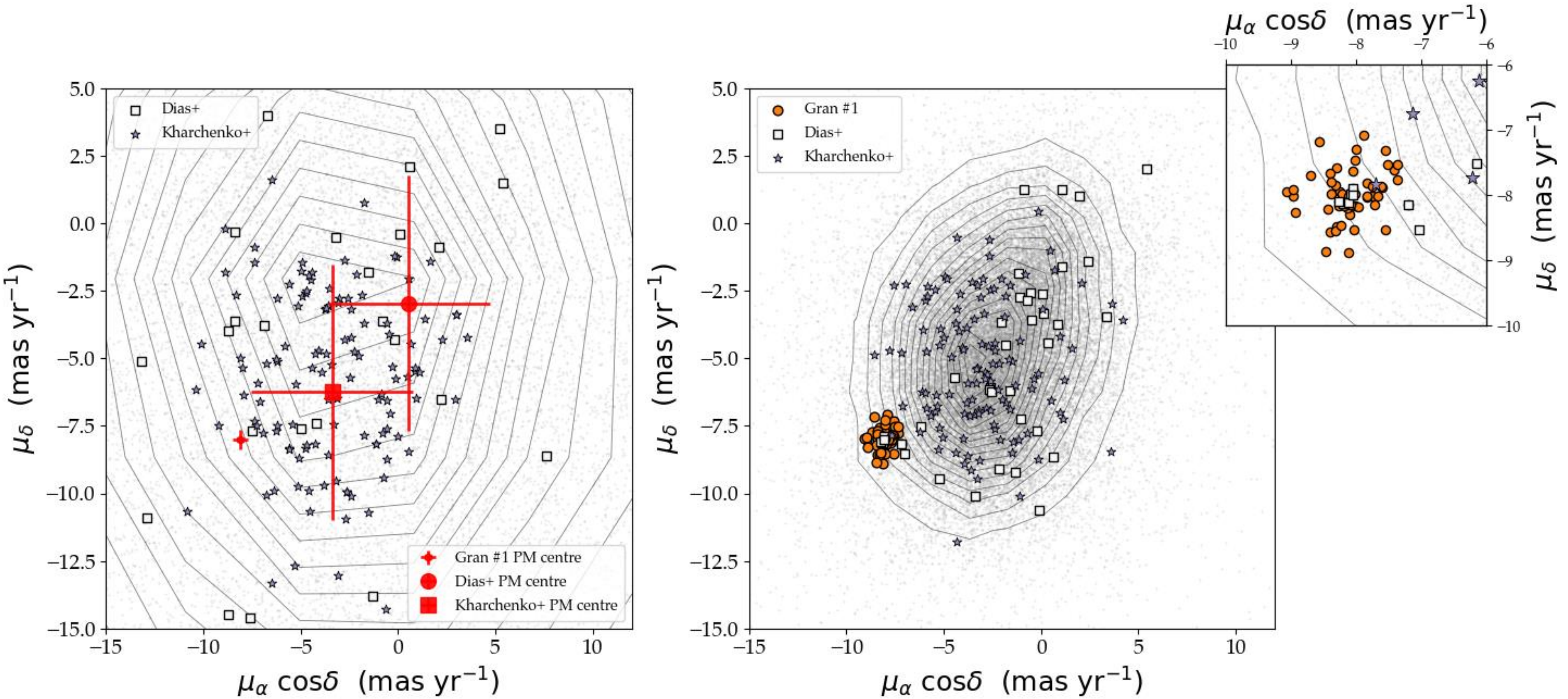
Backup slides :)



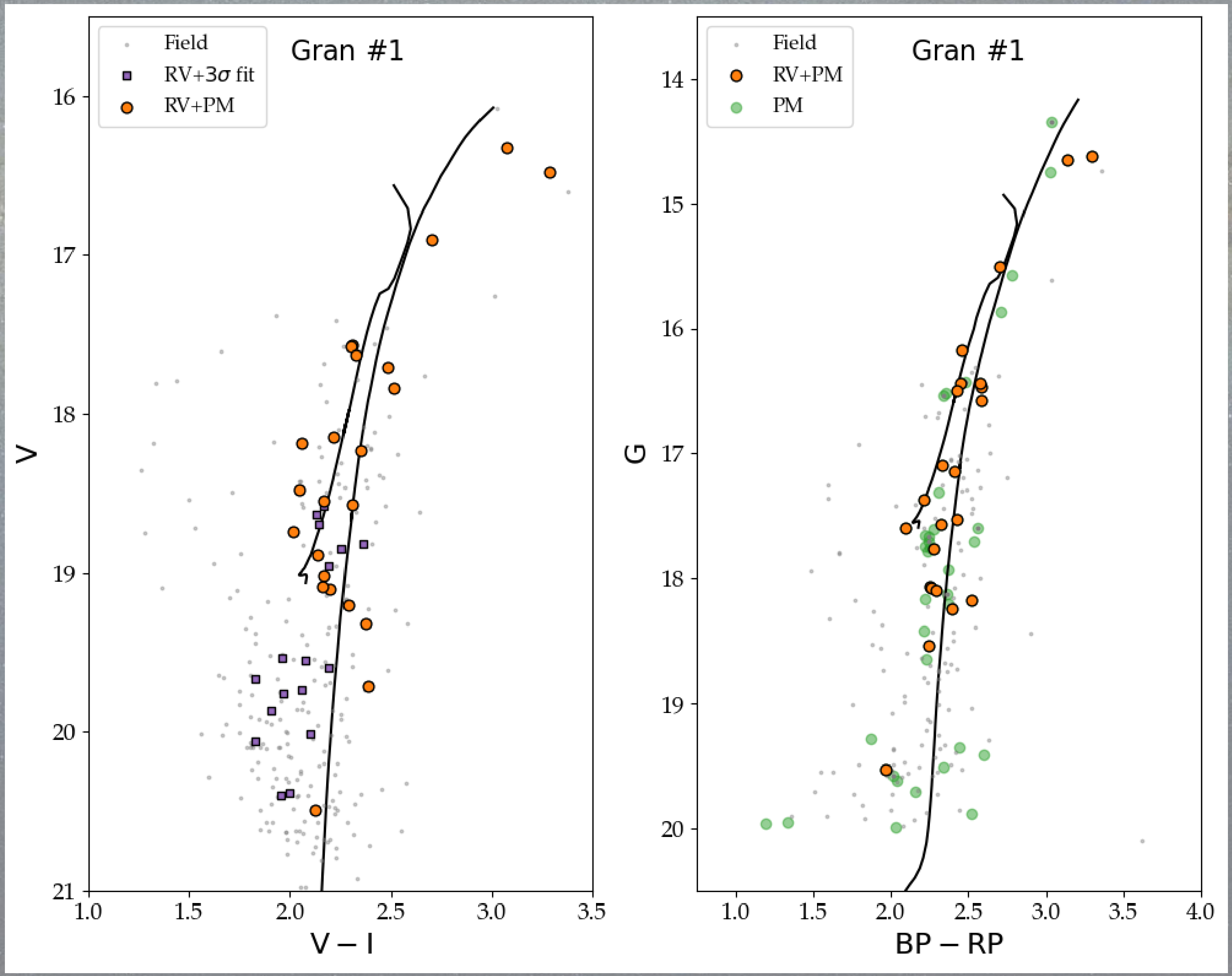
Backup slides :)



Backup slides :)



Backup slides :)



Backup slides :)