THE CONTRIBUTION OF GLOBULAR CLUSTERS TO THE GALACTIC HALO

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In collaboration with

FLAMES GC survey:

Eugenio Carretta, Raffaele Gratton, Sara Lucatello, Valentina D'Orazi, Antonio Sollima, Chris Sneden et (many) al.

Gaia-ESO Survey:

400+ co-Is (PIs : G. Gilmore, S. Randich)

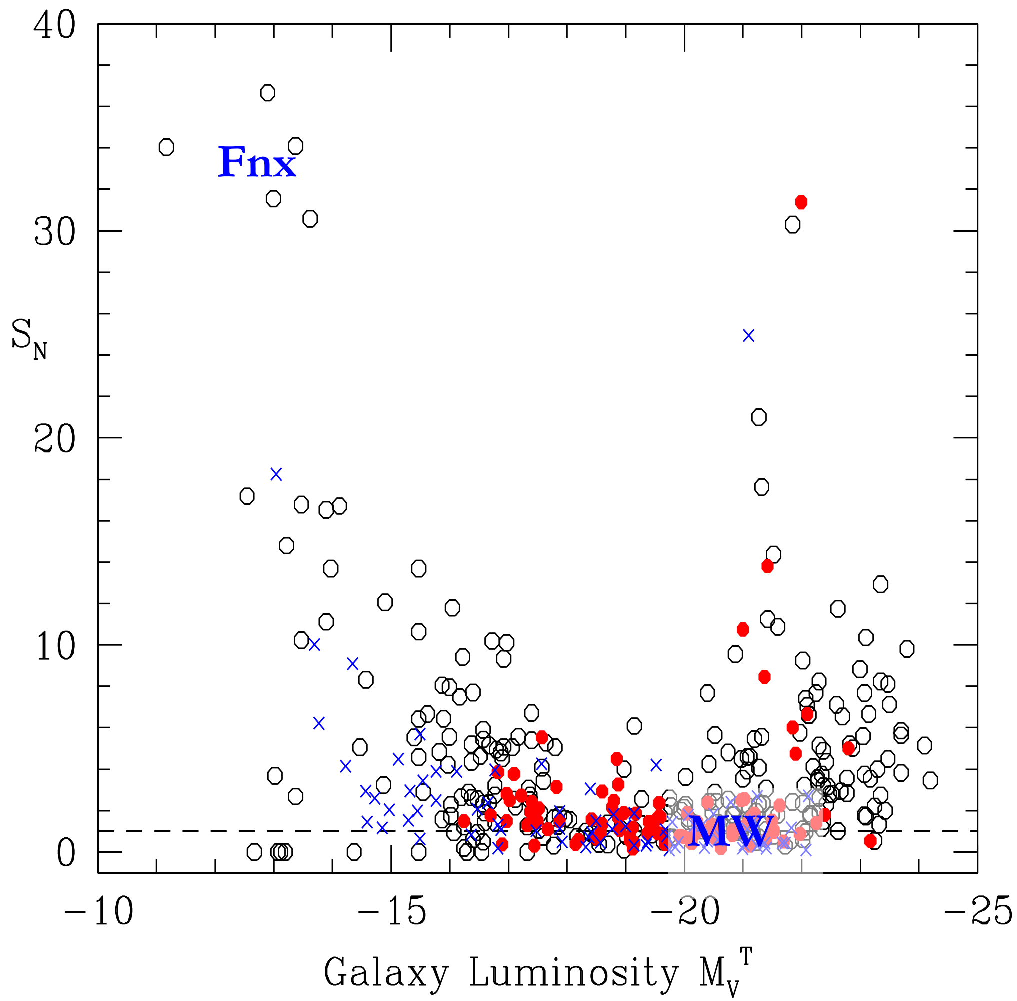
GC systems & galaxies

- ✓ GC systems are ubiquitous
- ✓ number/frequency of GC varies with morph. type
- ✓ mass ~10^5-10^6 M⊙
- ✓ Mv~-5 to -10
- ✓ r_c~1 pc
- ✓ metallicity ~ -2.5 to 0
- ✓ old (age ≥ 10 Gyr)

MW : nr ~ 160

S_N~ 0.5

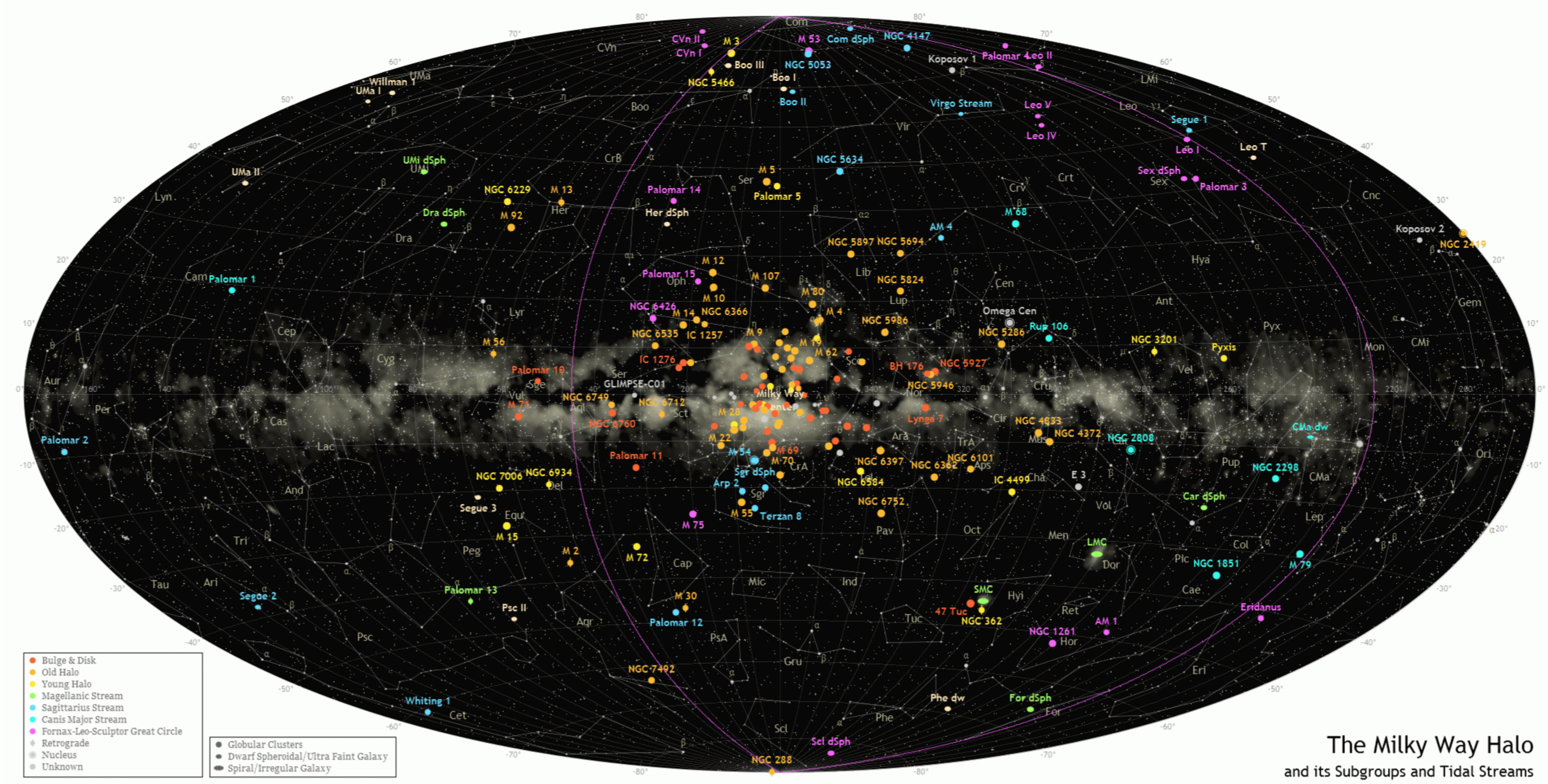
halo, disk, bulge



Harris+2013

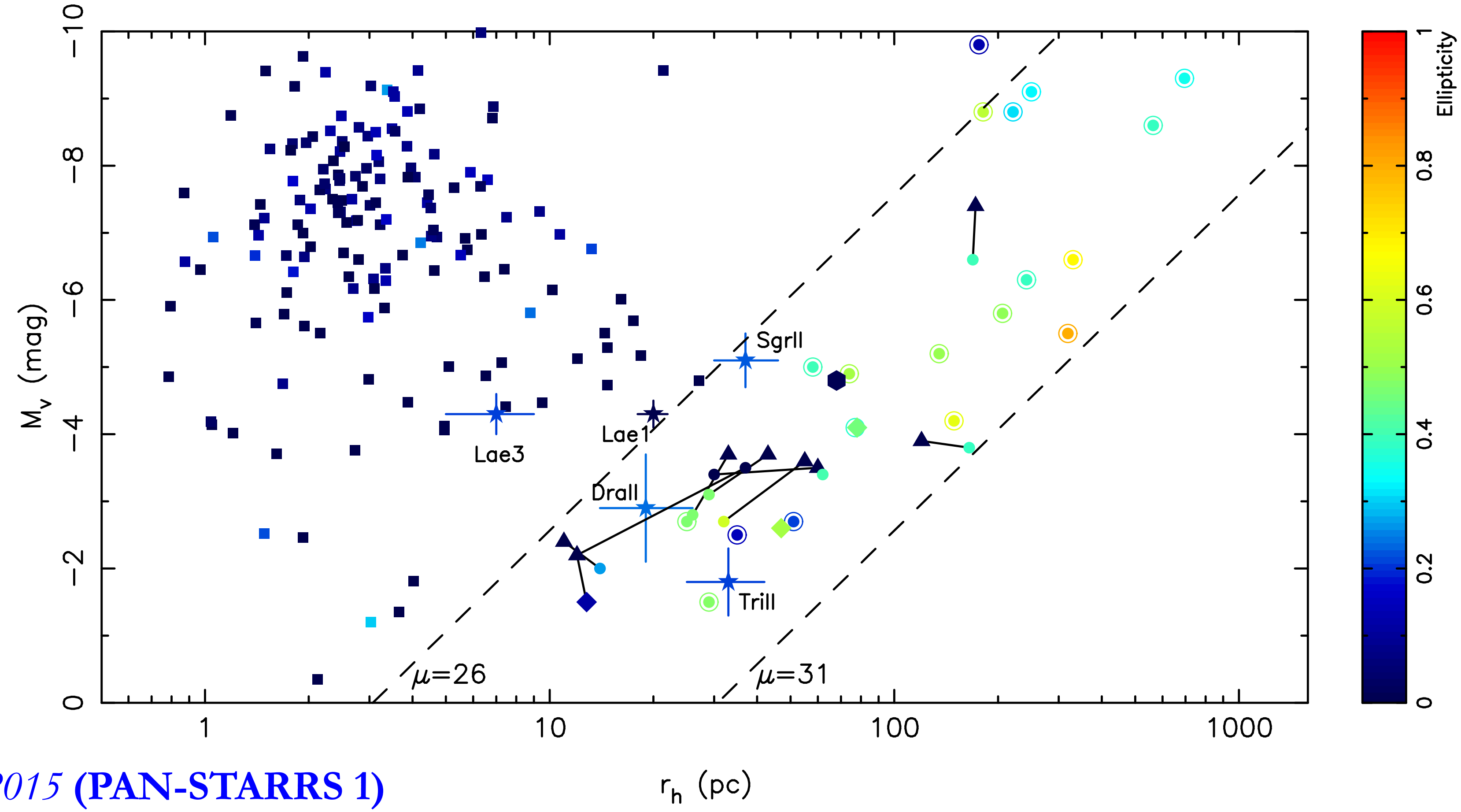
GCs in the MW

- **About 160 GCs in MW (about 2/3 in halo)**



GCs in the MW

- About 160 GCs in MW (about 2/3 in halo)
- More to be found ? Yes : far/extincted/small/extended

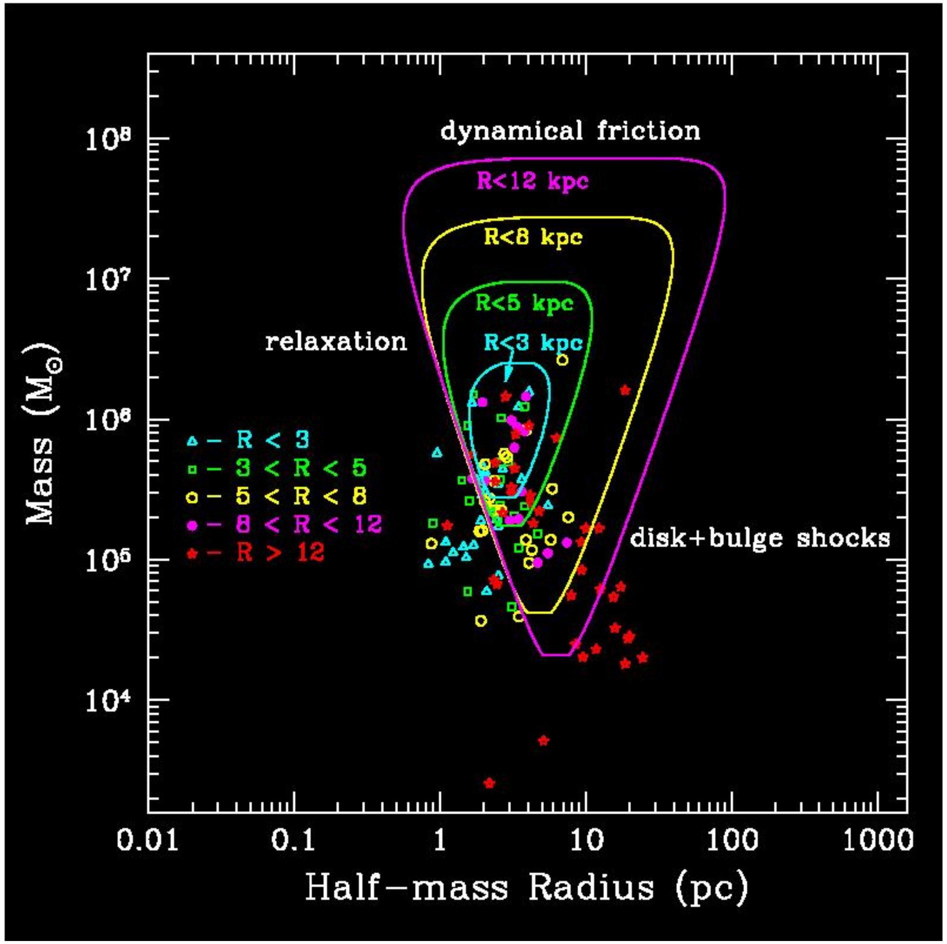


Laevens+2015 **(PAN-STARRS 1)**

GCs in the MW

vital diagram for MW GCs

(Gnedin & Ostriker 1997)



GCs lose mass/stars

- **violent relaxation (init.)**
- **two-body encounters**
- **tidal shocks**

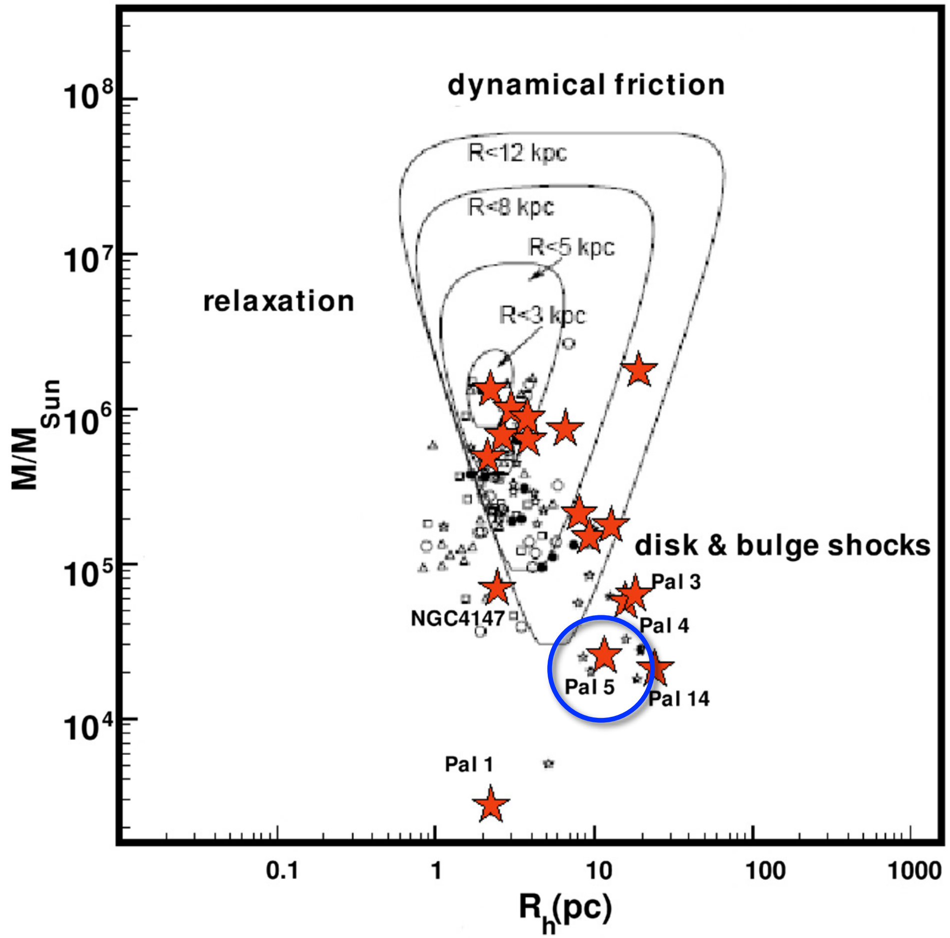
Present-day GCs:

- **less than in origin**
- **less massive than in origin**

GCs in the MW

vital diagram for MW GCs

(Gnedin & Ostriker 1997)



GCs do lose mass/stars

- **violent relaxation (init.)**
- **two-body encounters**
- **tidal shocks**

Jordi & Grebel 2010 **:**

17 GCs, SDSS,

search for extra-tidal features

Tidal tails & streams

Tails with clusters :

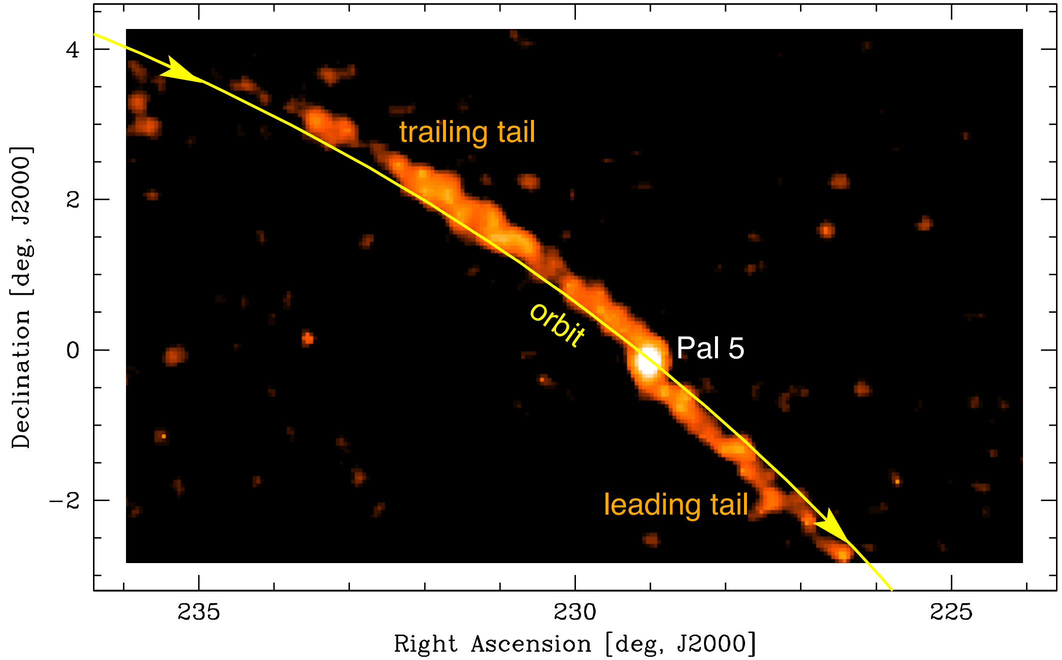
NGC 288 : *Grillmair+ 2013*
NGC 5466 : *Belokurov+ 2006*
NGC 5053 : *Lunchner+ 2006*
Pal 14 *: Sollima+2011*
Pal 1 *: Nieder-Ostholt+ 2010*
See also *Jordi & Grebel 2010*

Open identification :

Pyxis (ATLAS, *Koposov+ 2014)*

"Orphan" tails :

10+ (e.g. GD-1)

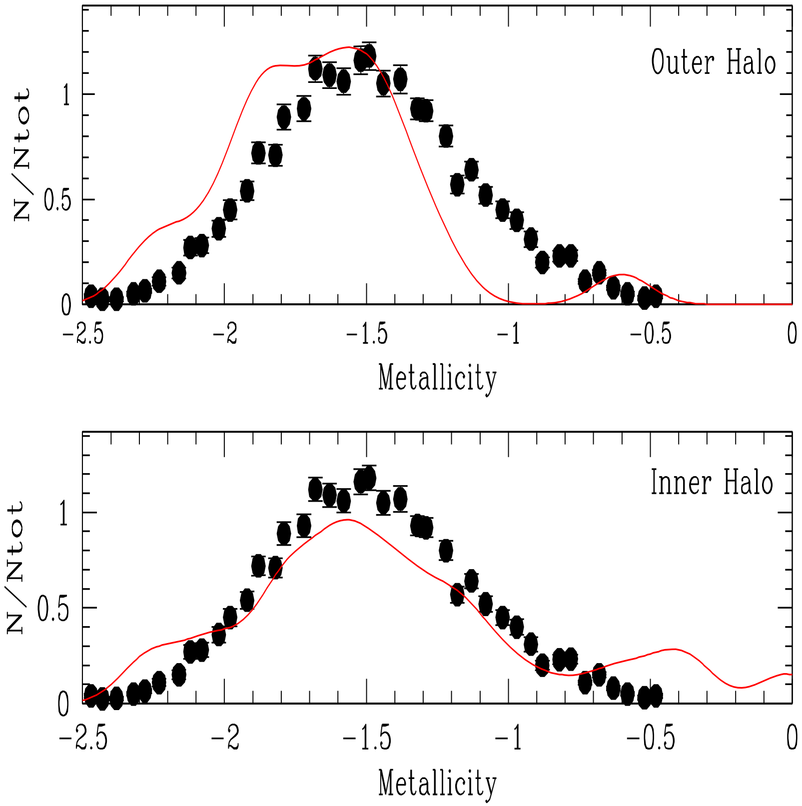


Pal 5 – SDSS (Odenkirchen+2001)

Grillmair (IAUS 317) : 21 nearby halo streams and more expected… imply original population of about 450 GCs

Chemistry: GC ≈ halo field stars ?

Metallicity

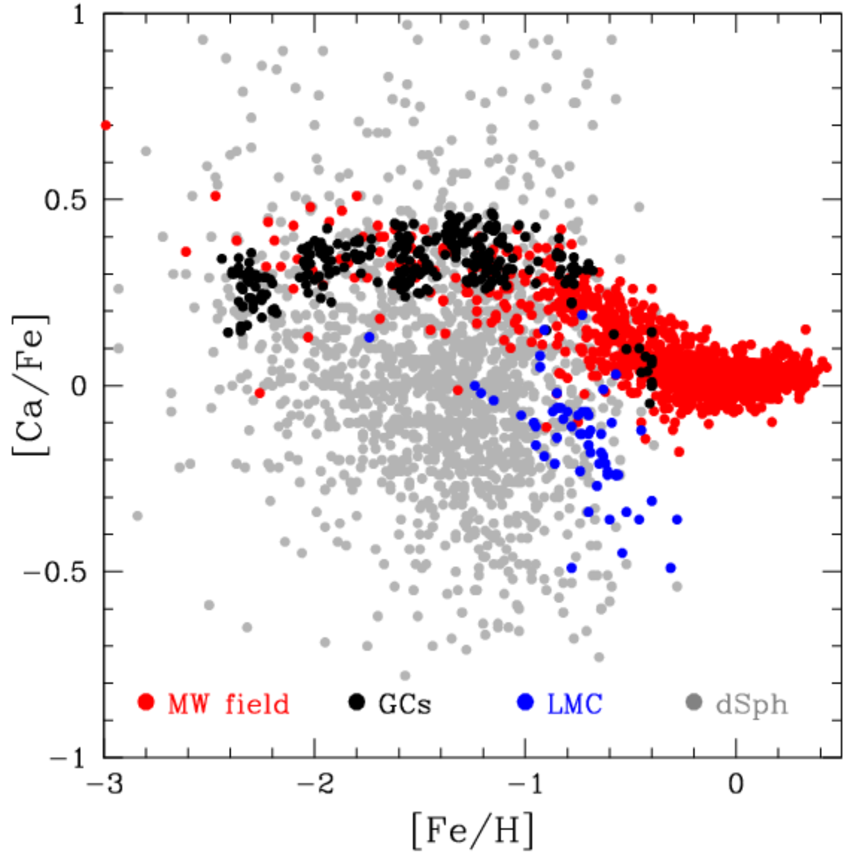


● **field halo stars**

— **GCs**

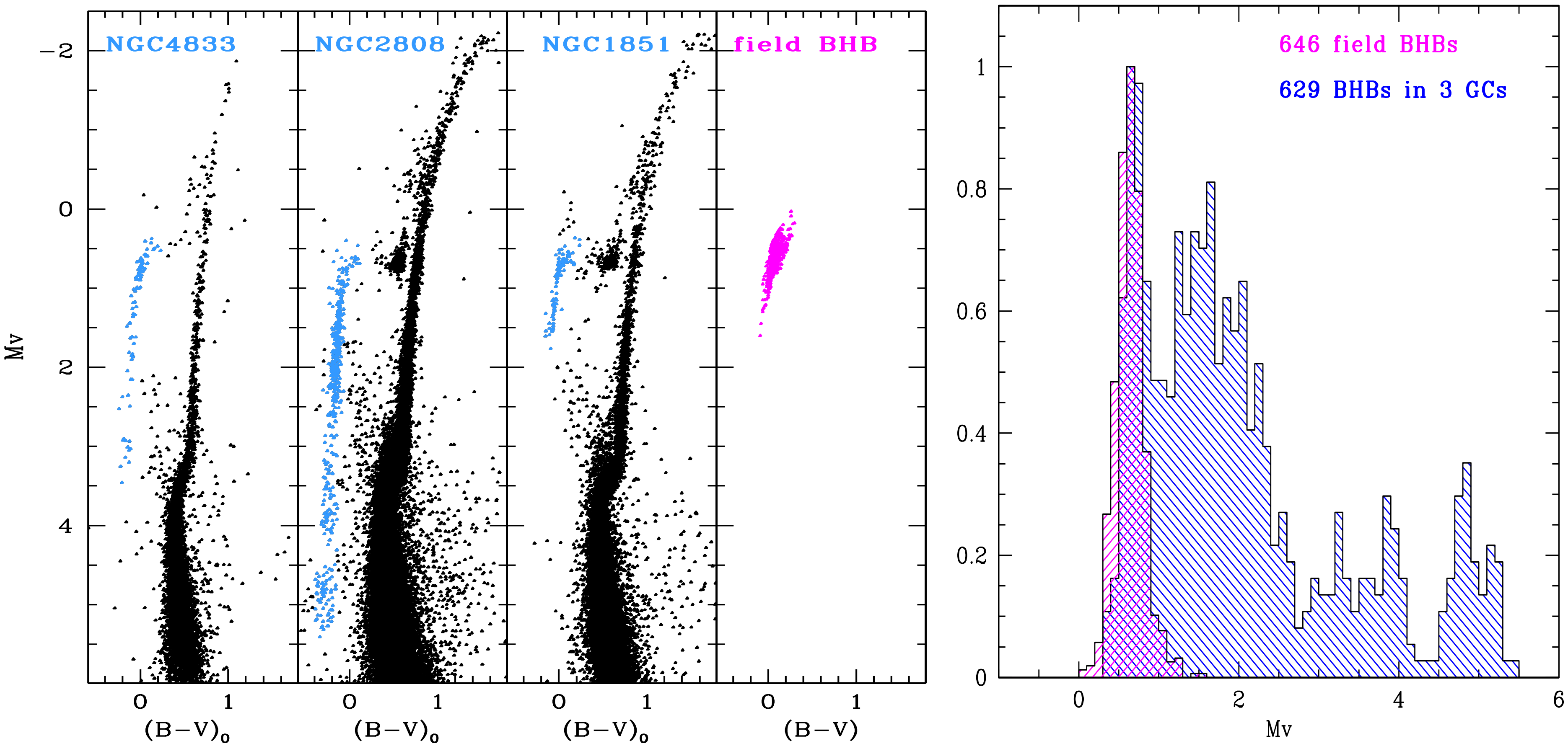
(Gratton+2012, Ivezic+2007)

α -elements



(Adibekyan+2012, Chen 2000, Gratton+2003, Jonsell +2005, Pompeia+2008, Carretta+2010, Kirby+2011)

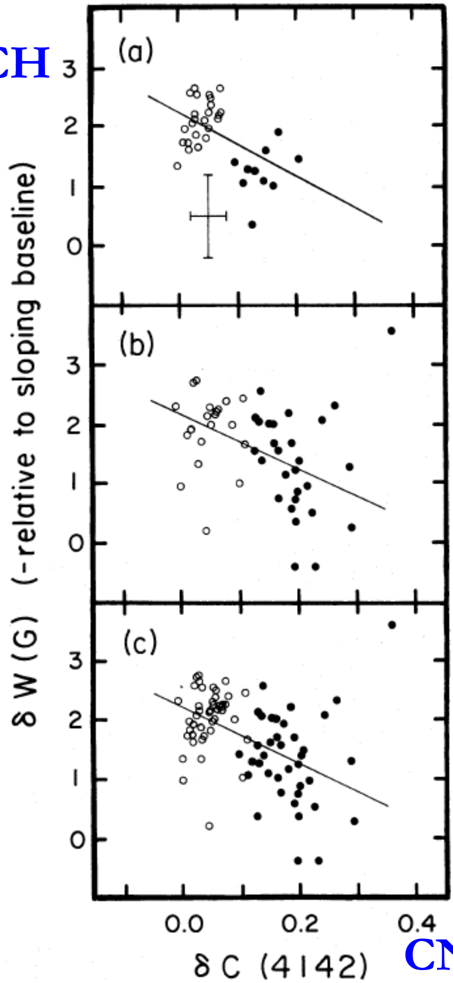
HB : GC ≠ halo field stars



3 GCs (Snapshot HST survey, *Piotto+2002***) & field** *BHB (Brown+2008)*

C & N : GCs ≠ field

CH

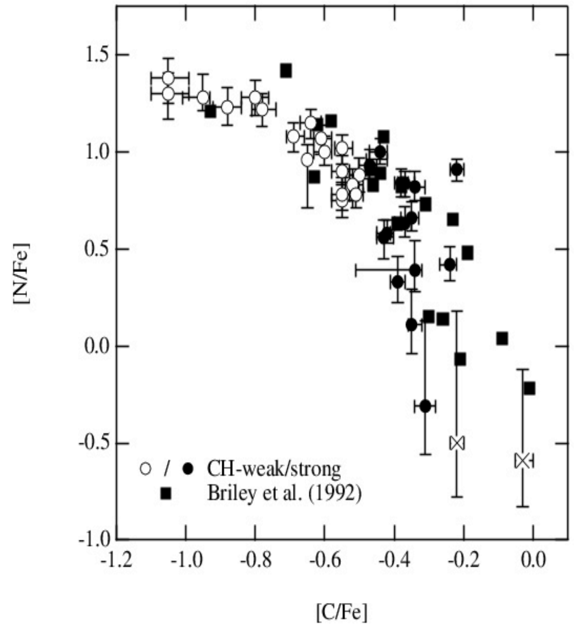


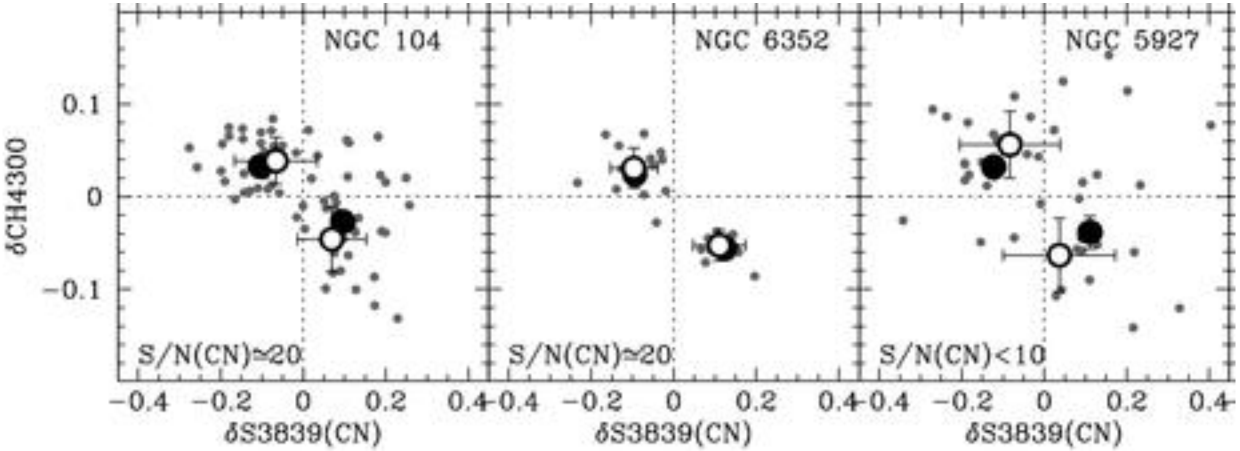
CN

47Tuc: *Norris+ 1984*

C,N anticorrelation
spread / bimodality

Cohen+2002



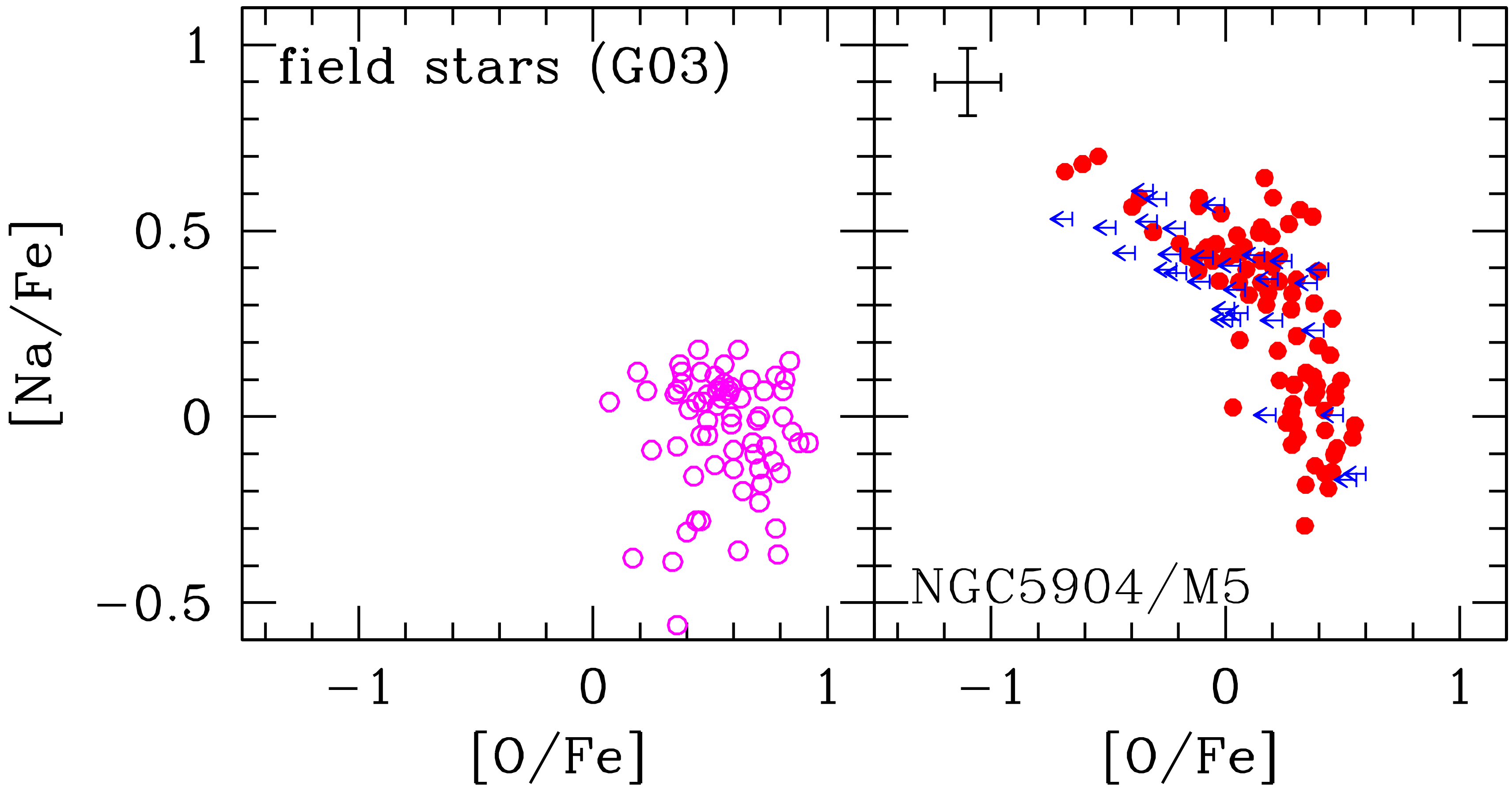


Pancino+ 2010

O & Na : GCs ≠ field

nothing peculiar

O,Na anticorrelation

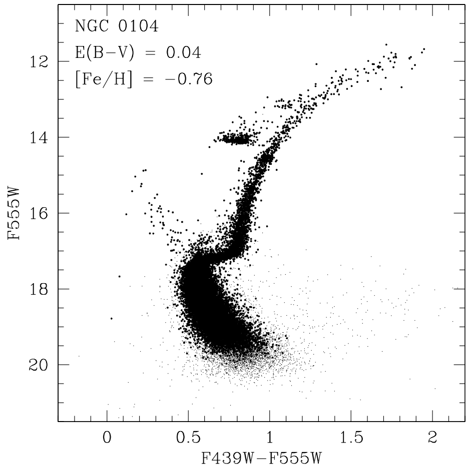


Gratton et al. 2003

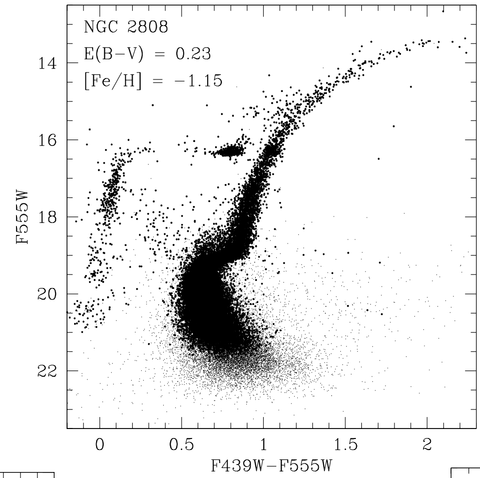
Carretta et al. 2009a,b

Our FLAMES GC survey

- **25+ massive GCs : Mv=-5.5 to -10**
- **FLAMES@VLT (UVES R=45000, 8x + GIRAFFE R=20000, 100x)**

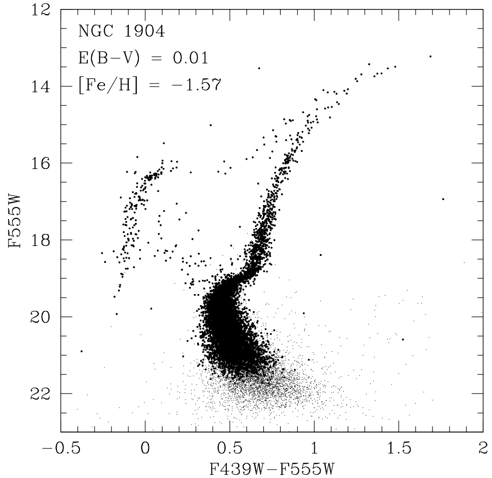


47Tuc

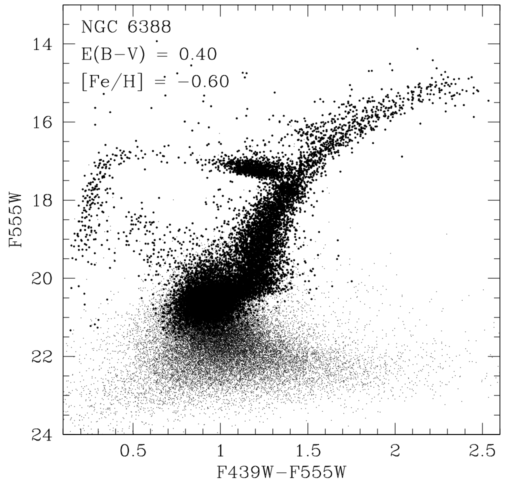


NGC2808

NGC1904

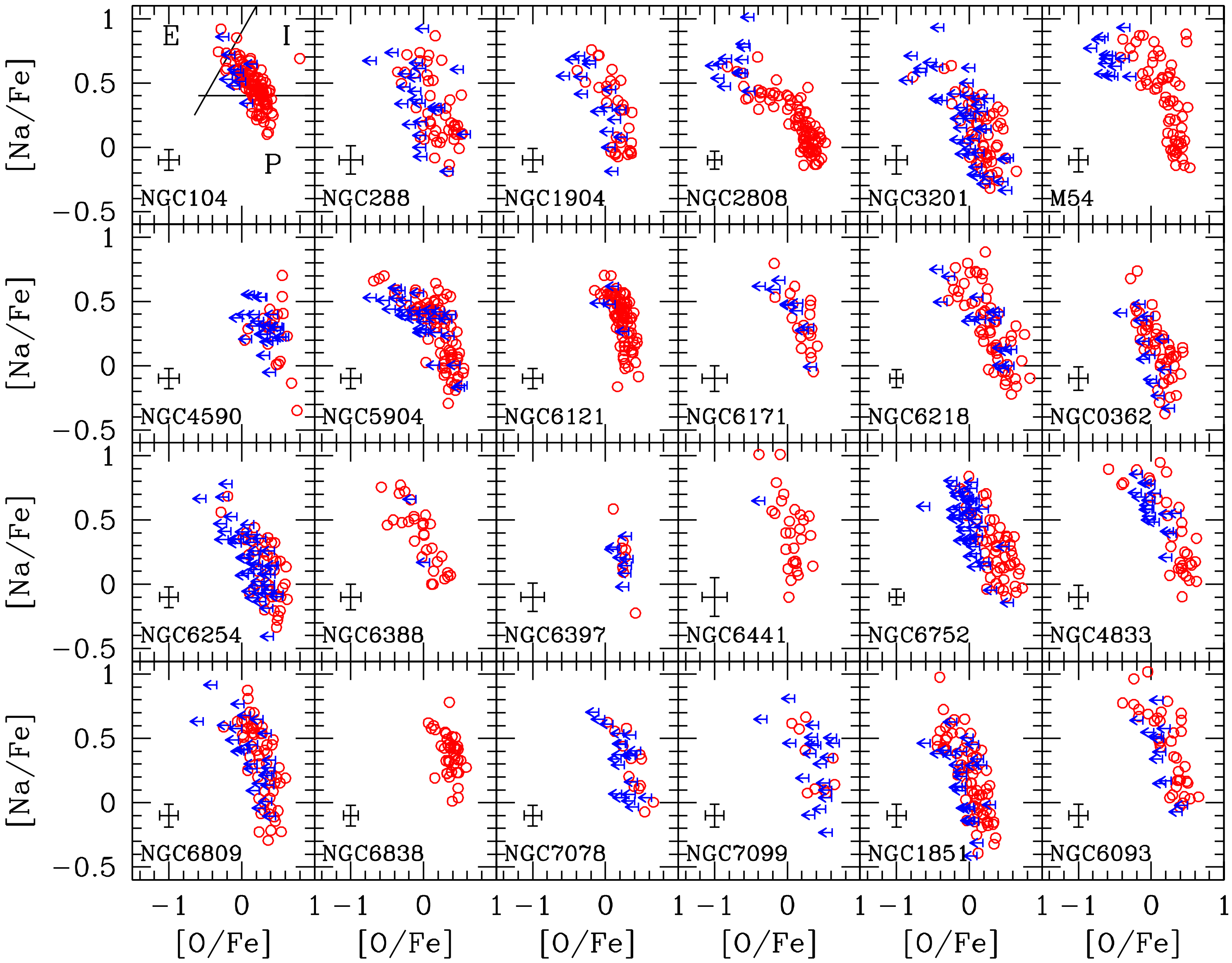


NGC6388



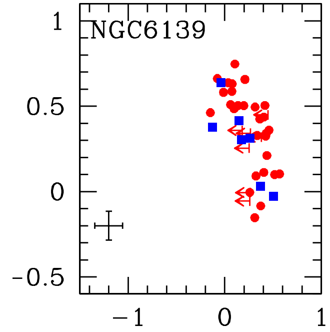
Piotto+2002,
HST snapshot

Na & O in GCs : FLAMES survey



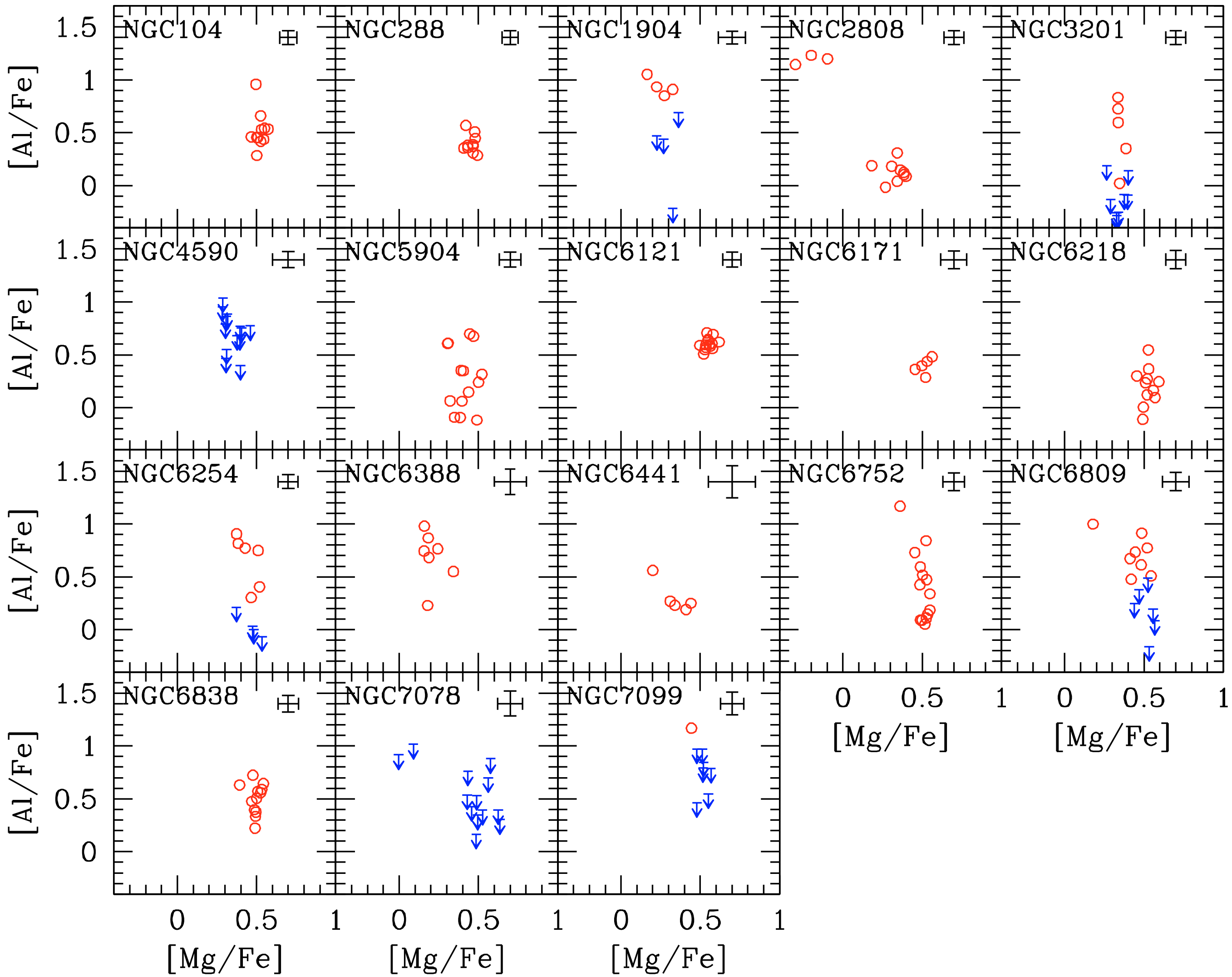
Our personal survey of 25+ GGCs with FLAMES

Carretta+
Gratton+
Bragaglia+
2006-2015



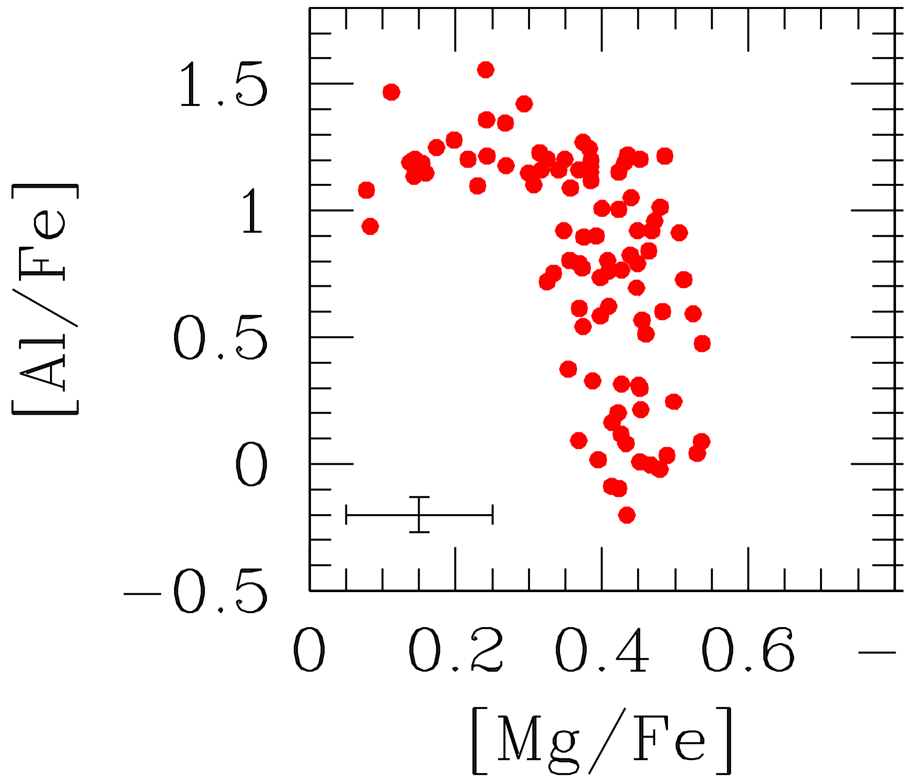
also Mg & Al …

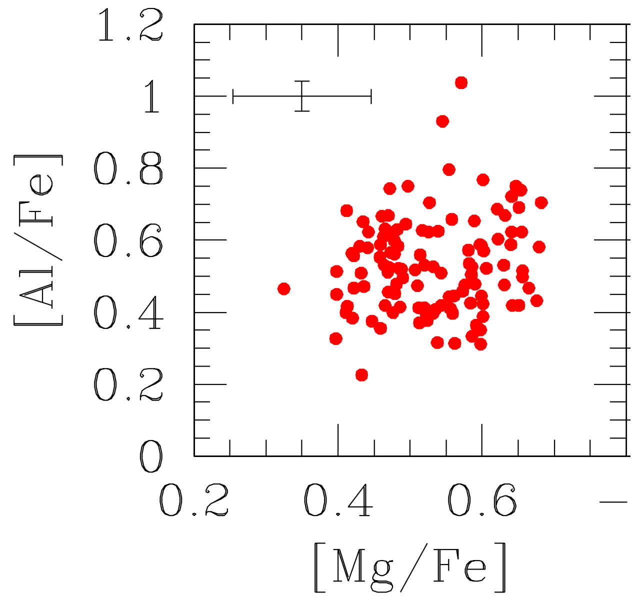
only UVES

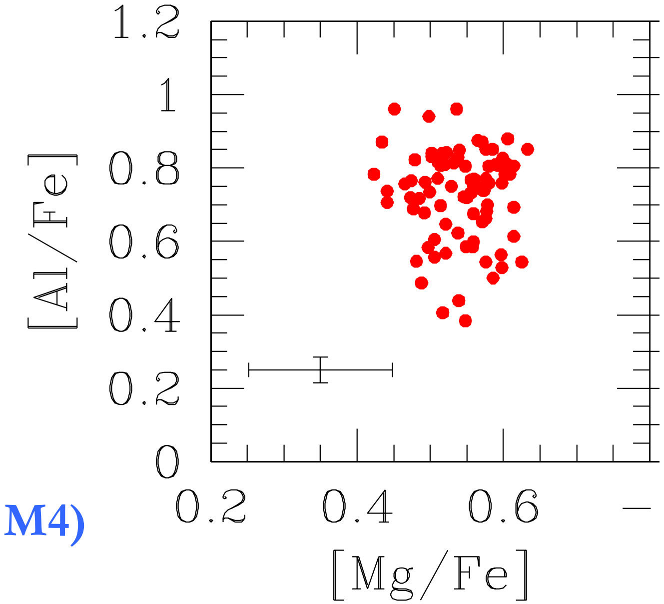


Carretta+2009b

also Mg & Al …

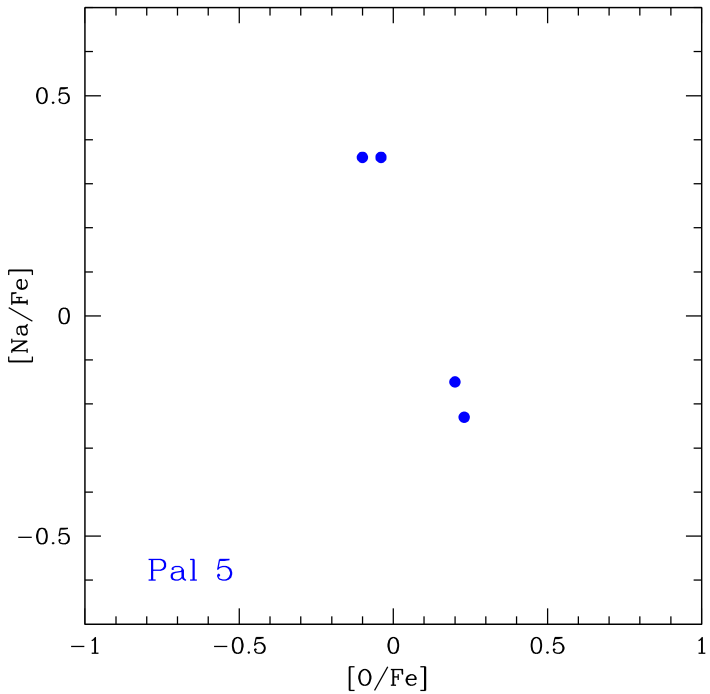


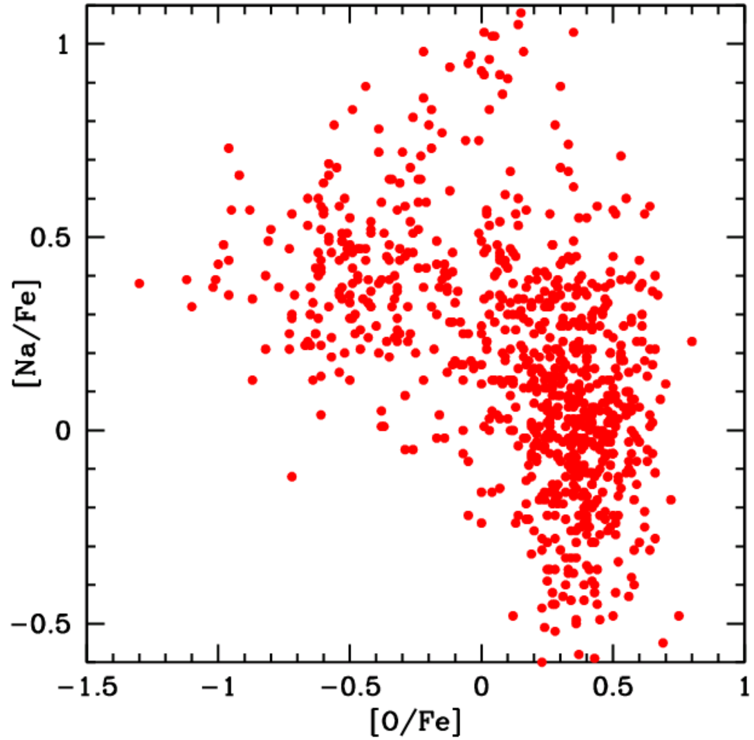




Carretta+2012 **(NGC6752)** ; *Carretta+2013* **(47 Tuc, M4)**

Na & O : do all GCs have anticorrelation ?





Pal 5 *(Smith et al. 2002)*

Mv= -5.17

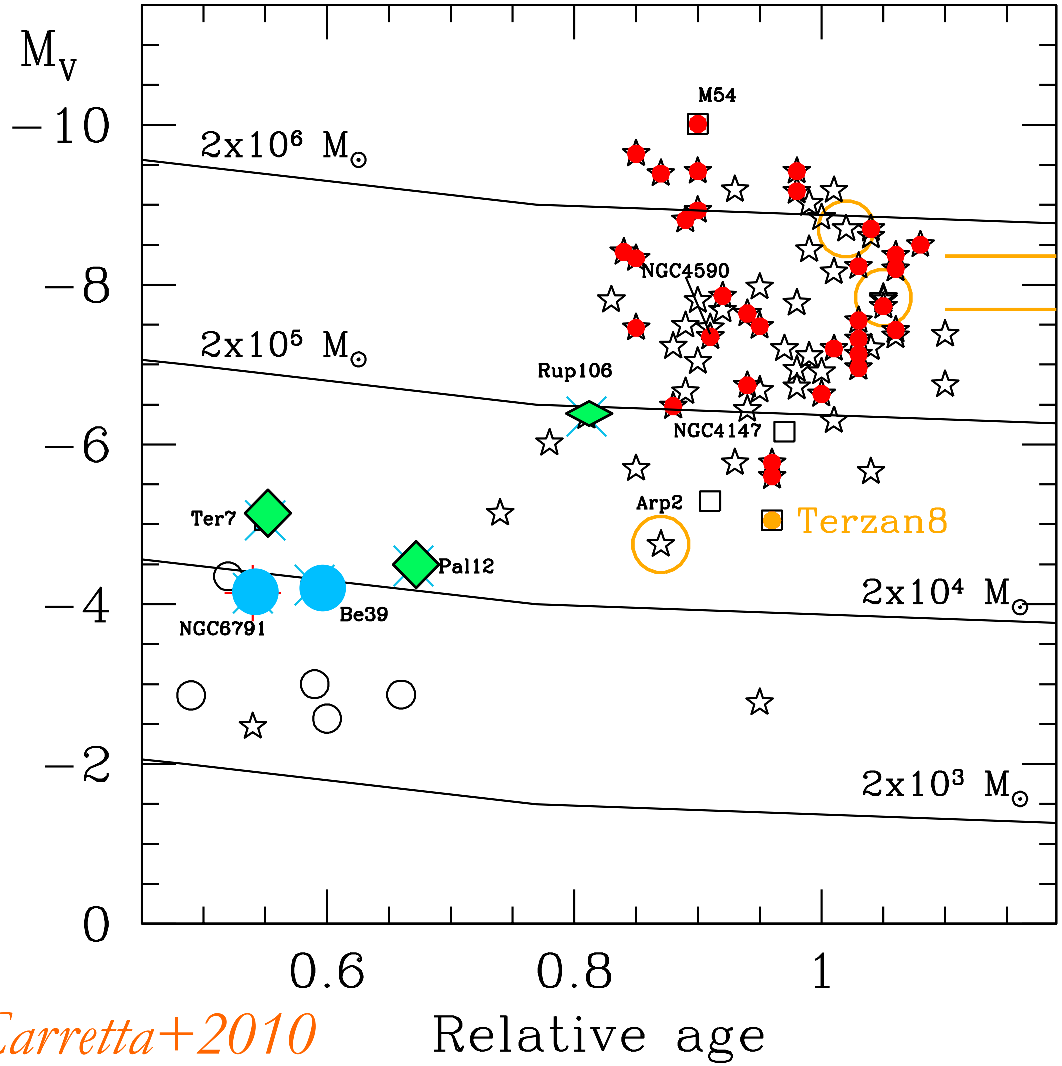
mass ~ 1.5 x 10^4 M⊙

ω Cen *(Johnson & Pilachowski 2010, Marino et al. 2011)*

Mv= -10.29

mass ~ 2.3 x 10^6 M⊙

Na-O anticorrelation = GC ?



Carretta+2010

Always?

Na-O anticorrelation

no data

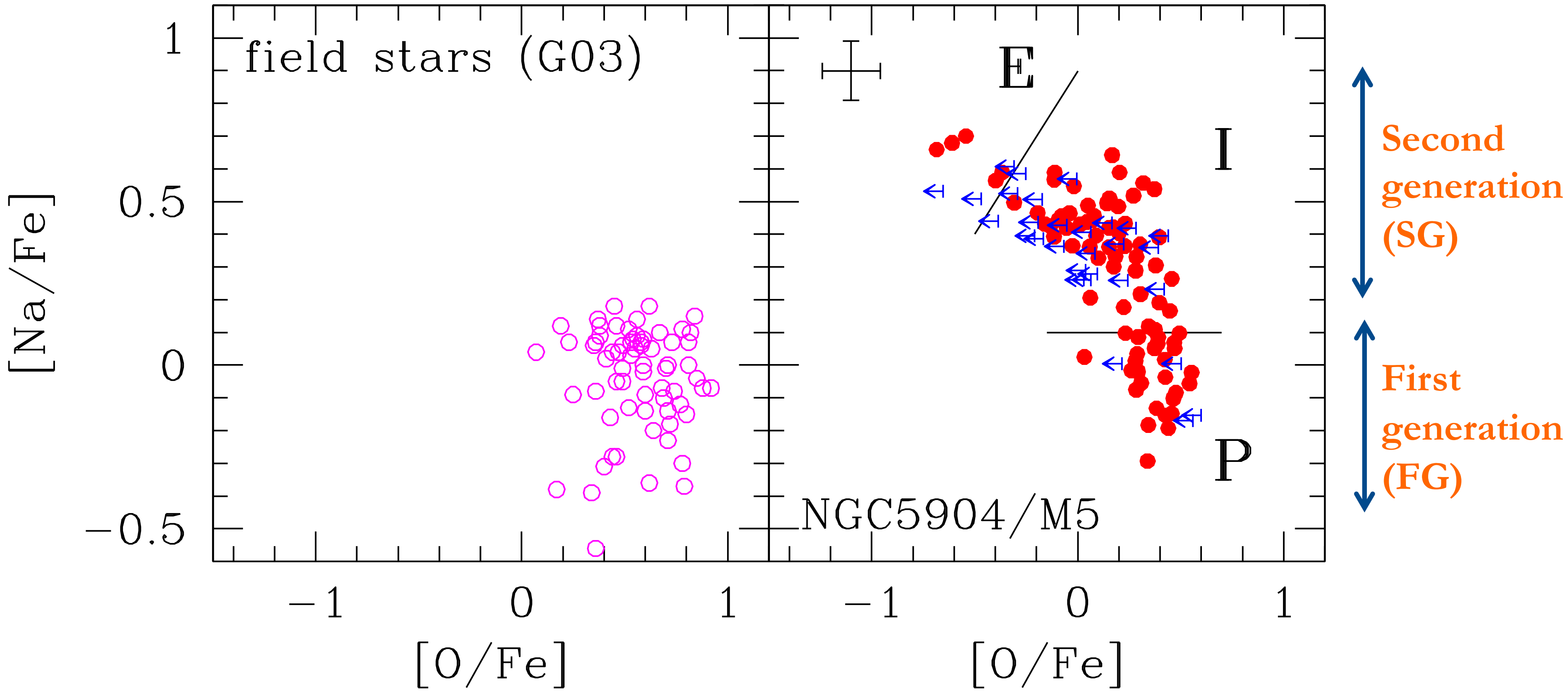
Ter 7, Pal 12 : no?

Rup 106 : no

Be39, NGC 6791 : no

Tautavaisiene+2004,
Sbordone+2007
Cohen 2004
Villanova+2012
Bragaglia+2012
Bragaglia+2014

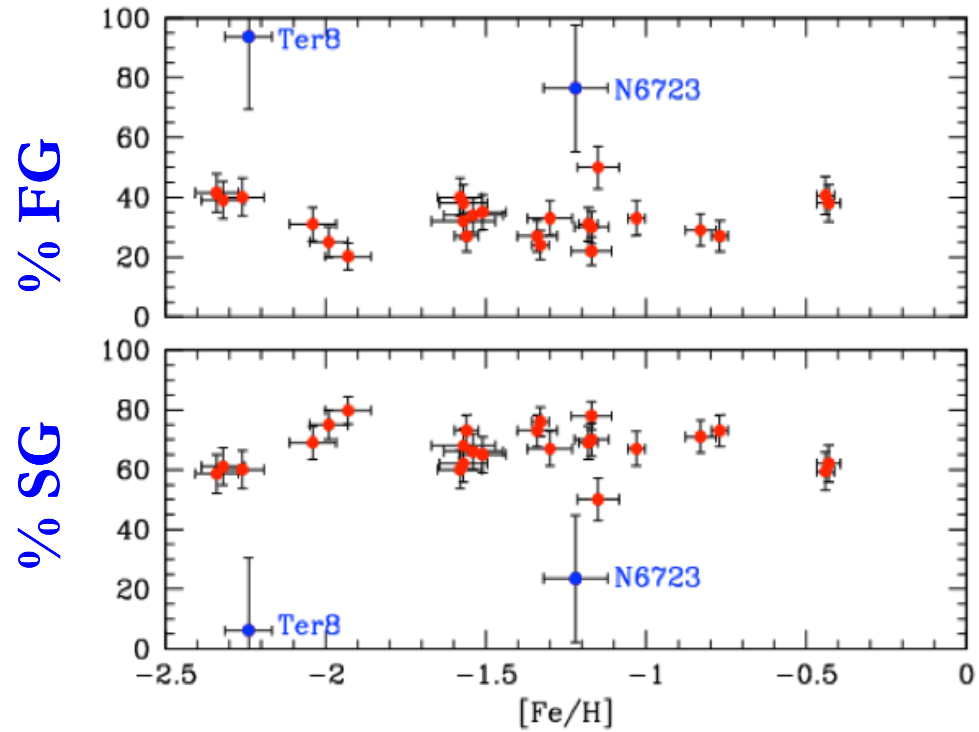
Na & O in GCs ≠ field

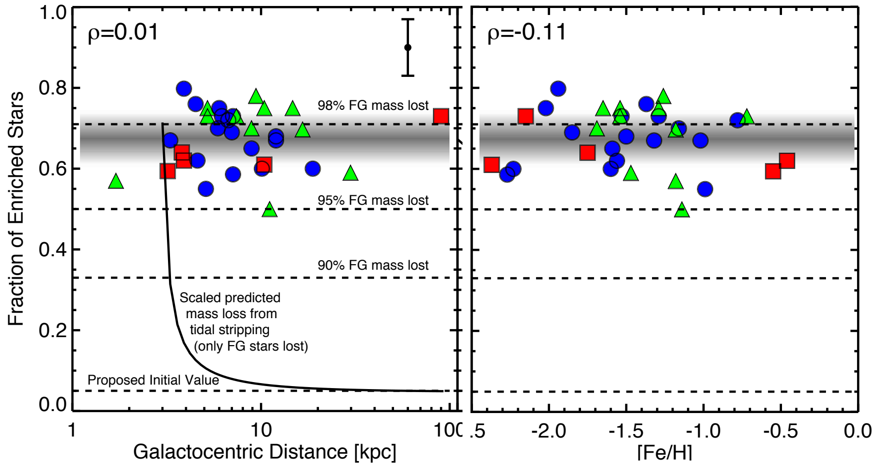


Gratton et al. 2003

Carretta et al. 2009a,b

FG & SG in GCs





FG ~ 1/3 SG ~ 2/3

Carretta+2010

Bastian & Lardo 2015

Present-day mass << original mass?

- if SG formed by ejecta of FG
- only part of original stellar mass in ejecta
- GCs much more massive to have now 2/3 SG stars
- and/or very different IMF in FG
- they've lost most of their mass/stars (>90%)
- mostly of FG

  ➔ halo MAY contain 6-20 % of GC stars

only the SG stars are "easy" to find …

GC stars contribution to halo (Carretta IAUS 317)

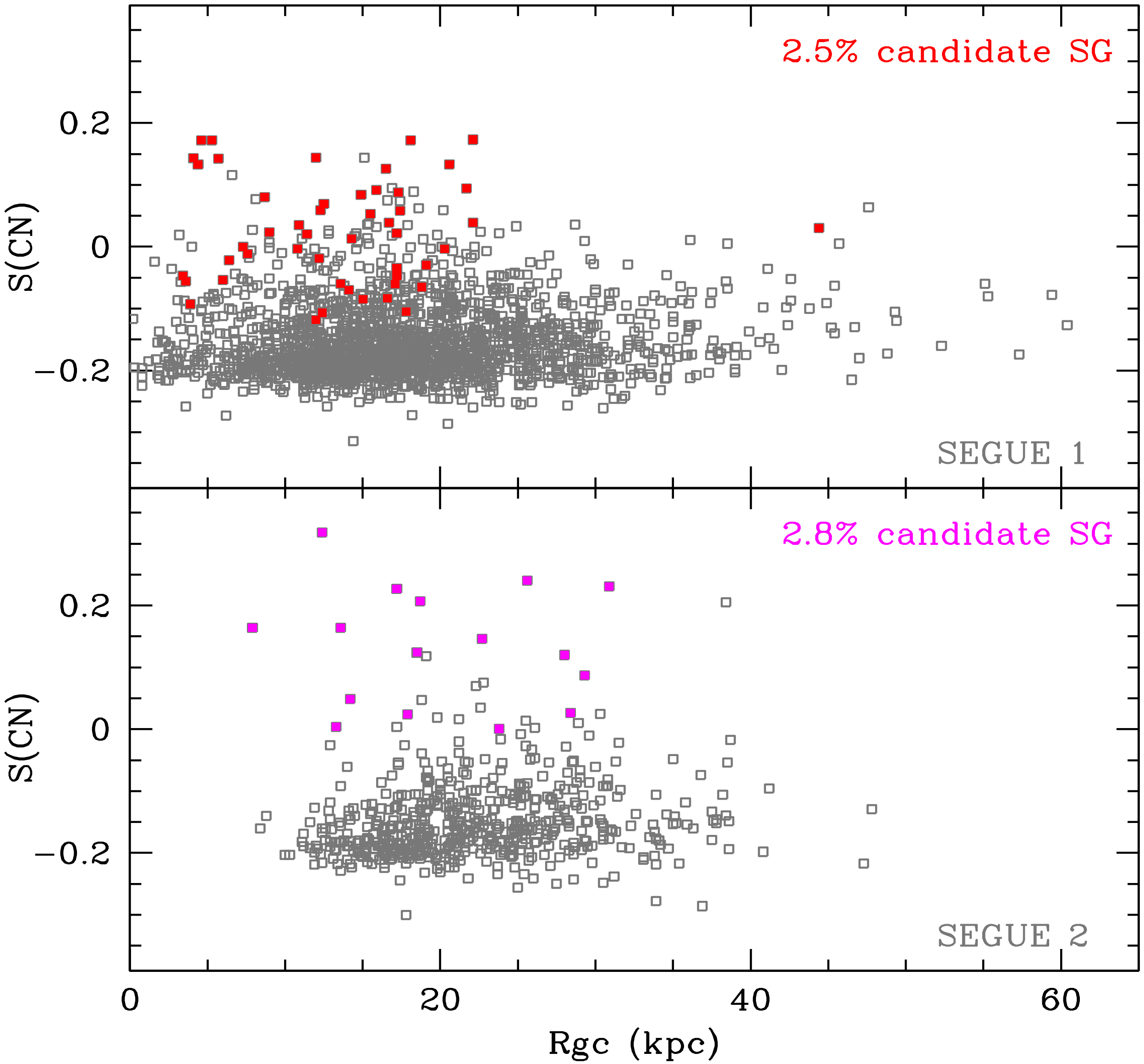
Theo/oss	fraction of SG in halo	and	originally in GCs	if	ref
Hydrodynam. simulations	<4-6% < 7-9%	K93 IMF K01 IMF	20-40% 30-60%	K01 IMF K93 IMF	Vesperini+2010
FRMS model	2.5%	FG/SG=0.5	5-8% 10-20%	SG escaped=0 2.5% SG from GC	Schaerer & Charbonnel 2011
Na max	1.4% 2.8%	FG/SG=0.5	~25% ~13%	Juric+2008 norm. Morrison 1993 norm.	Carretta+2010
CN-strong	2.85%	FG/SG=0.5	~17.5% ~50%	Low mass stars Full mass spectrum	Martell+2011
O-poor/Na-rich st.	3±2% 1.5±1.5%	If G53-41 binary			Ramirez+2012
Na,CN excesses	2.5%	FG/SG=0.5	5%	1.2% halo mass still in GCs	Gratton+2012
Na,CN excesses	2.5%	FG/SG=0.5	50%	Initial GC 10x larger	Gratton+2012

C & N in the field : SG-like stars ?

focused discovery

SEGUE 1
49 CN-strong over 1957

SEGUE 2
16 CN-strong over 561



Martell & Grebel 2010
Martell+ 2011

FLAMES GC Survey: SG-like stars ?

serendipitous discovery

● [Na/Fe]min

in GCs

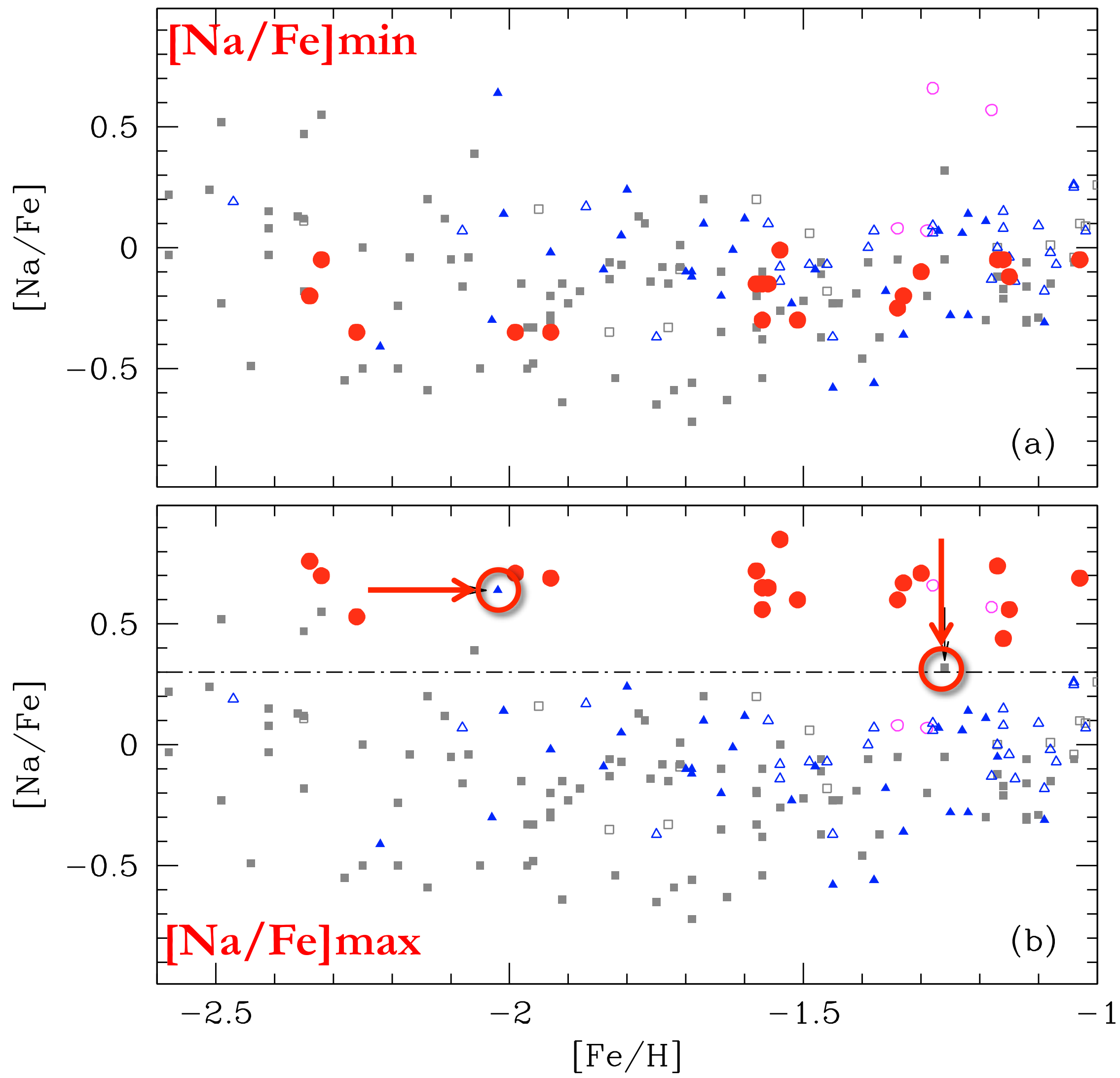
● [Na/Fe]max

2 stars over 144

= 1.4% "SG"

➔ 2.8 % (FG+SG)

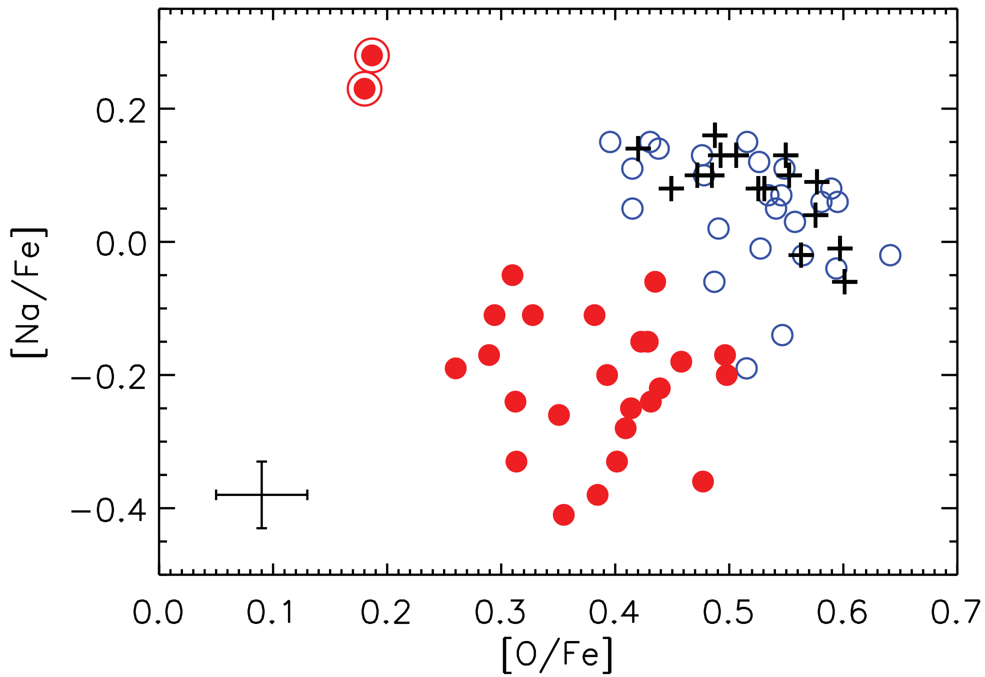
Carretta+2010



Two SG-like stars lost ?

serendipitous discovery

High Na, low O
(also [α /Fe]~0.2 ;
one of the two has
high Ba)

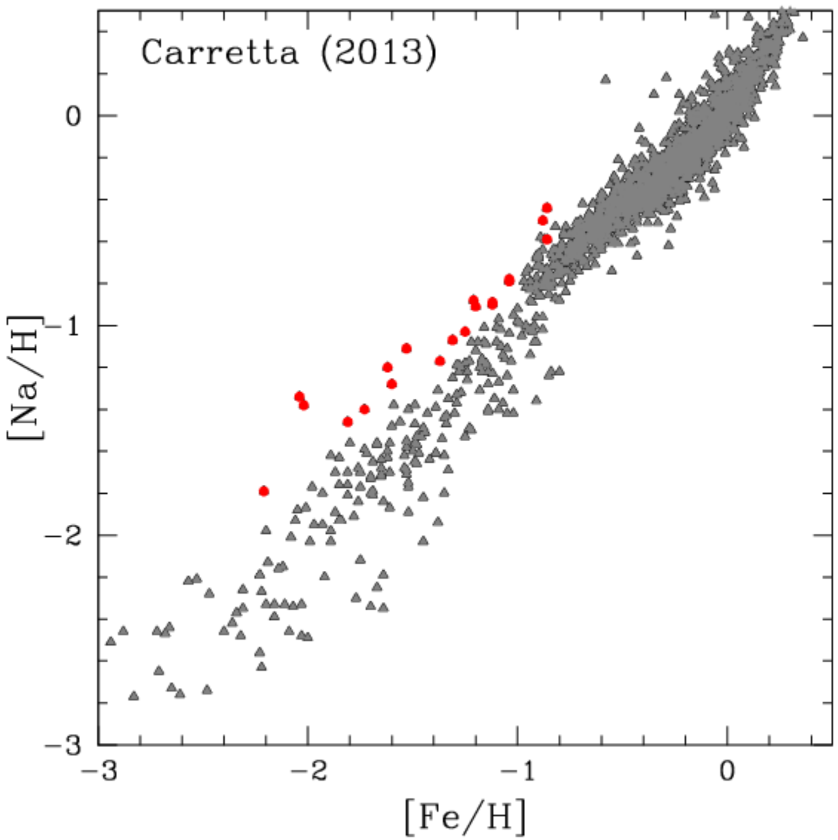


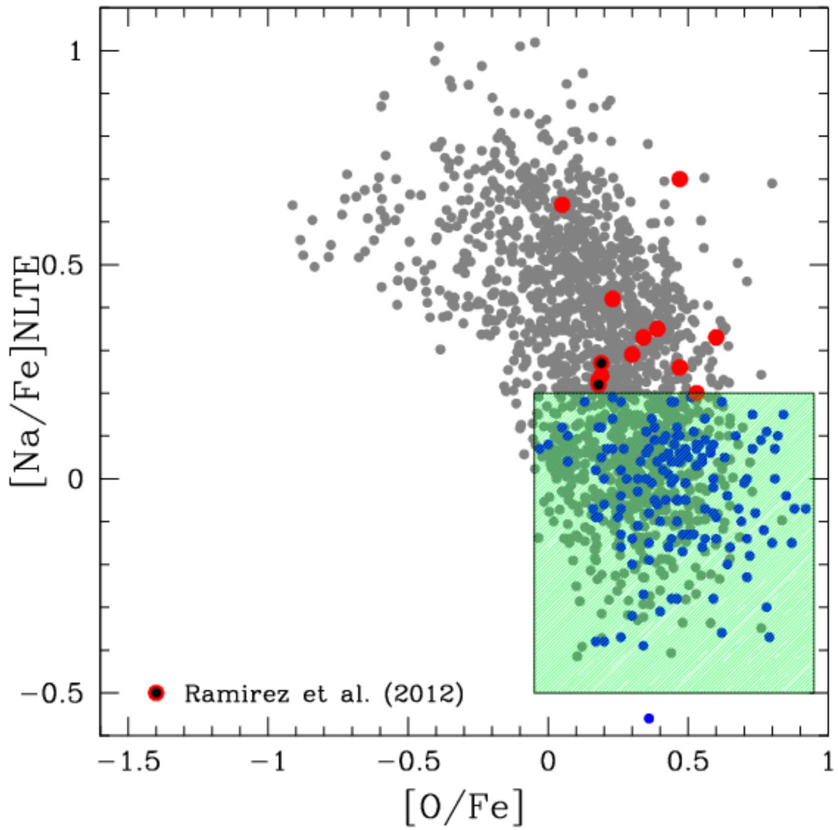
2 stars over 67

"3 ± 2 % of local field metal-poor star population was born in GCs"

Ramirez+ 2012

Many SG-like stars lost ?

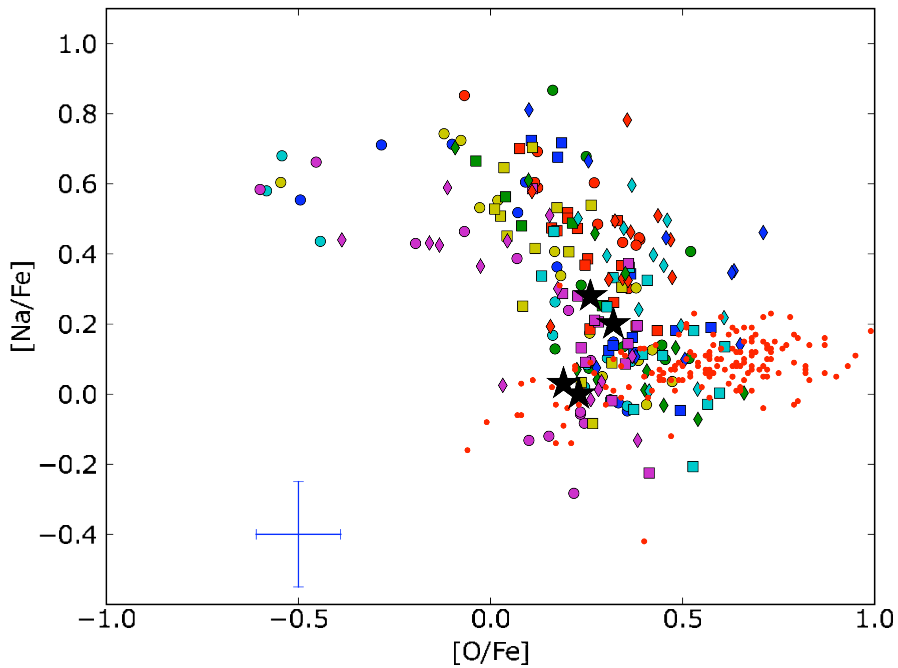




Carretta (2013) : **1891 field stars (-2.3≤[Fe/H]≤ -0.8) with Na, Fe shifted to the same abundance system (Gratton et al. 2003 and FLAMES survey of GCs)**

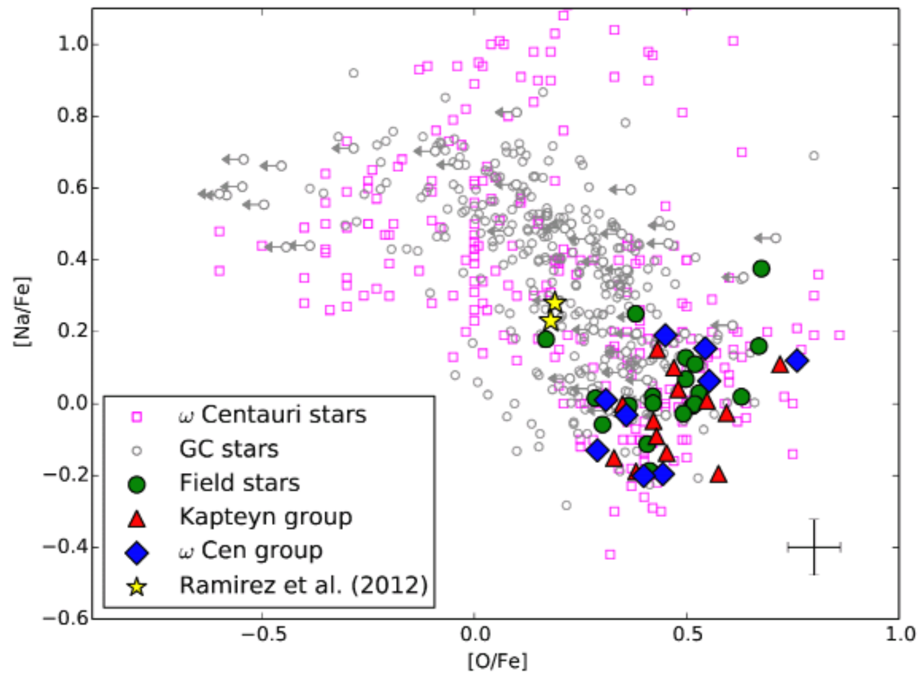
Candidate SG-like : 4.7% (before binarity check)

… use with streams & moving groups

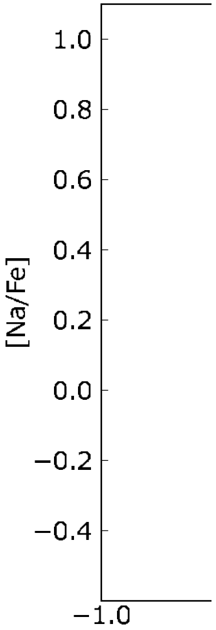


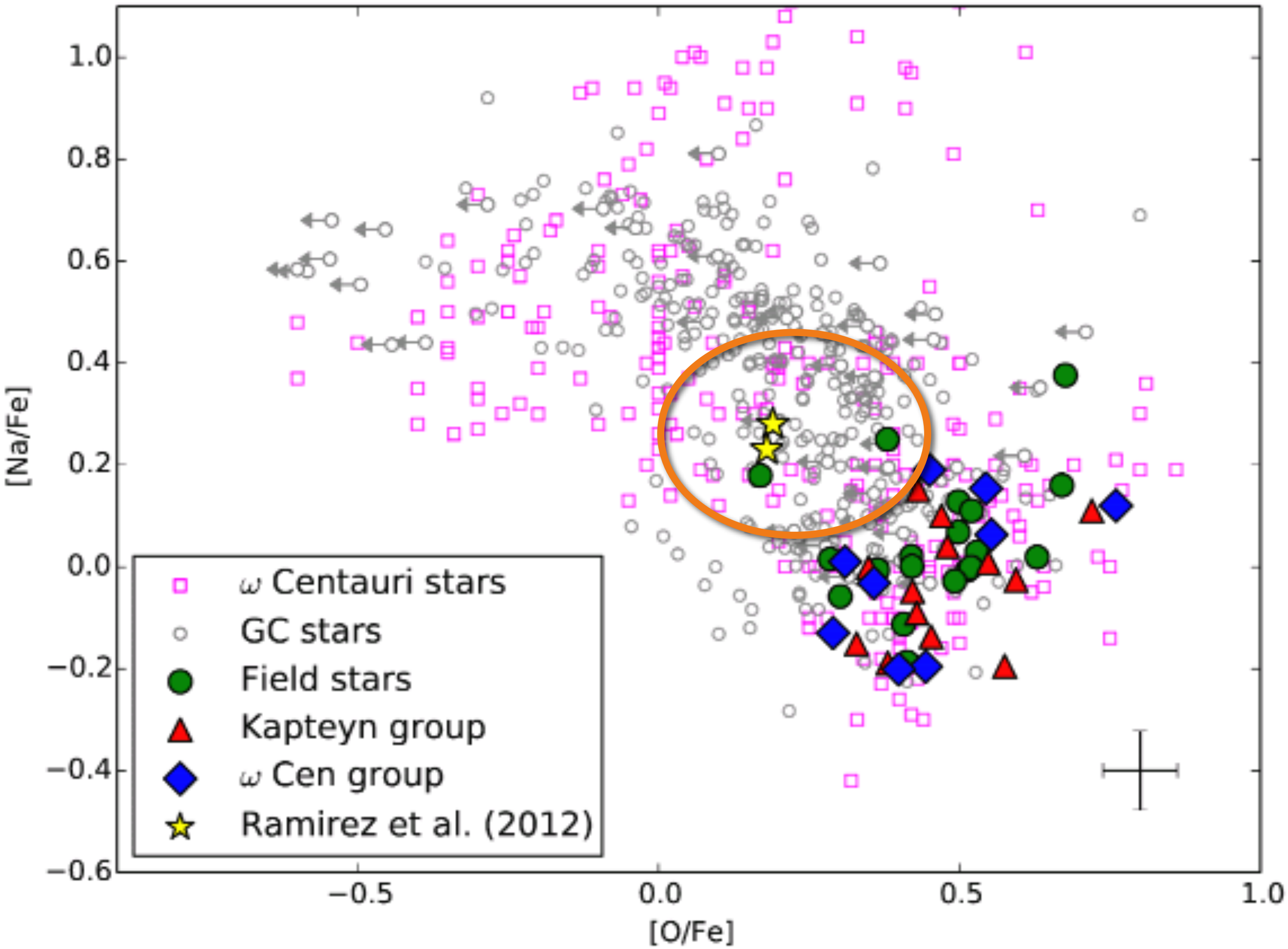
Wylie-de-Boer+2012 **:**
Aquarius stream origin : GC (15 members, from RAVE), 6with high-res spectra ★) ✓

Navarrete+2015 **:**
✓ Kapteyn group ▲
does not come from ω Cen □



… use with streams & moving groups



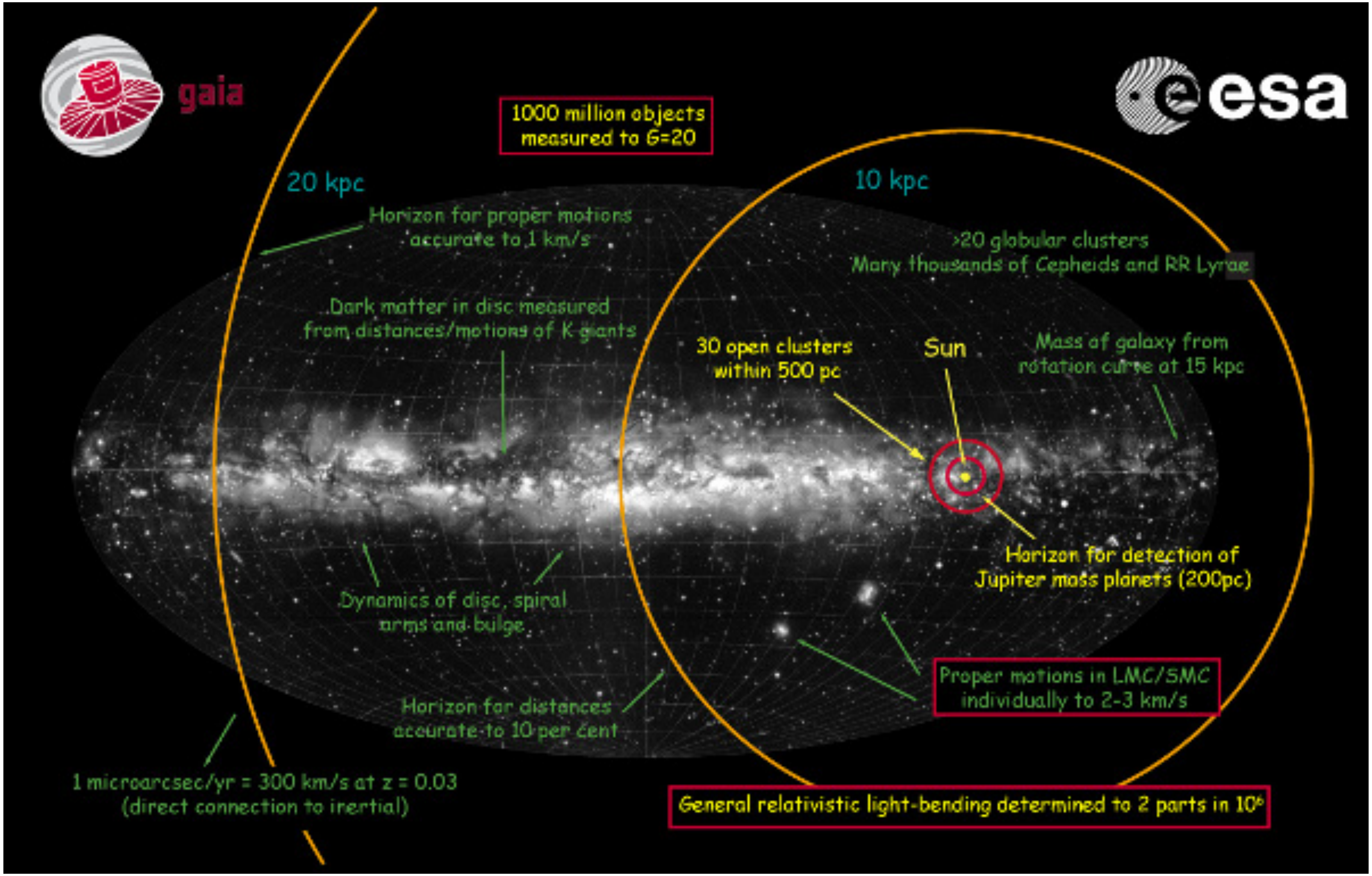


Na

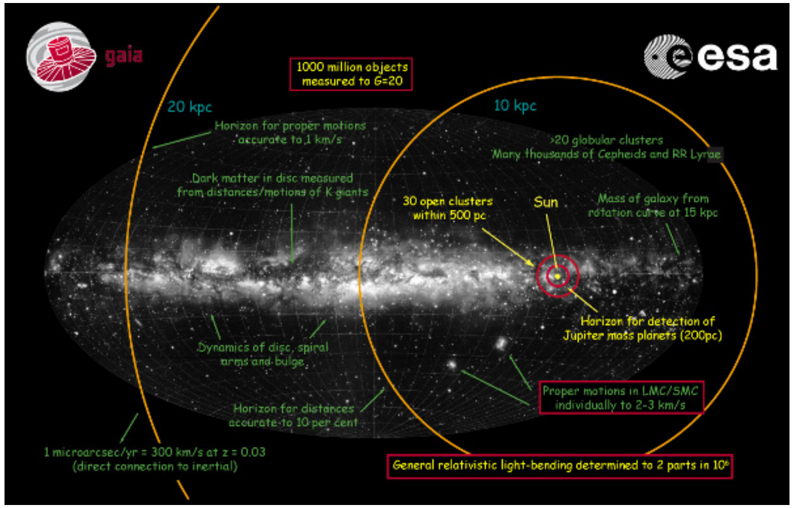
Ka

doe

The era of large surveys



The era of large surveys



GaiaESO

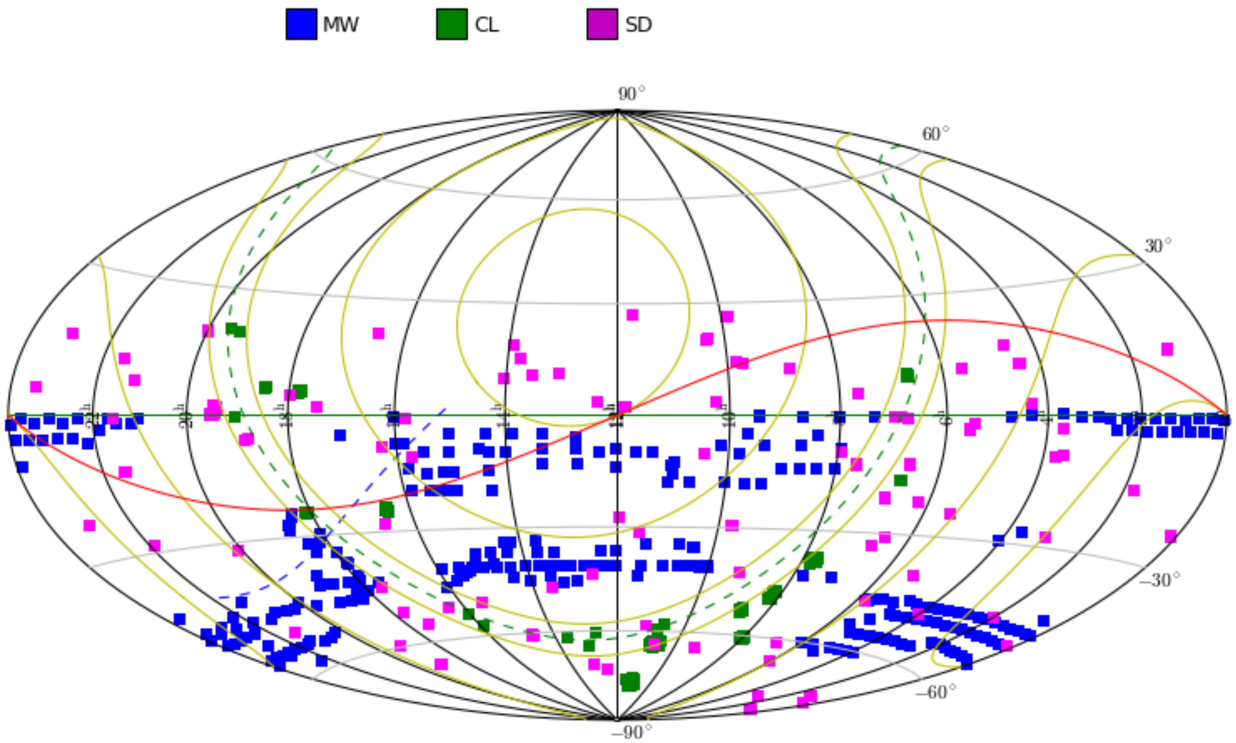
See also :

- RAVE
- APOGEE
- GALAH
- LAMOST

& future :

- WEAVE
- 4MOST

Gaia-ESO Survey in a nutshell



- PI Randich/Gilmore
- 450+ researchers
- 300 VLT nights/5 years
- FLAMES
- 10^5 MW stars
- 70+ open clusters
- STD / GCs
- distributed analysis

For information : http://www.gaia-eso.eu

Gaia-ESO GCs : O & Na

[Fe/H]<-1

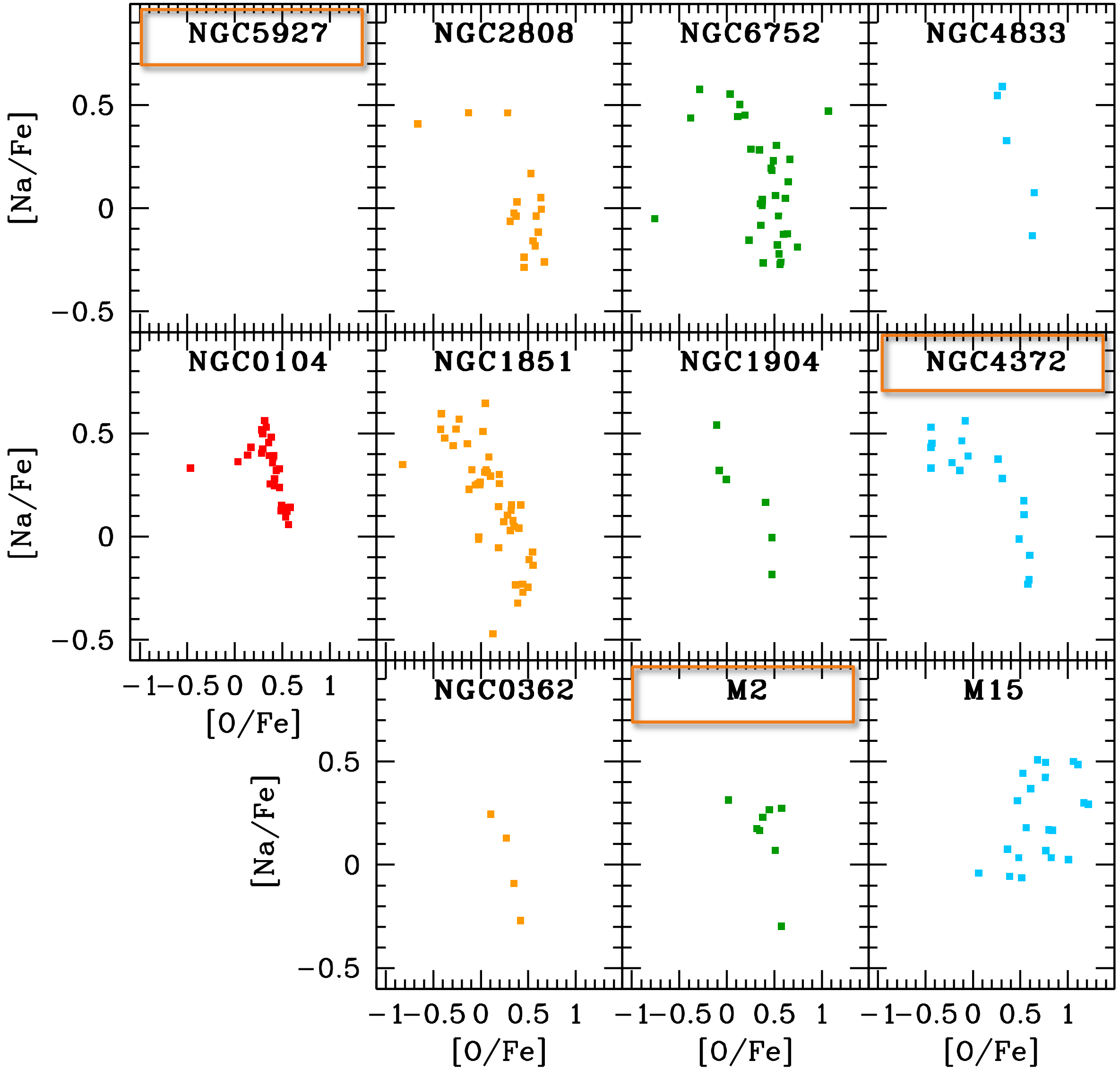
[Fe/H]~-1.2

[Fe/H]~-1.5

[Fe/H]<-2

only UVES

New/scarcely studied



Gaia-ESO GCs: Mg & Al

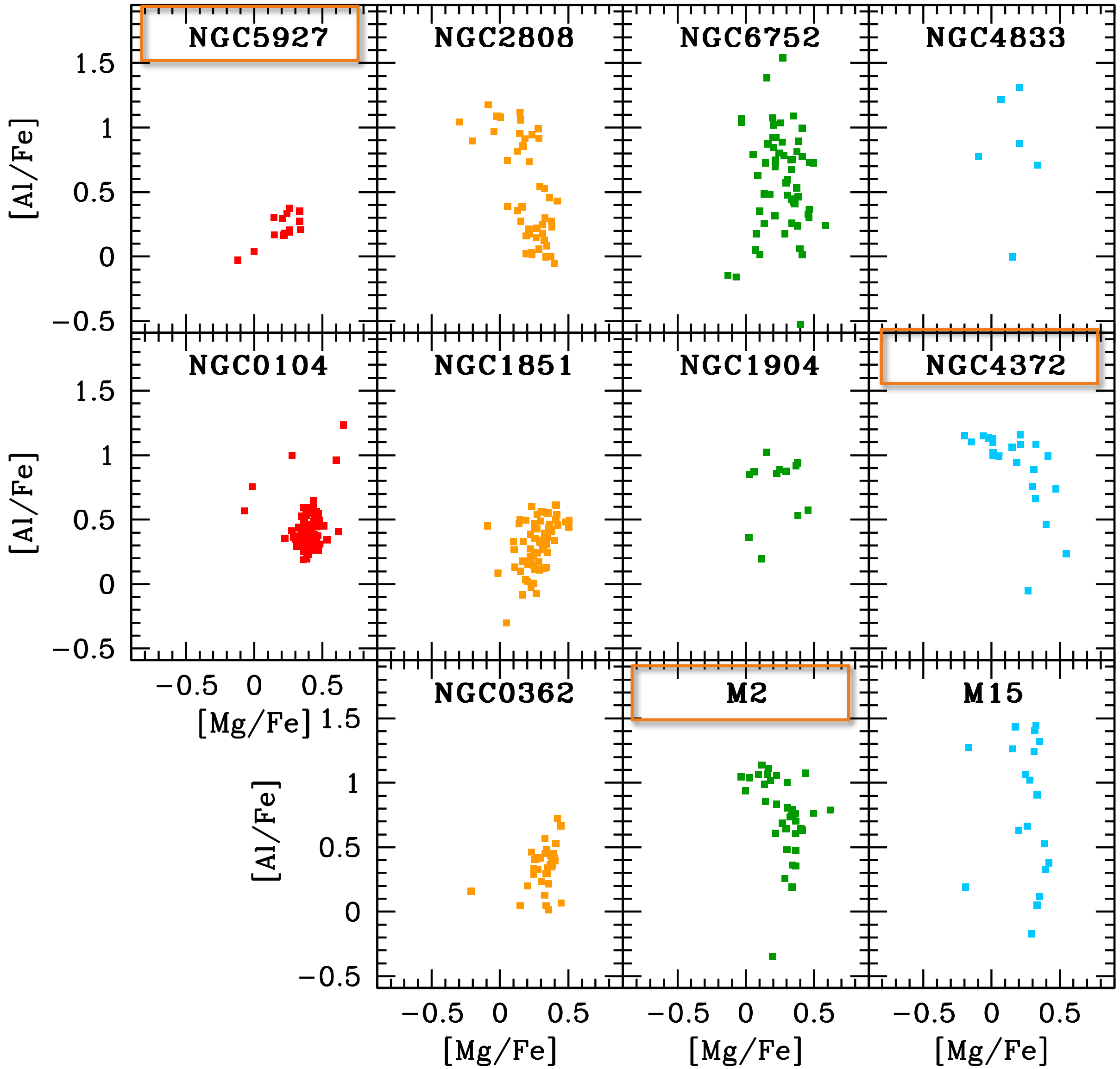
[Fe/H]<-1

[Fe/H]~-1.2

[Fe/H]~-1.5

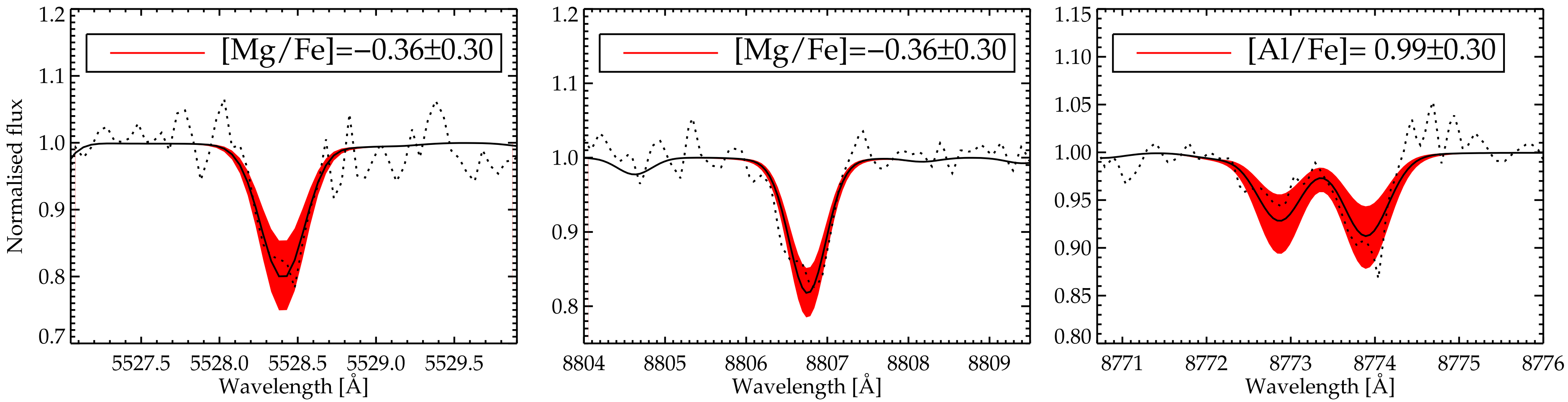
[Fe/H]<-2

New/scarcely studied



Gaia-ESO Survey data

Lind + 2015 : one GC escapee



22593757-4648029 (1 in 7300 FGK stars)

Teff/logg/[Fe/H]=5260/2.84/-1.49

[Mg/Fe]= -0.36

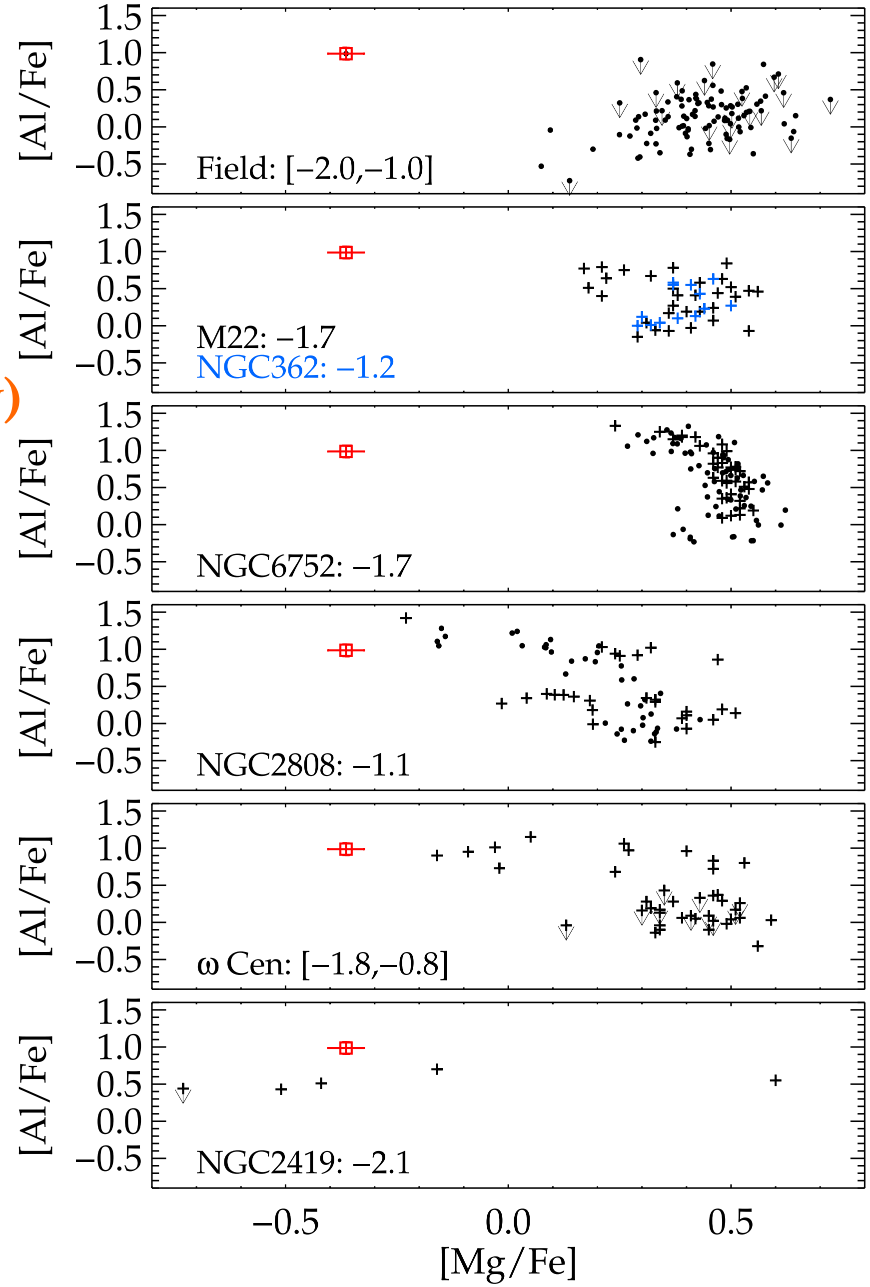
[Al/Fe] =+0.99

Gaia-ESO Survey data

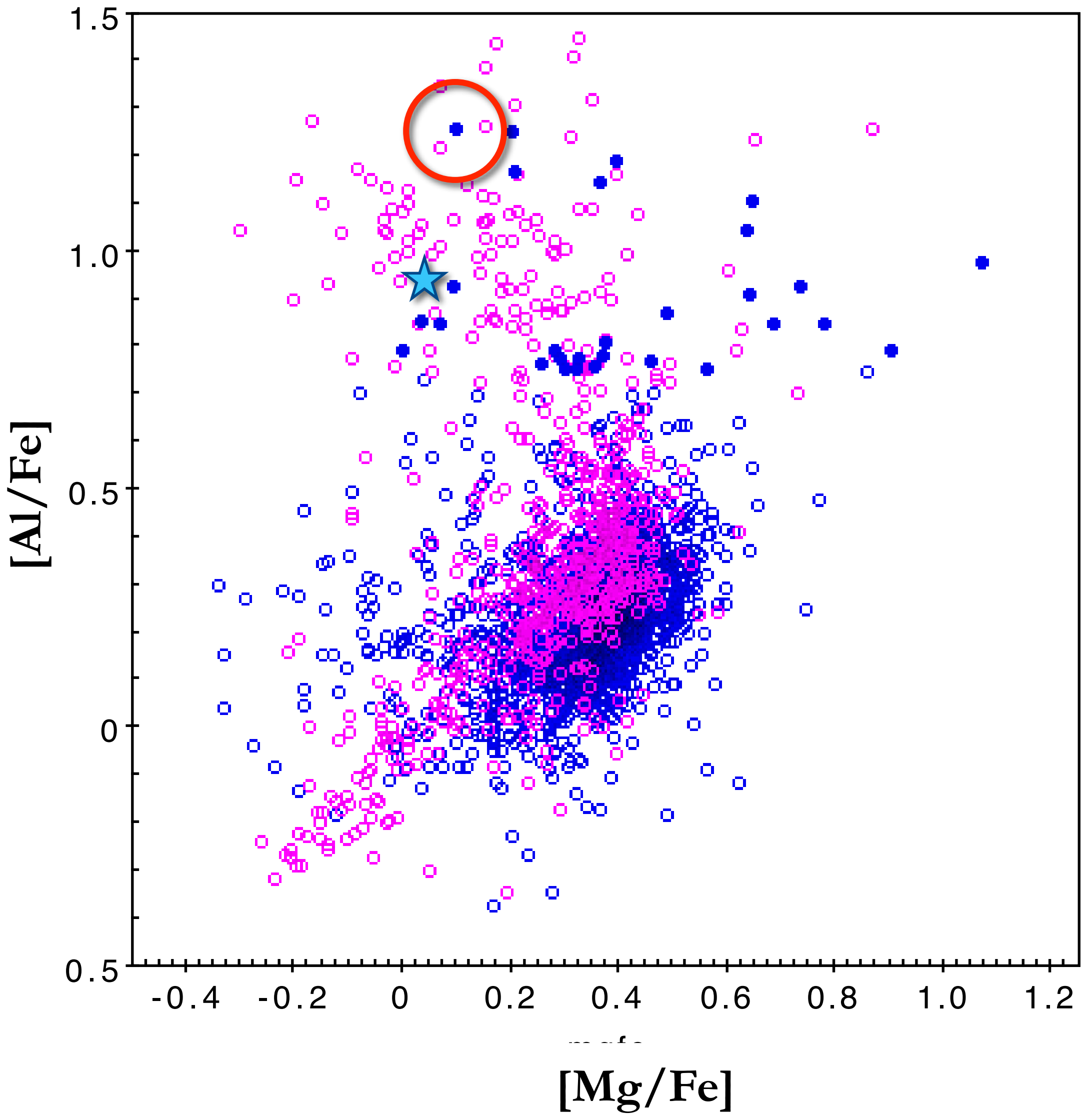
Lind + 2015 : one GC escapee

- Ca,Si,Ti normal for halo (no dSph-like)
- Y normal (no s-enhancement from binary)
- parent GC (if not disrupted) ?
  N2808 too m-rich, N2419 too m-poor
  ω Cen?
- metallicity alone not enough
- orbits star & GCs
- if ejected at high velocity
  ω Cen, M22, N362

need follow up for chemical tagging



Gaia-ESO Survey data



Field stars -2.5<[Fe/H]<-0.5

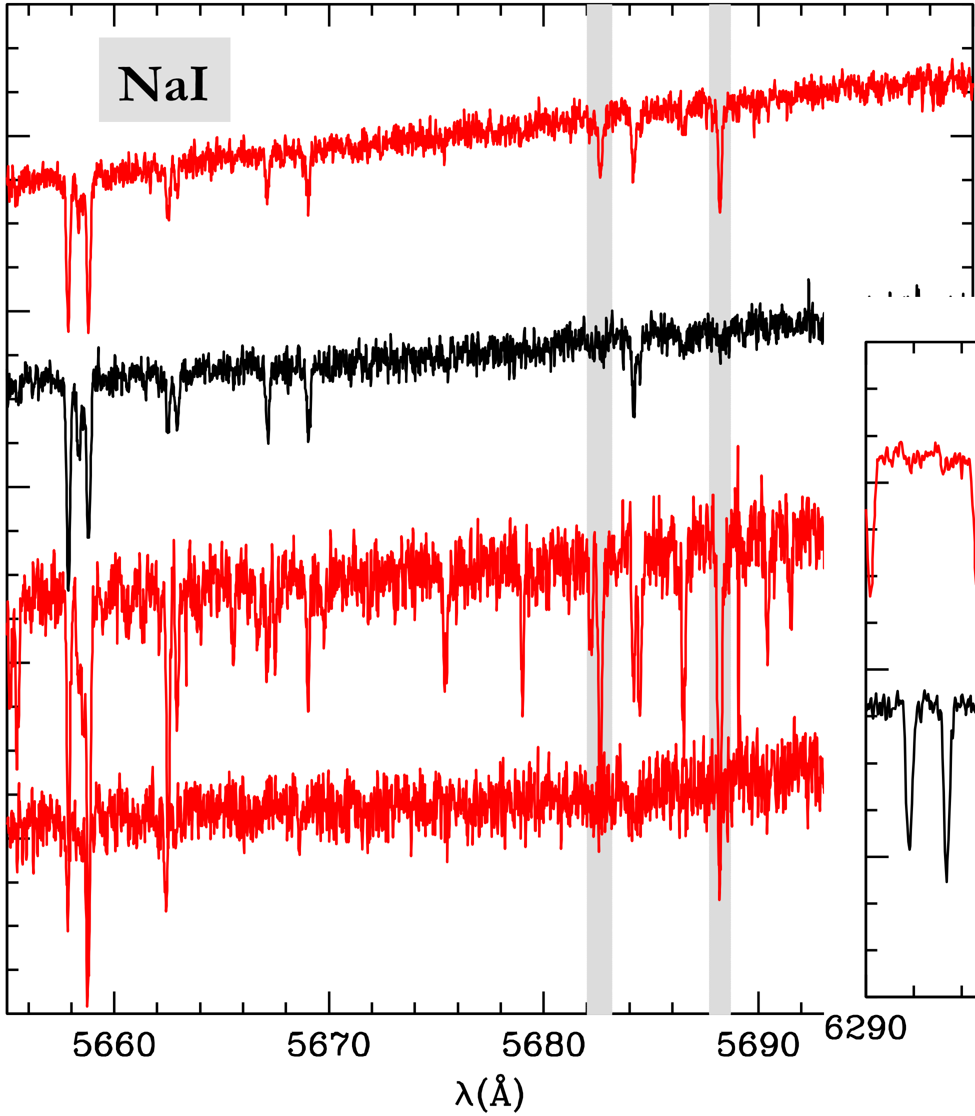
candidates

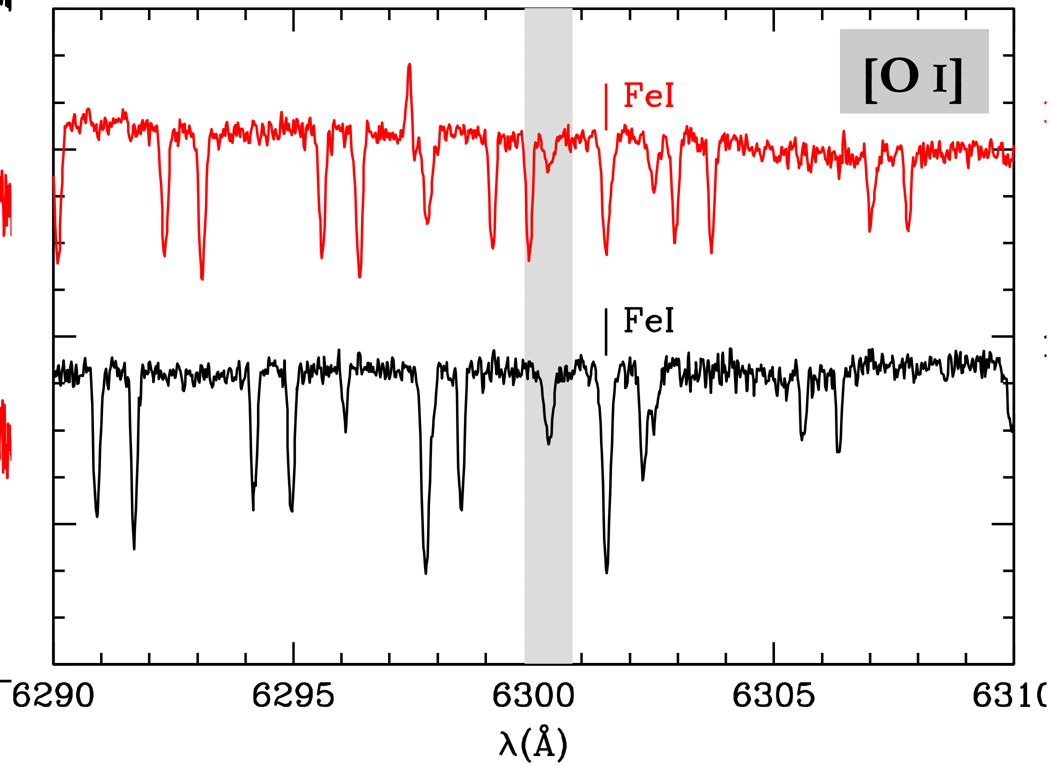
11 GCs

Lind+15

Gaia-ESO Survey data

Candidate selected for Mg-Al looks OK also for O-Na





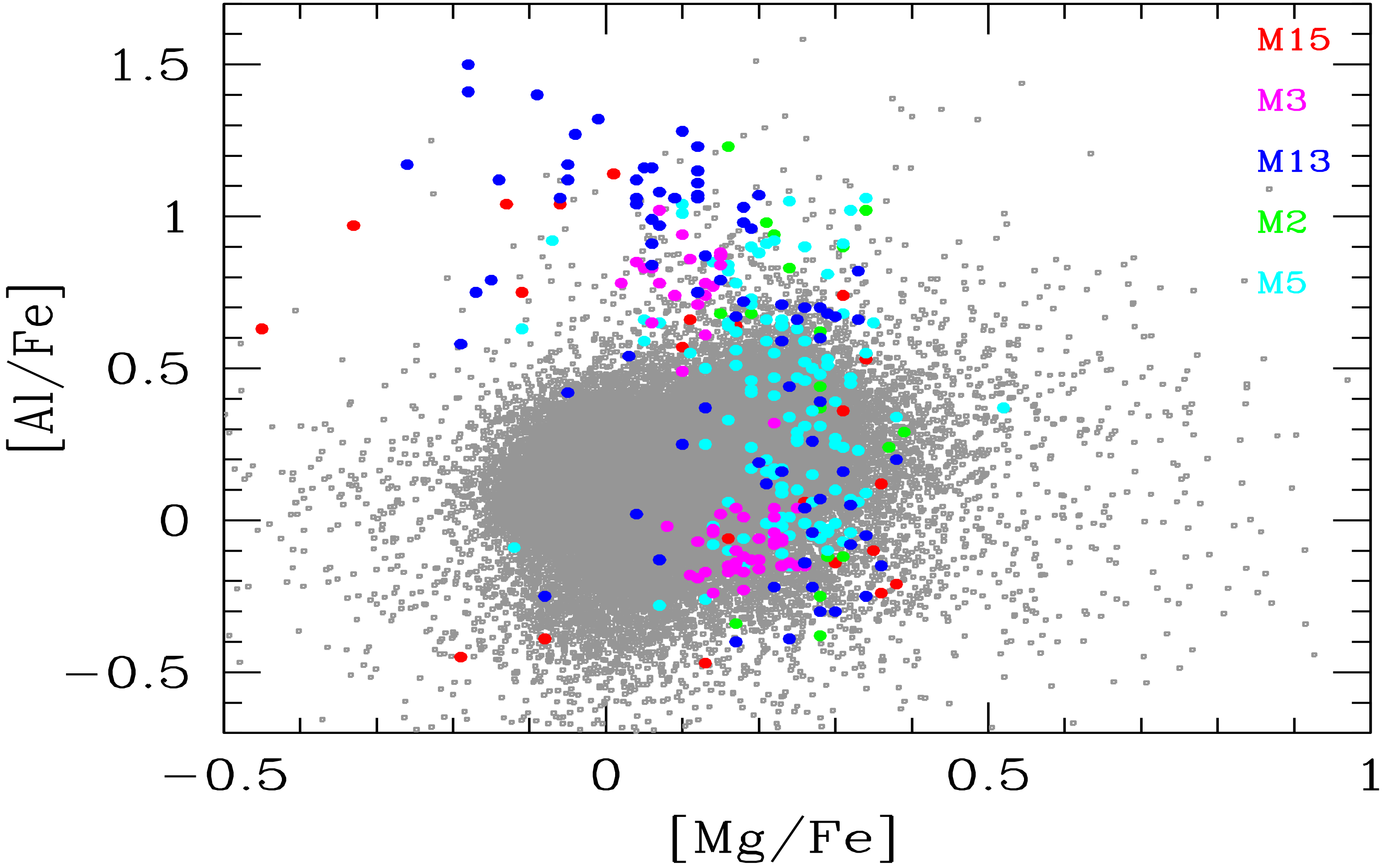
Gaia-ESO Survey data

SG-like field halo star (born in a GC) ?

here is a checklist :

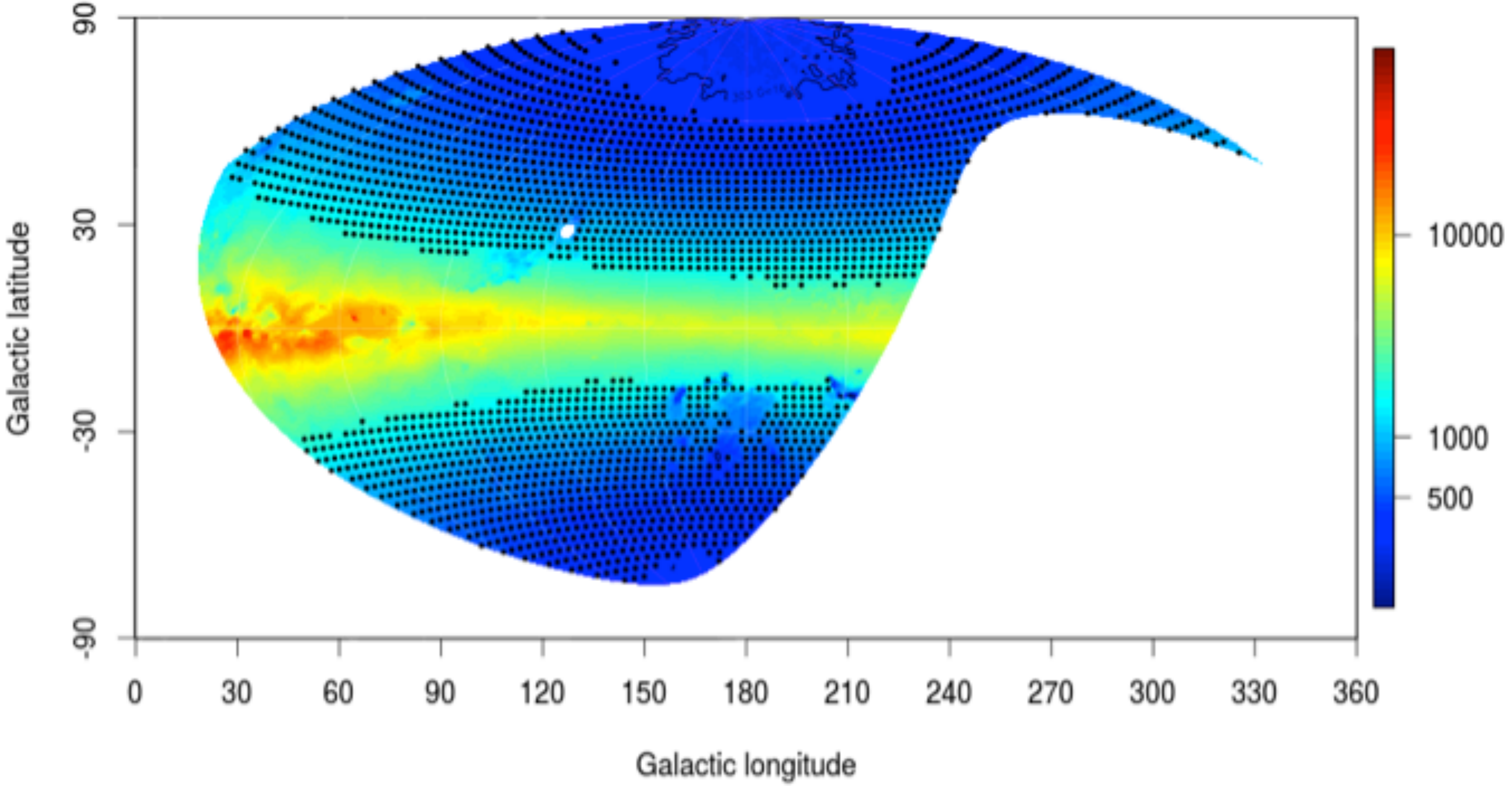
- metallicity -2.5 to -0.5 ? ✓
- low [Mg/Fe] coupled with high [Al/Fe] ✓
- low [O/Fe] coupled with high [Na/Fe] ✓
  (giants/dwarfs : [O I])
- binary ??
  follow-up RV ??
  no high s-process ✓
- orbit ??
  to be done (GES RV, Gaia 5-parameters catalogue 2017)

APOGEE data : SG-like stars?

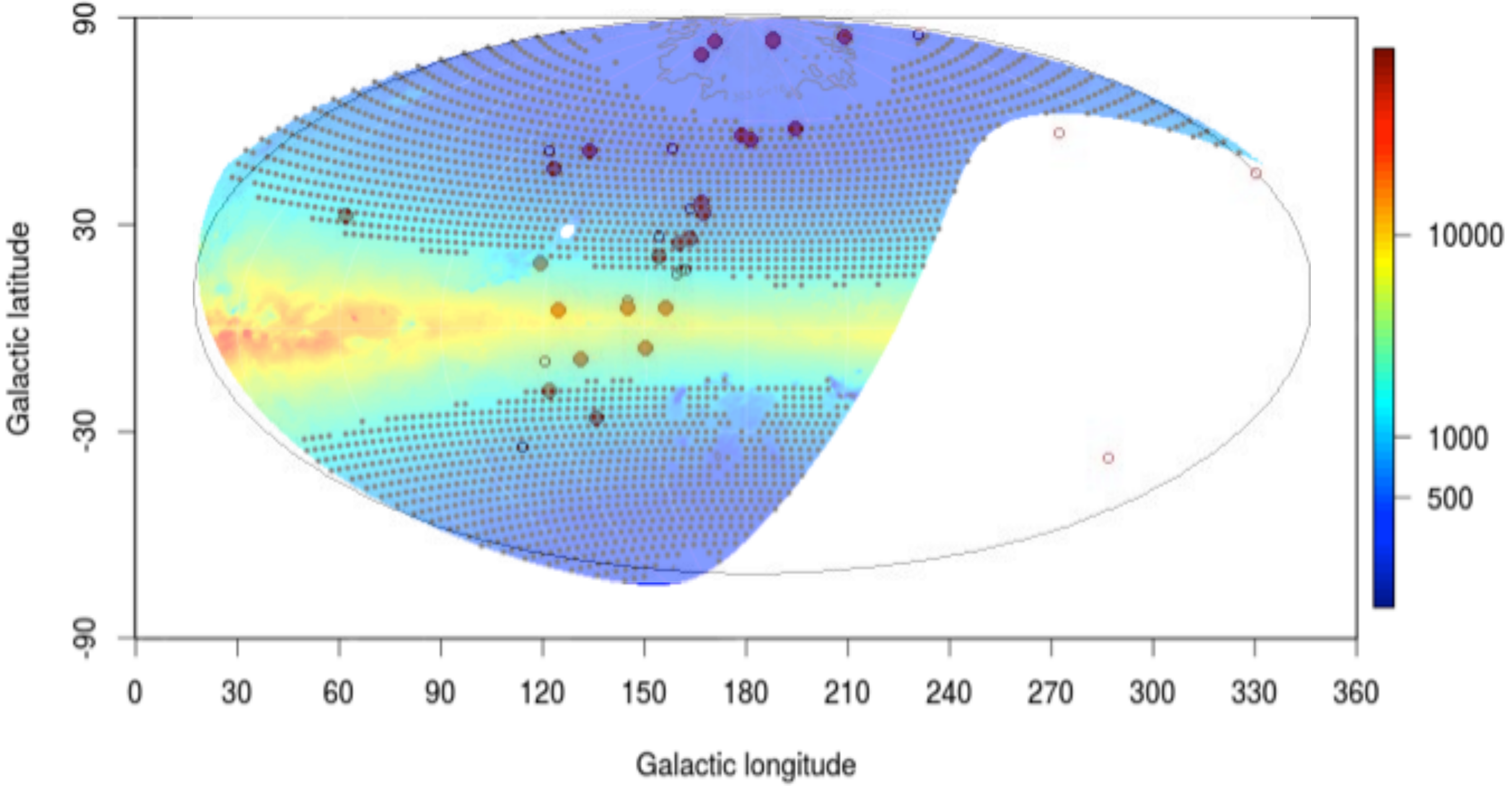


APOGEE DR12 *(allStar-v603)* **&** *Meszaros+2015* **(for GCs)**

WEAVE


Galactic latitude
90
30
-30
-90
0
30
60
90
120
150
180
210
240
270
300
330
360
Galactic longitude
10000
1000
500

WEAVE



90
30
-30
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Galactic latitude
0
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120
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240
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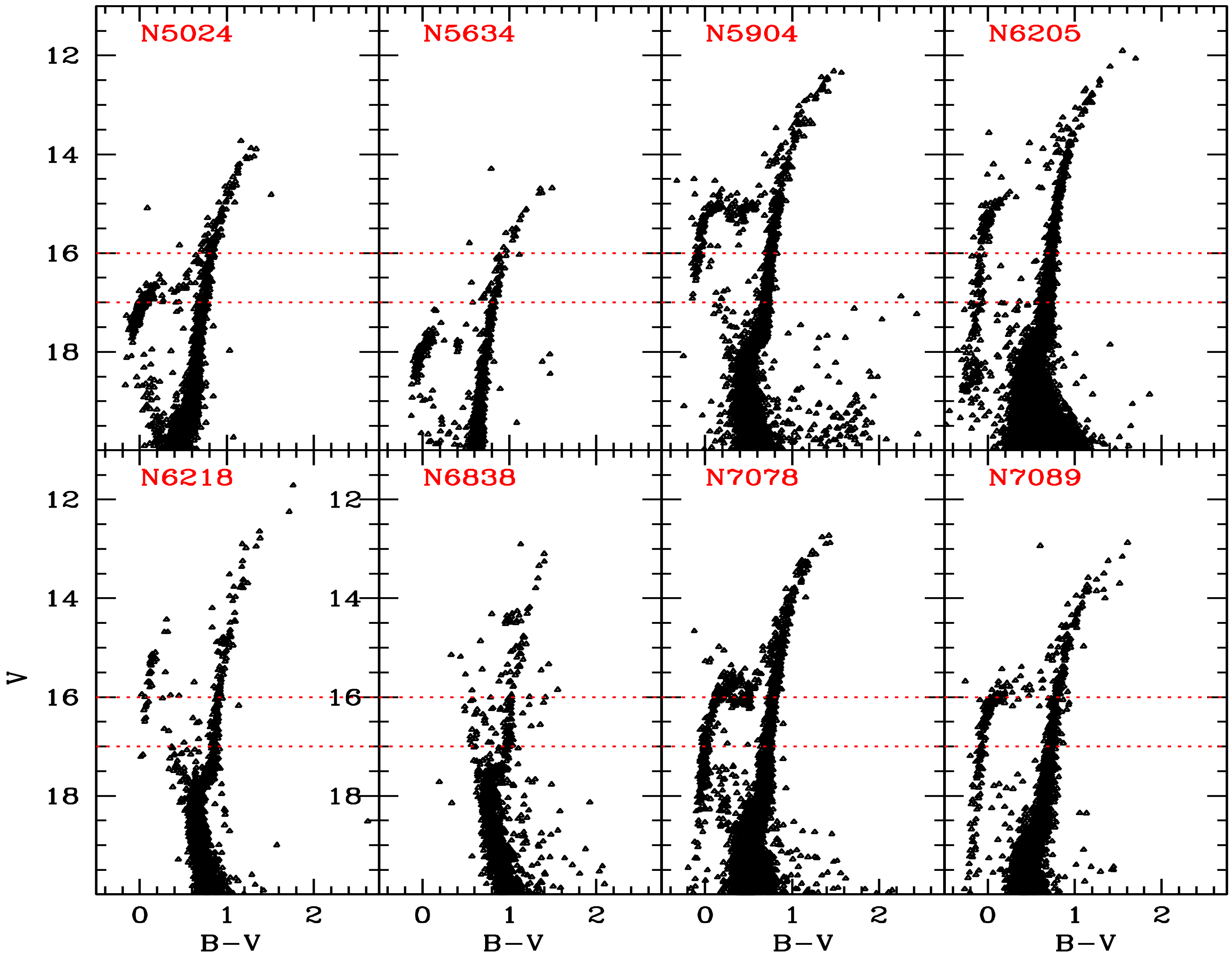
Galactic longitude
10000
1000
500

WEAVE



blue arm:
404 - 465 nm
or
473 - 545 nm
plus
red arm:
595 - 685 nm

LR: 5000
HR: 20000

Summary

- **GCs did contribute (and are presently contributing) stars to the MW halo**
  (formation & destruction mechanisms)

- **We can recover stars lost by GCs via chemical tagging**
  (FG vs SG chemistry)

- **About 3-5% is the minimum (observed) contribution**
  (CN excess, high Na-low O, high Al-low Mg)

- **Mass budget problem: up to 50% of halo comes from GCs???**
  (GCs ~10x more more massive)

(as usual) : more data, improved modeling required