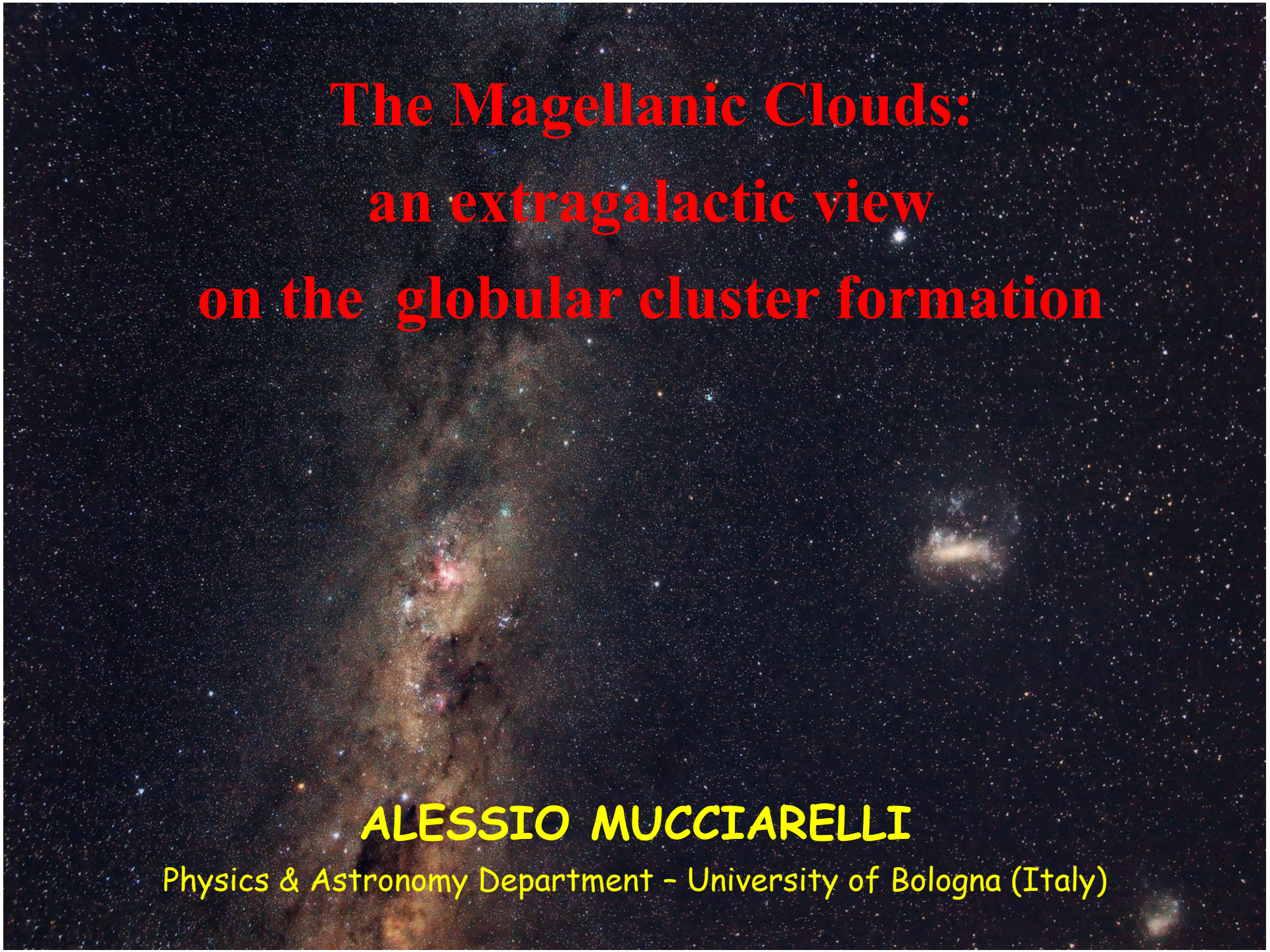


The Magellanic Clouds: an extragalactic view on the globular cluster formation

ALESSIO MUCCIARELLI

Physics & Astronomy Department – University of Bologna (Italy)

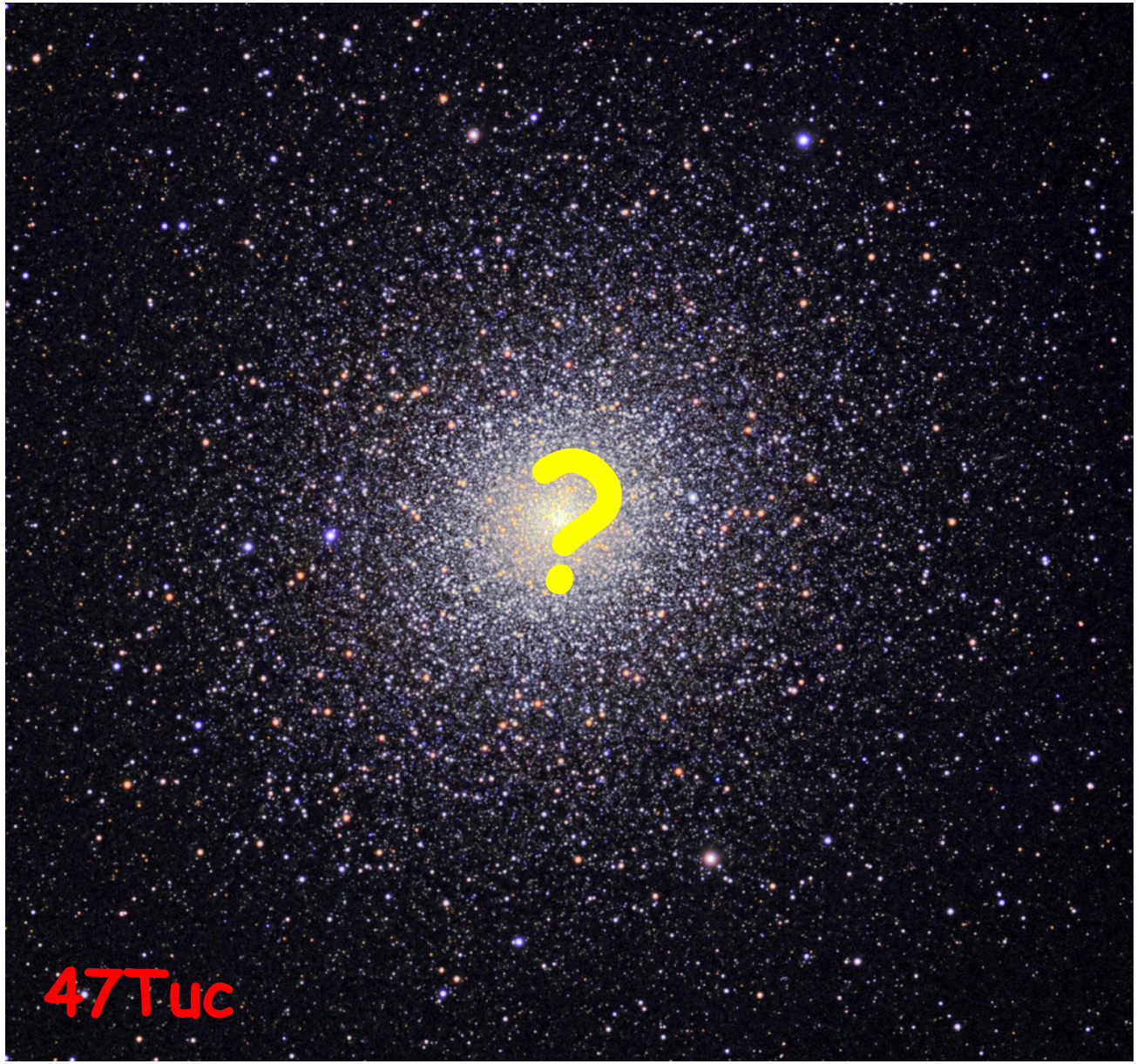
Cosmic-Lab

- 5-year project
- *Advanced Research Grant* funded by the European Research Council (ERC)
- PI: Francesco R. Ferraro (Dip. of Physics & Astronomy – Bologna University)
- AIM: **to understand the complex interplay between dynamics & stellar evolution**
- HOW: using **globular clusters** as cosmic laboratories and

Blue Straggler Stars
Millisecond Pulsars
Intermediate-mass Black Holes

} as probe-particles

Globular Clusters as Simple Stellar Populations



Globular Clusters as Simple Stellar Populations

Simple Stellar Population (SSP)

- single stars (no binaries)
- same age (only one formation burst)
- same initial chemical composition

GCs are useful tools to study

- Stellar evolution
- Chemical enrichment history of the parent galaxy
- Unresolved Stellar Populations

.....

Globular Clusters as Simple Stellar Populations

GOLDEN RULE

Genuine GCs are homogeneous in their Fe content
(and Fe-peak elements)

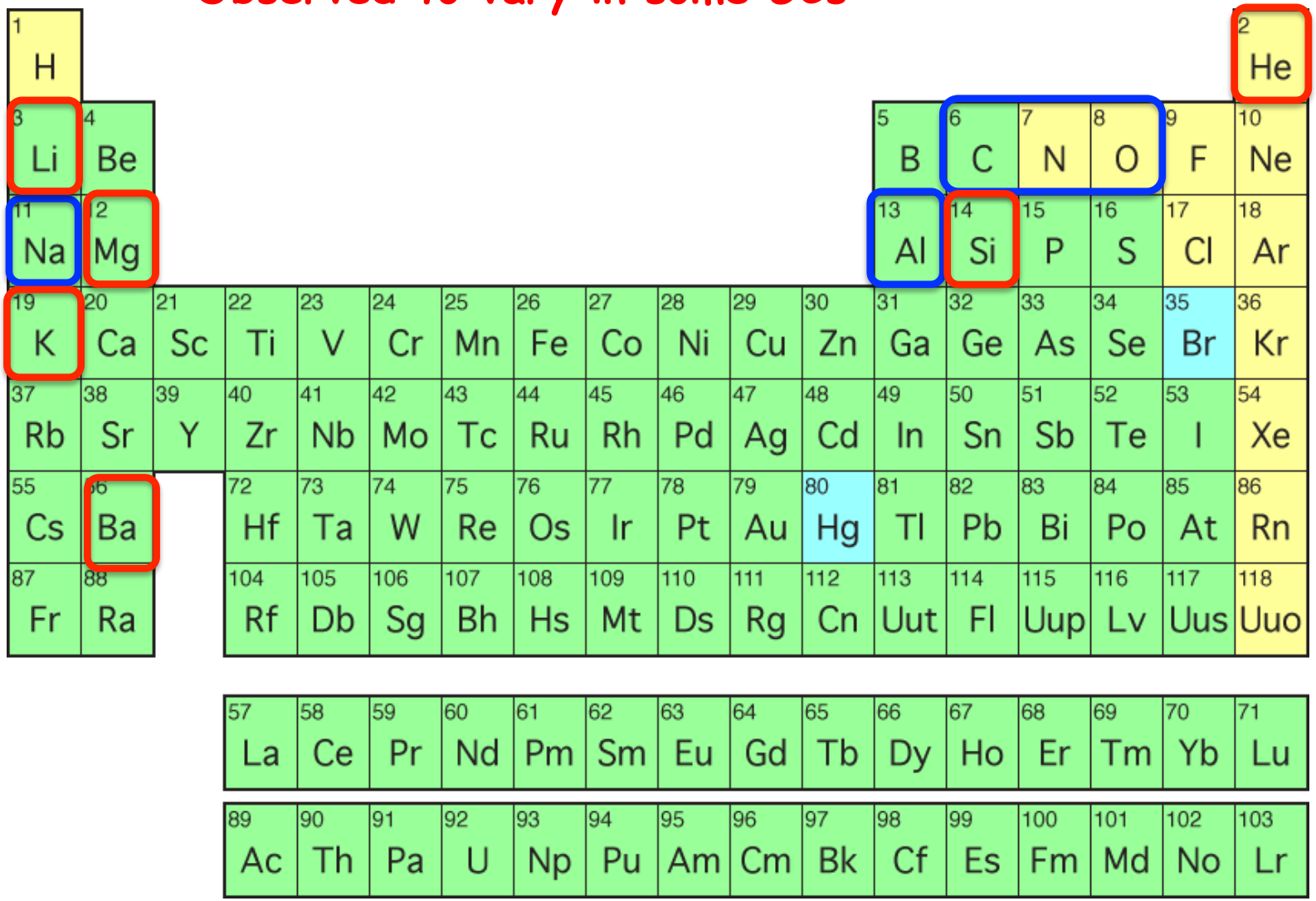
Fe produced by SN II + SN Ia

Fe spread → The system is able to retain the SNe ejecta

Genuine GCs → These systems did not retain the SNe ejecta

Observed to vary in all GCs

Observed to vary in some GCs

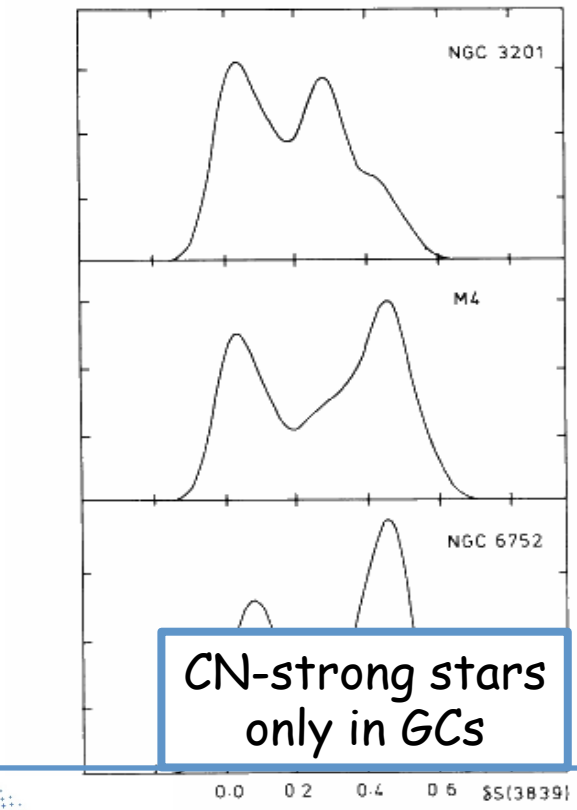


Light elements (C, N, O, Na, Al)

Low-res spectroscopy

CN bimodality
CN-CH anticorrelation

Smith & Norris 1982



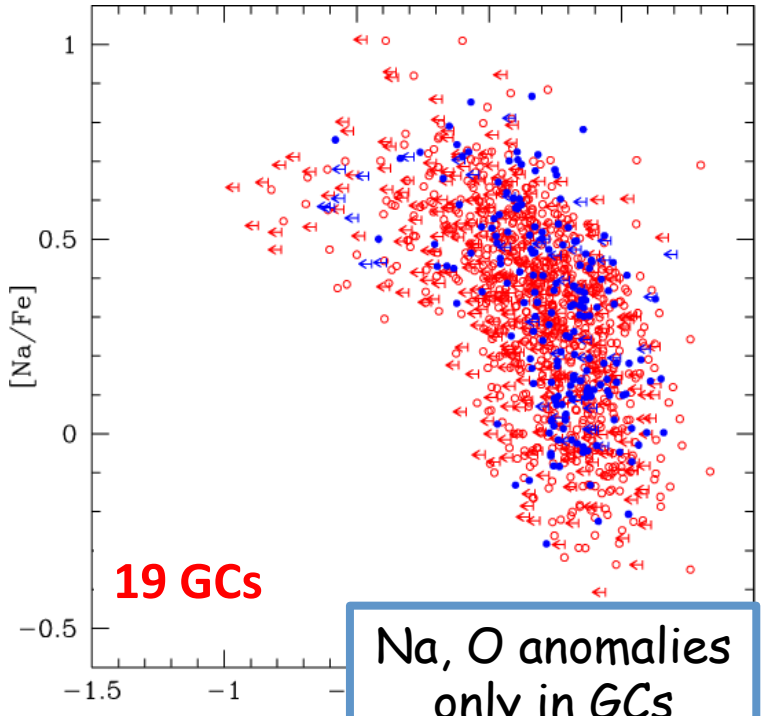
CN-strong stars only in GCs

CN

High-res spectroscopy

CN-Na/Al correlation
CN-O correlation
Na-O anticorrelation
Mg-Al anticorrelation

Carretta+09



Na, O anomalies only in GCs

A general framework for GCs chemical anomalies

- CN-CH anticorrelation
- CN bimodality
- NaO anticorrelation
- MgAl anticorrelation

Signatures of hot **H-burning** CNO, NeNa and MgAl chains

Several models (and open issues)

D'Ercole+08, Decressin+10, Bekki+11, Conroy & Spergel+11, Valcarce & Catelan+11 …

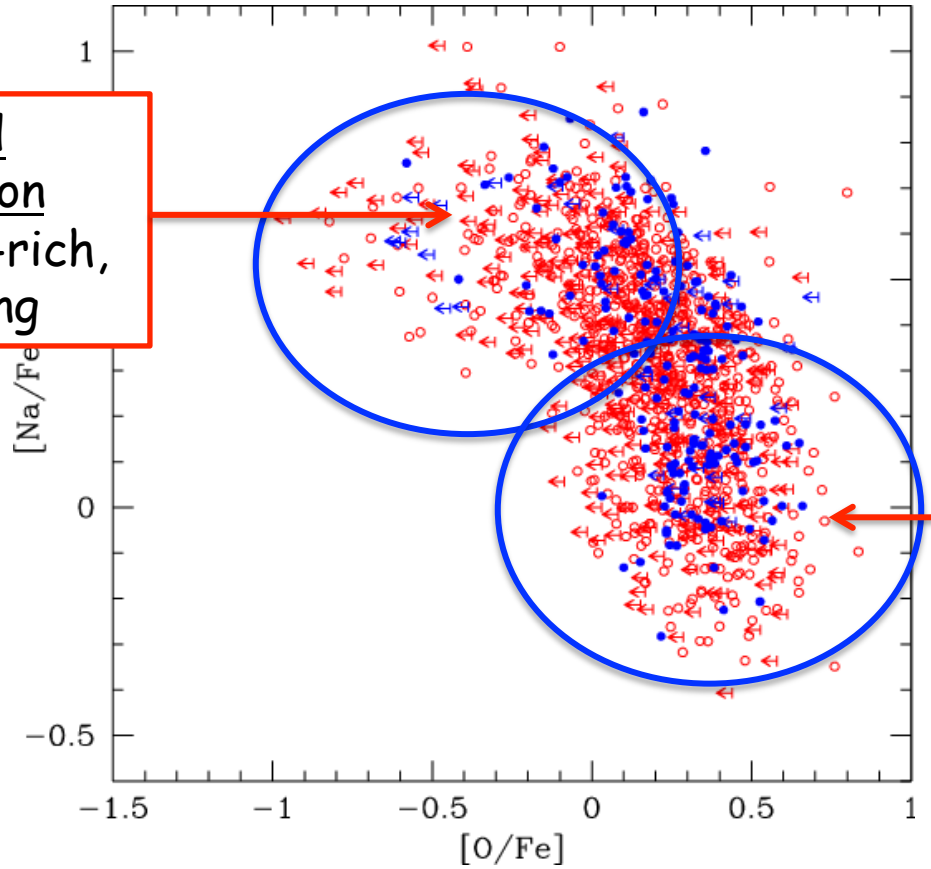
First Generation	**Self-enrichment** in timescale < 200 Myr	Second Generation
O-rich, Na-poor, CN-weak	→ (AGB ? FRMS ?)	O-poor, Na-rich, CN-strong

BUT …

a recent model proposed by Bastian+13 ("early disc accretion") explains the chemical anomalies without age spread

Brutal but efficient classification

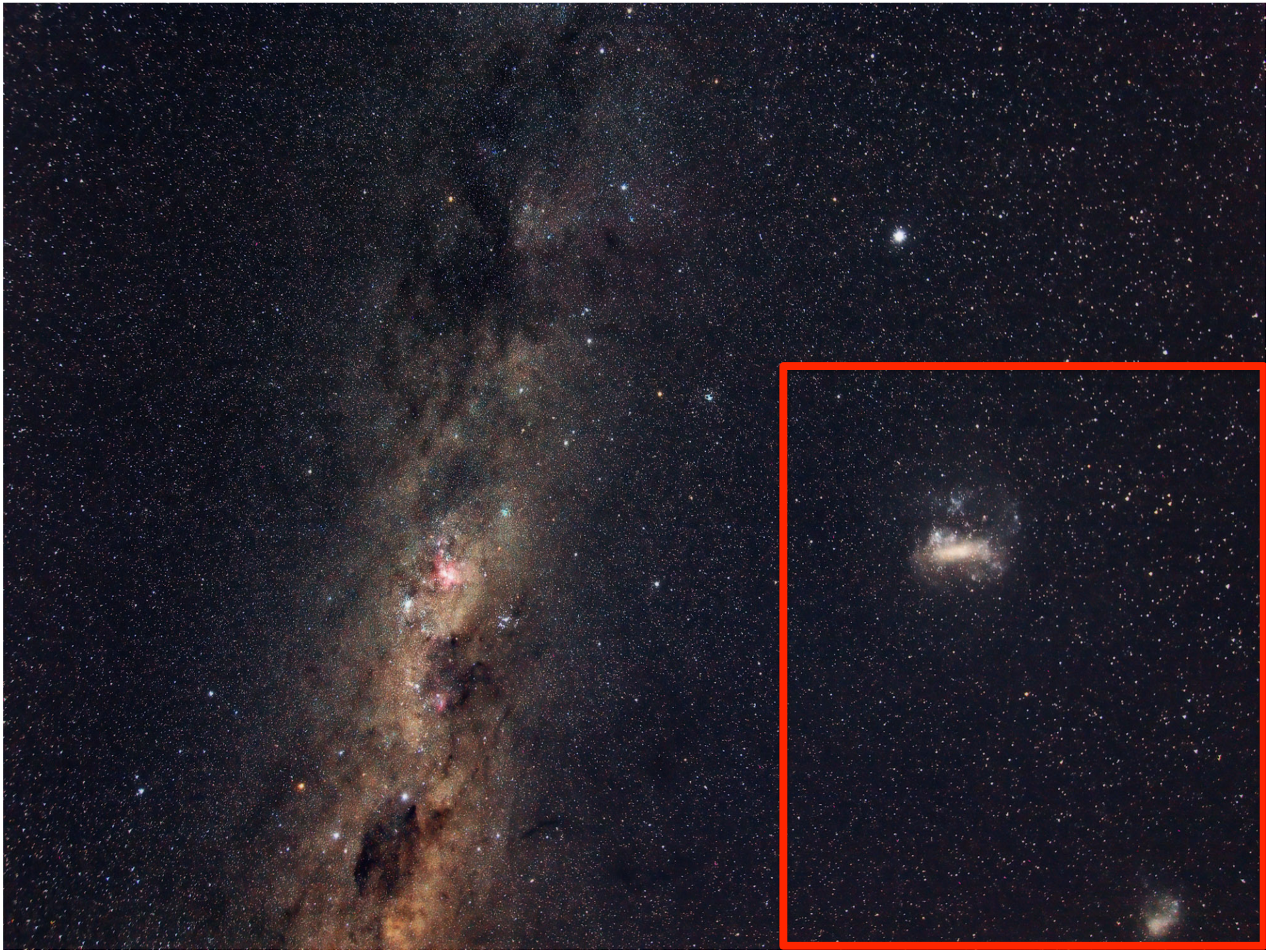
Carretta+09



Second Generation
O-poor, Na-rich, CN-strong

First Generation
O-rich, Na-poor, CN-weak

A typical feature of all the old GCs in the Milky Way
What happen in other galaxies?




MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD


LMC
SMC

The globular cluster system in the LMC/SMC

A huge range of ages and metallicities

(1) **OLD** GCs:
~15 old GCs in the LMC (coeval to the Milky Way ones)
~ 1 in the SMC (NGC121, ~10-11 Gyr)

(2) **INTERMEDIATE-AGE** GCs (**no** Galactic counterparts)
~ in the LMC: between 1 and 3 Gyr
(Age Gap, lack of GCs between 3 and 12 Gyr)
~in the SMC: continuous distribution of GCs between 1 and 11 Gyr

(3) **YOUNG** GCs (**no** Galactic counterparts)
~ GCs younger than 1 Gyr (peaks at ~100 and ~500 Myr)

The main project

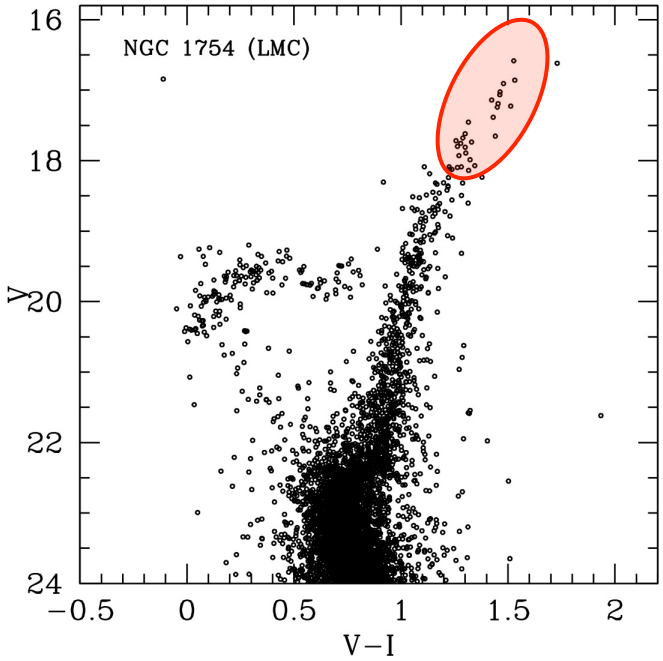
Study the chemical composition of the Magellanic GCs

- To compare old GCs formed in different galaxies
- To investigate young/interm.-age, massive GCs (not available in the MW)

High-res spectroscopy with **FLAMES@VLT**
Multi-object spectrograph
132 GIRAFFE (R~20000) + 8 UVES (R~40000) fibers
FoV = 25 arcmin diameter

Extra-galactic GCs : the main observational problems

Olsen+98



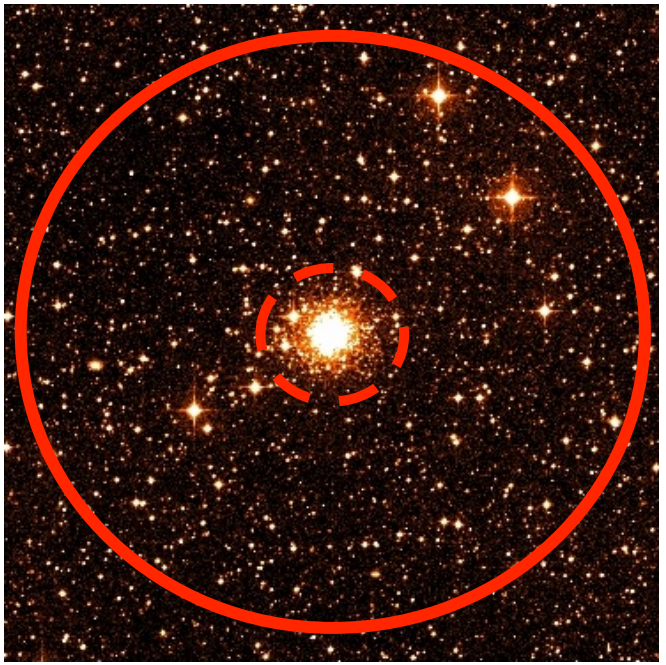
Small angular size of the GCs

The innermost regions (<20") cannot be observed with fiber-fed facilities (i.e. FLAMES)

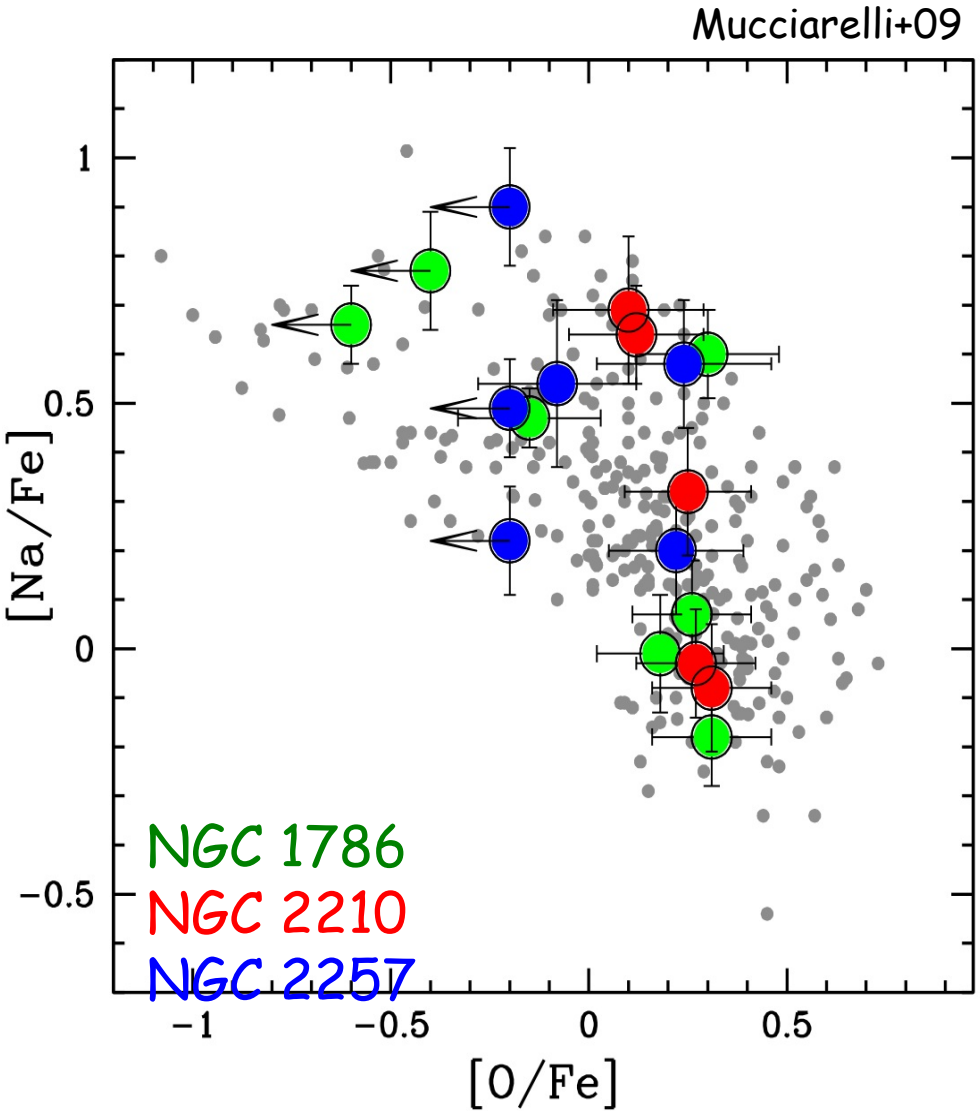
A small number of stars (~15) can be observed close to the cluster region

Small available magnitude range:
1 night of VLT time (UVES)
V~18 SNR ~ 20-30
V~17 SNR ~ 50-60

FLAMES Field of View



The old LMC GCs



Chemical analysis
of 3 old LMC GCs

- Metal-poor
  [Fe/H] between -2.0 and -1.6
- Massive M ~ 10^5 M_{SUN}
- Homogenous in Fe and other elements but …
- … Na, O, Mg and Al

First discovery of Na-O anticorrelations in extra-galactic GCs

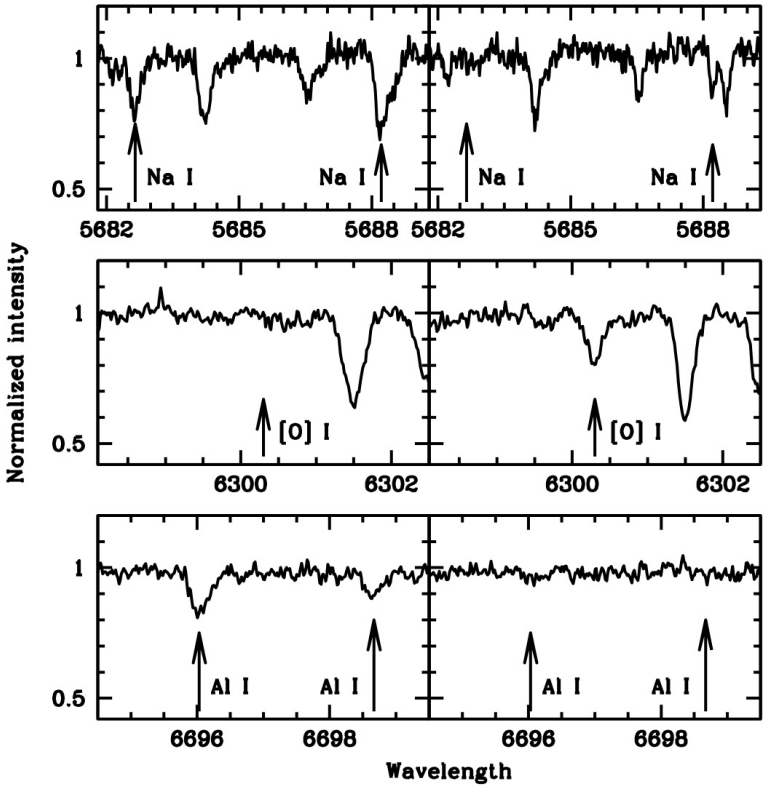
The old LMC GCs

2 RGB stars with the same parameters (the different line strength is only due to different abundances)

Na

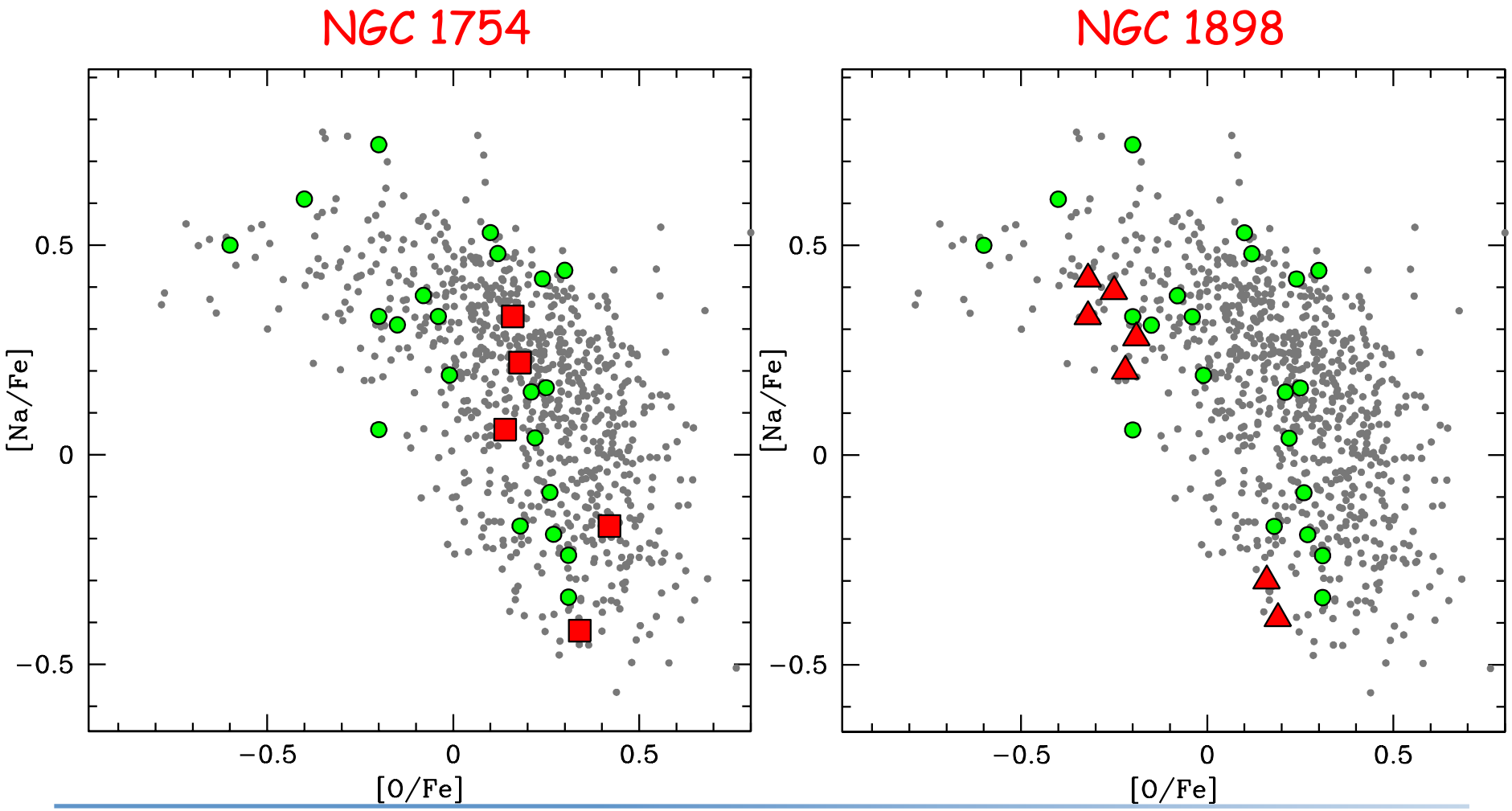
O

Al



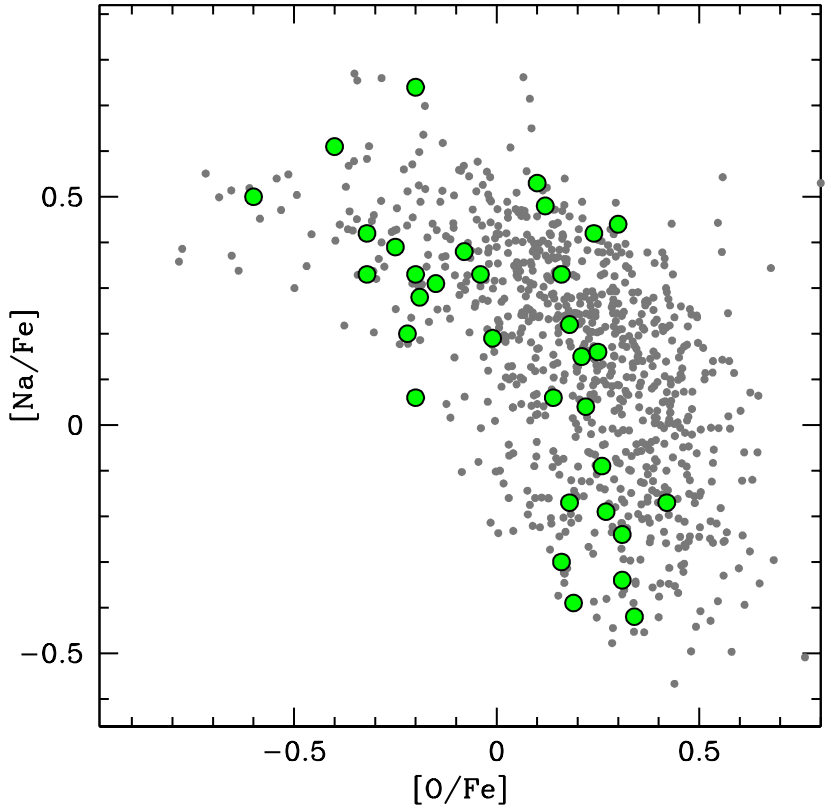
The old LMC GCs

2 *"new"* old LMC GCs: NGC1754 and NGC1898 (Mucciarelli et al, in prep.)



The old LMC GCs

The old LMC GCs are "twins" of the MW ones…
- similar ages
- similar masses
- similar chemical anomalies

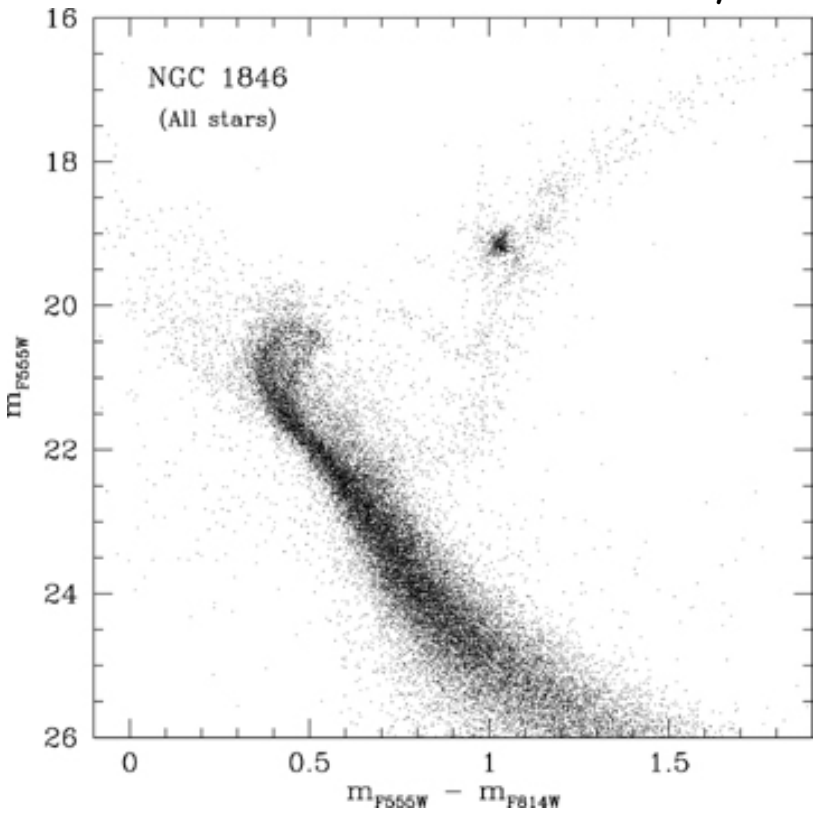


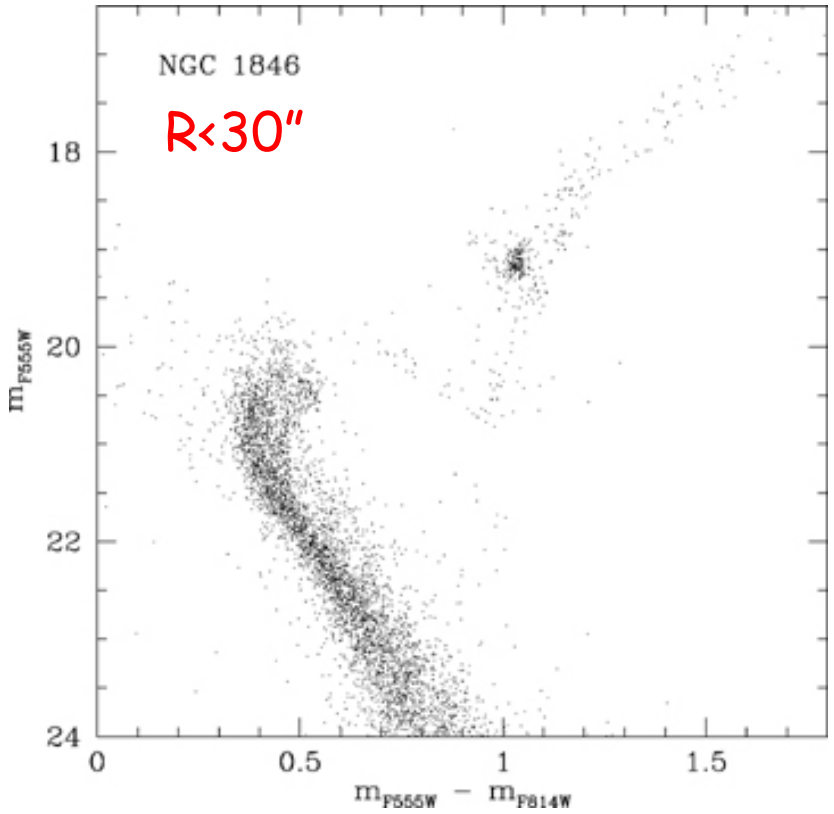
And in massive, younger GCs?

The first analysis of intermediate-age LMC GCs (Mucciarelli+08) suggests a general homogeneity in all the elements (also Na, O, Mg, Al …)

Intermediate-age MC clusters with a double turnoff

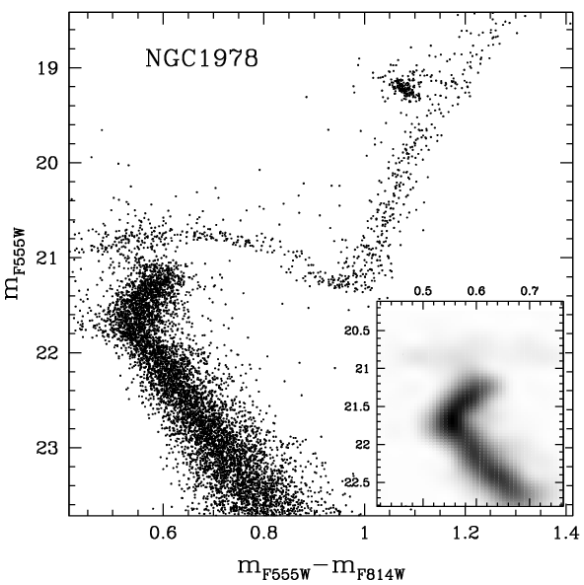
Mackey+07



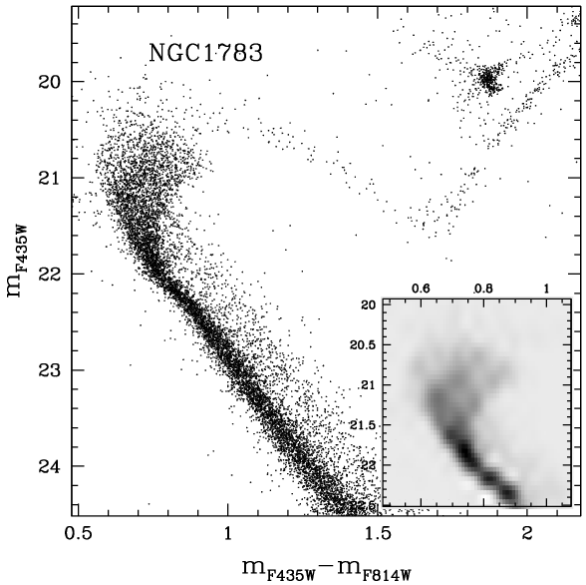


Intermediate-age MC clusters with a double turnoff

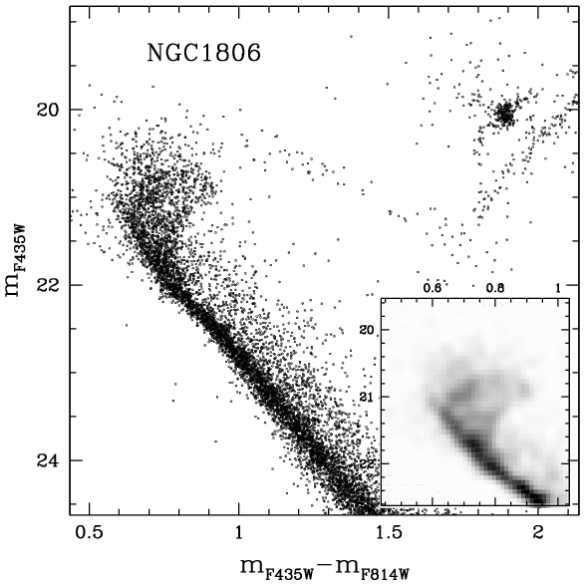
Single Turn-Off



Broad Turn-Off



Double Turn-Off



Milone+09

Possible solutions:

The most obvious: an **age spread**
(signatures of a continuous/bursty star-formation activity)

Fast-rotating stars (Bastian & de Mink 09):
these stars can evolve at lower temperatures
(but … conflicting results, see e.g. Girardi+10,Yang+13)

Interactive binaries (Yang+11):
these stars can evolve at higher temperatures
(but … this scenario explains only the dual MSTO
assuming that all the cluster stars are in binary systems)

Some observational evidence:

- The MSTO can be explained with an age difference < 200-300 Myr

- The anomalous MSTO is observed only in the more massive GCs

- The brighter (younger?) MSTO stars account for 50-70% for the total MSTO stars

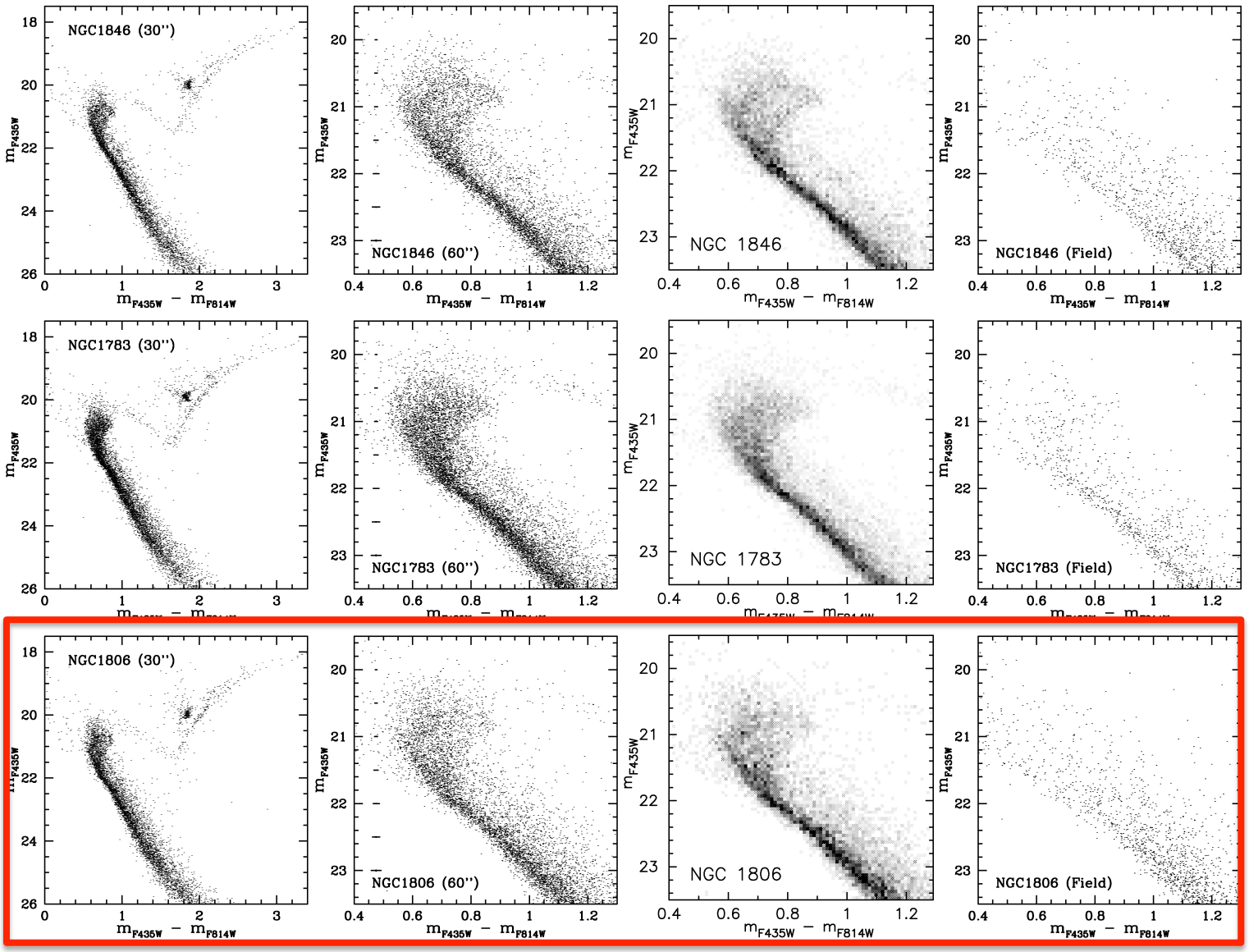
- The brighter MSTO stars are more centrally concentrated with respect to the faintest MSTO ones (very conflicting results!)

"*… a strong prediction: extended Main Sequence turnoff clusters will exhibit abundance variations in the light-elements characteristic of the ancient GC population.*"

Keller+11

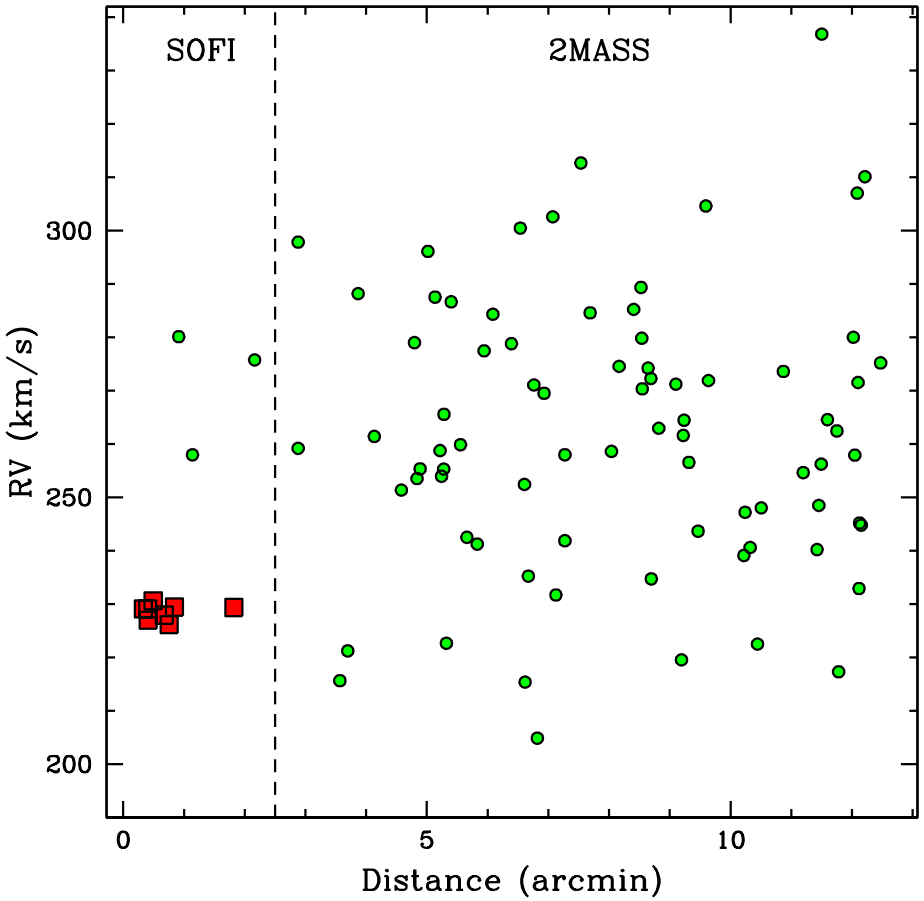
NGC 1806

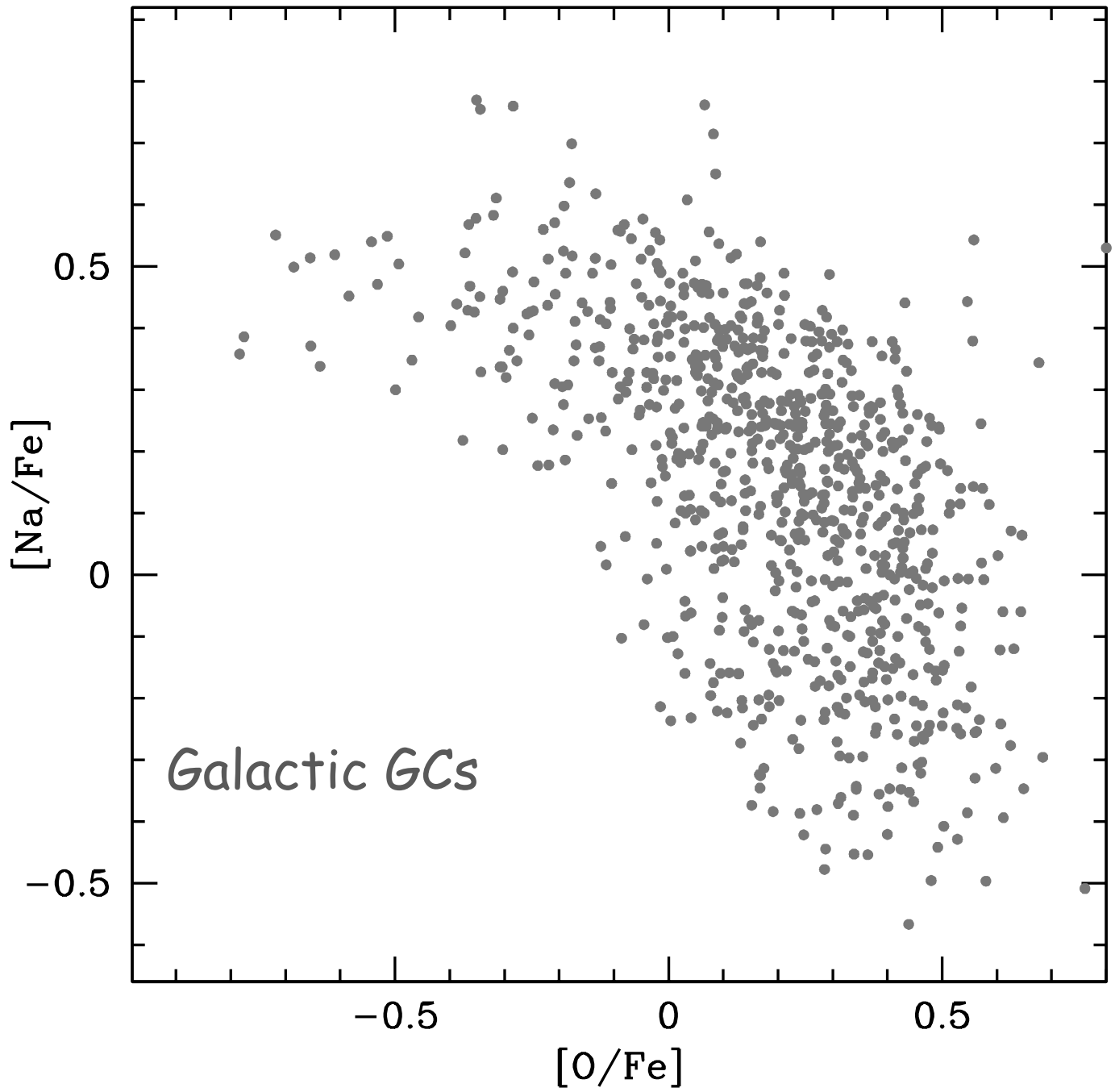
Mackey+08

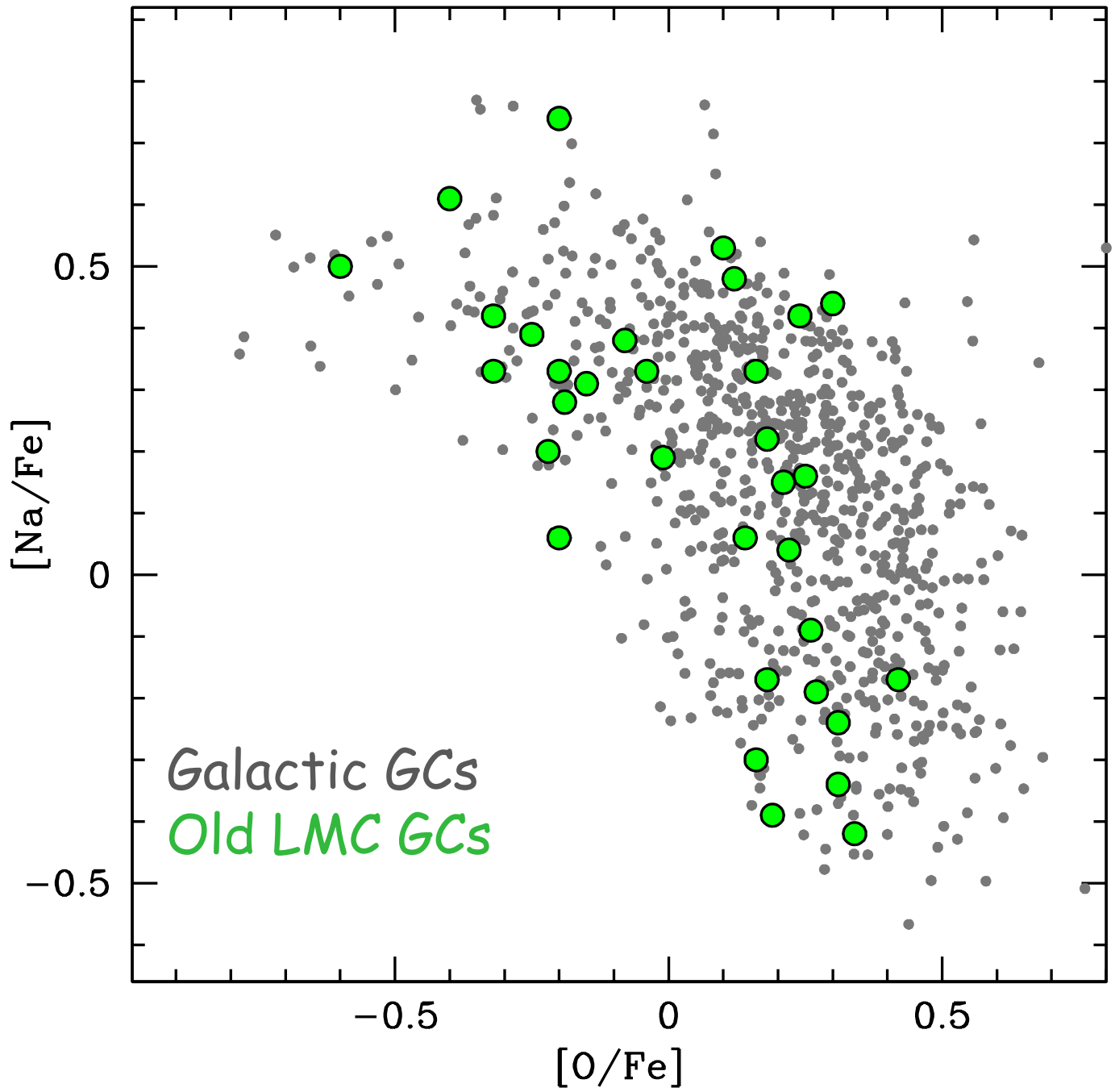


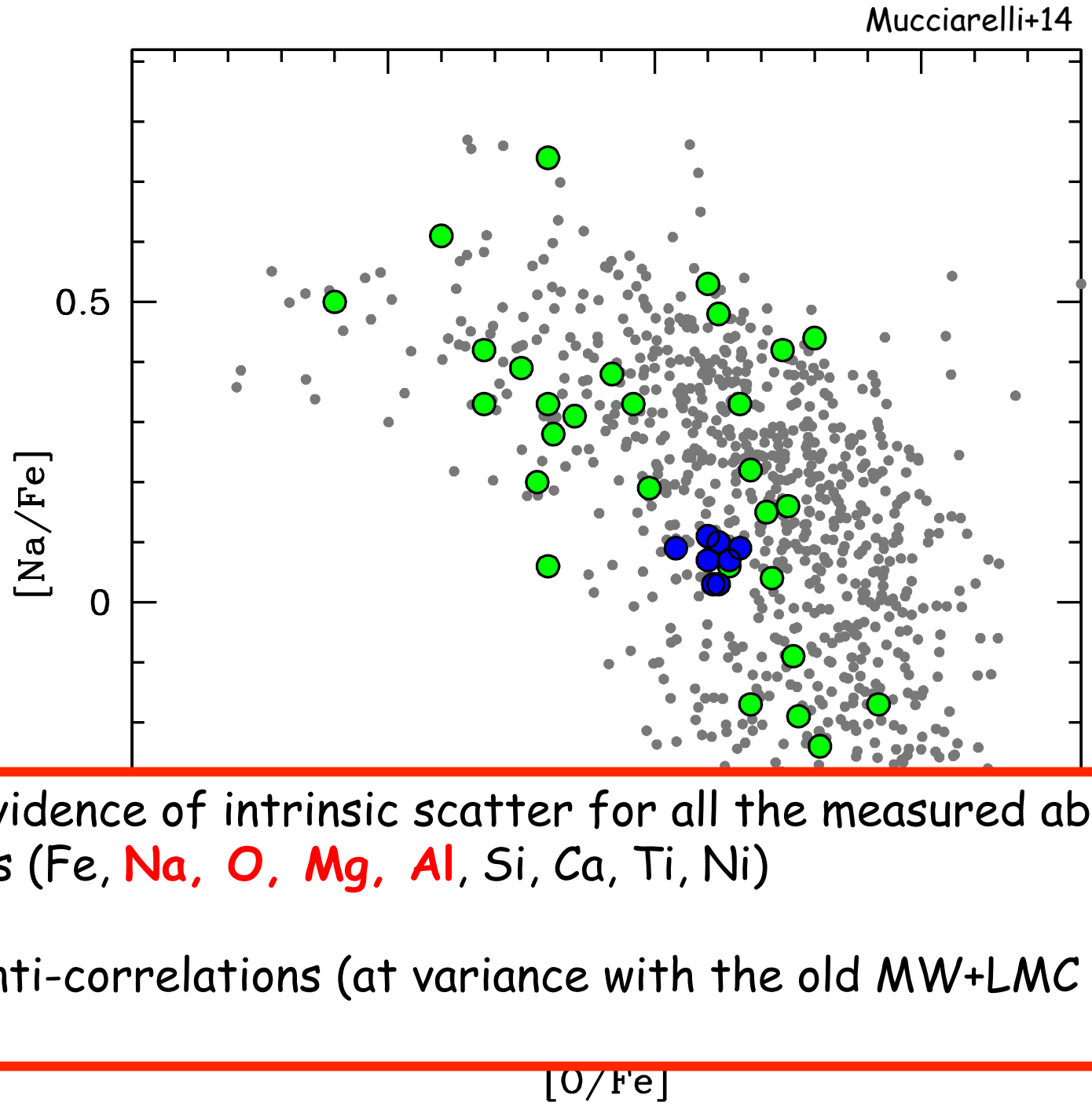
NGC 1806

FLAMES high-res spectra (SNR > 70)
8 RGB stars members of the clusters + 80 LMC field stars !!!
< [Fe/H] > = -0.60±0.01 dex




0.5
0
−0.5
[Na/Fe]
−0.5
0
0.5
[O/Fe]
Galactic GCs

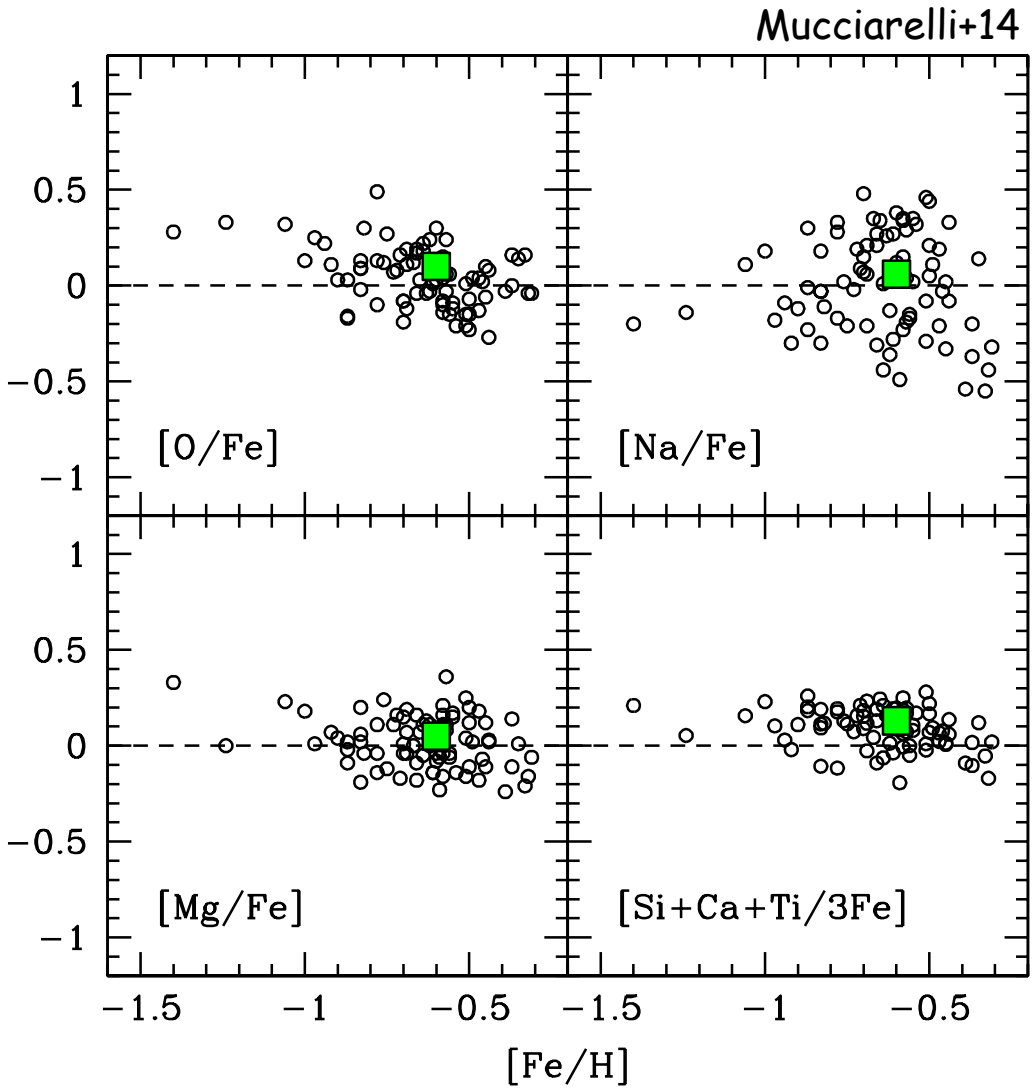

0.5
0
−0.5
[Na/Fe]
−0.5
0
0.5
[O/Fe]
Galactic GCs
Old LMC GCs



No evidence of intrinsic scatter for all the measured abundance ratios (Fe, **Na, O, Mg, Al**, Si, Ca, Ti, Ni)

No anti-correlations (at variance with the old MW+LMC GCs)

NGC 1806: comparison with the surrounding field



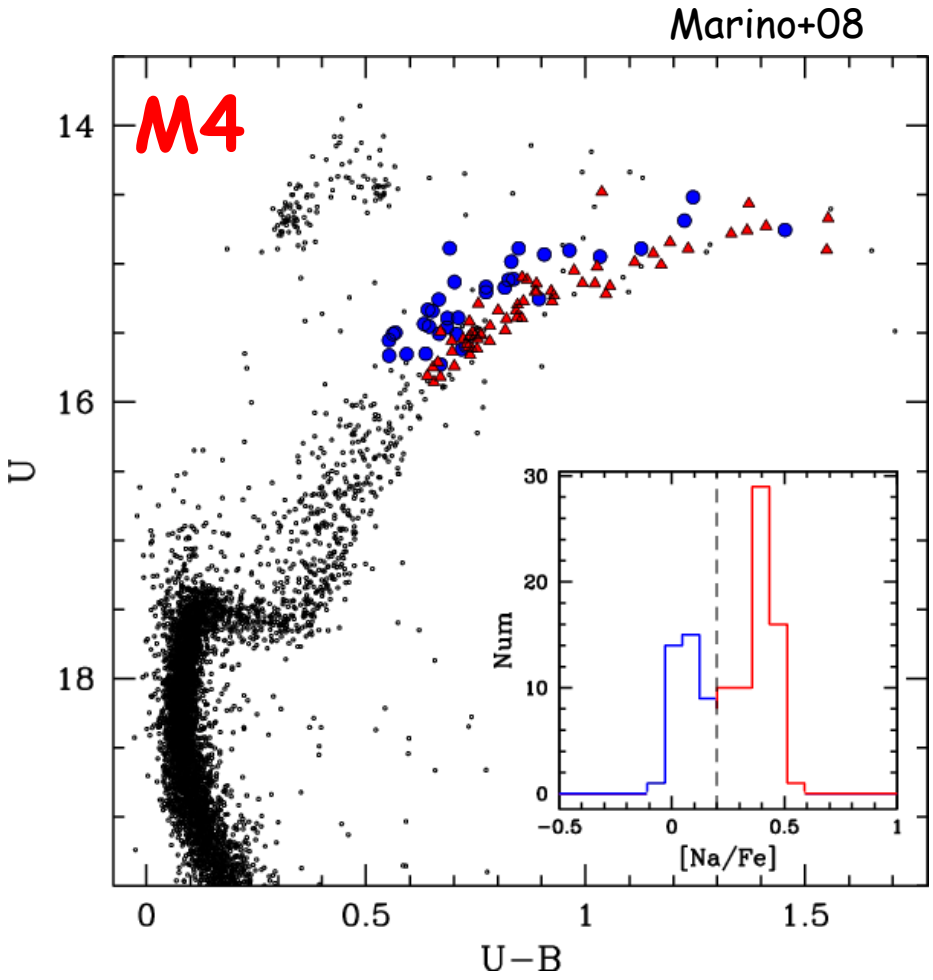
[O/Fe] and [Mg/Fe] similar to the field stars and to the other [α/Fe] in the cluster

All the stars belong to the first generation

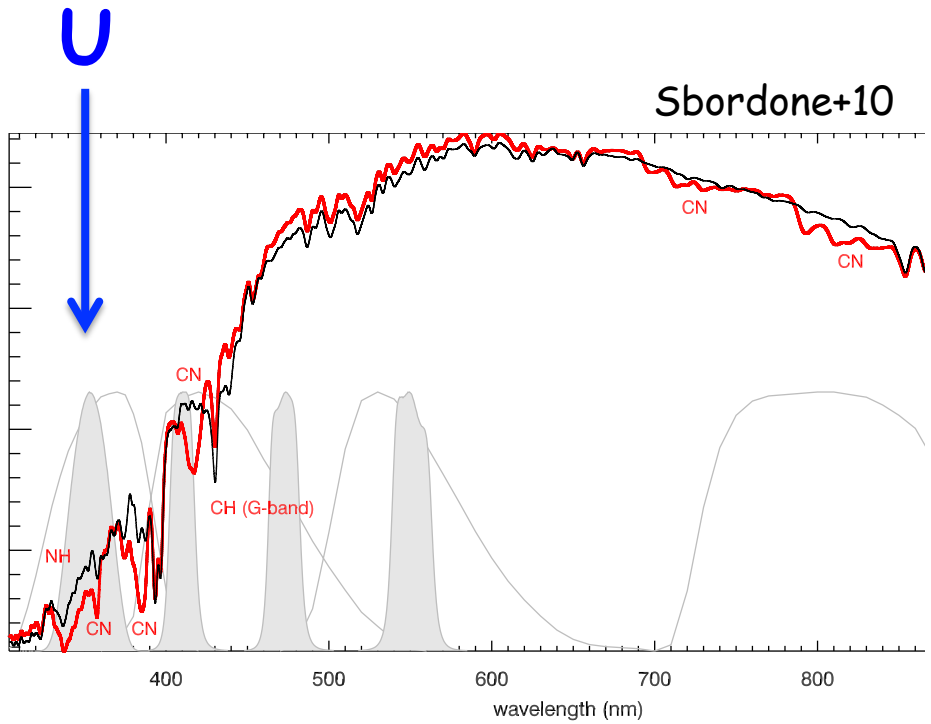
Where are the second generation stars ???

Possible selection bias: all the targets R > 20″ from the cluster center

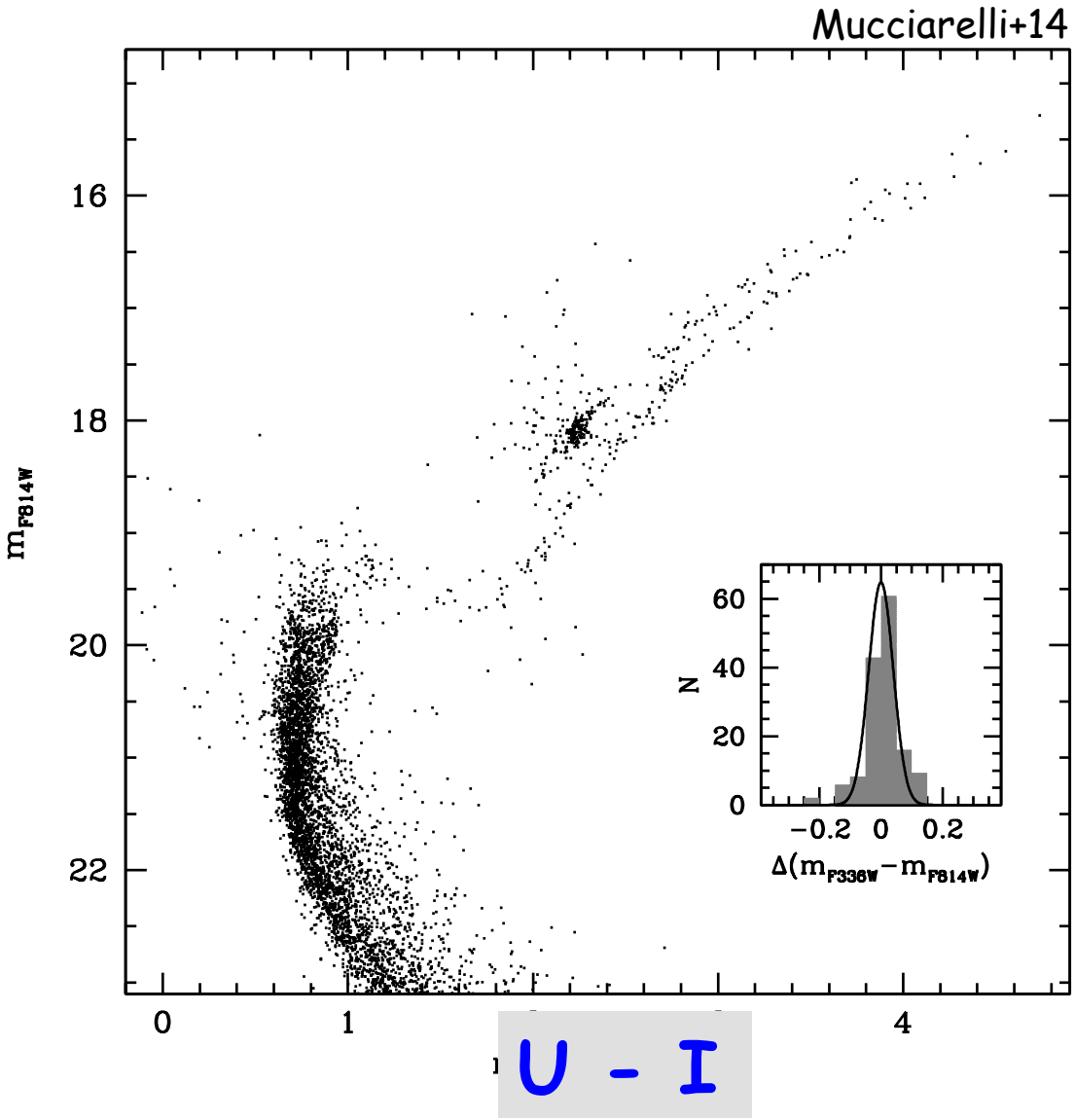
NGC 1806: UV photometry



CMDs with U filters show RGB splitting due to CN-NH variations



NGC 1806: UV photometry (ACS@HST)



U, U-I plane:
RGB splitting observed in old GCs
(Marino+08,Lardo+11,Monelli+13)

NO sign of RGB splitting.
The broadening of the RGB is fully compatible with the photometric uncertainties

NO variations of C and N
(also in the innermost region without FLAMES targets)

Some conclusions about NGC1806

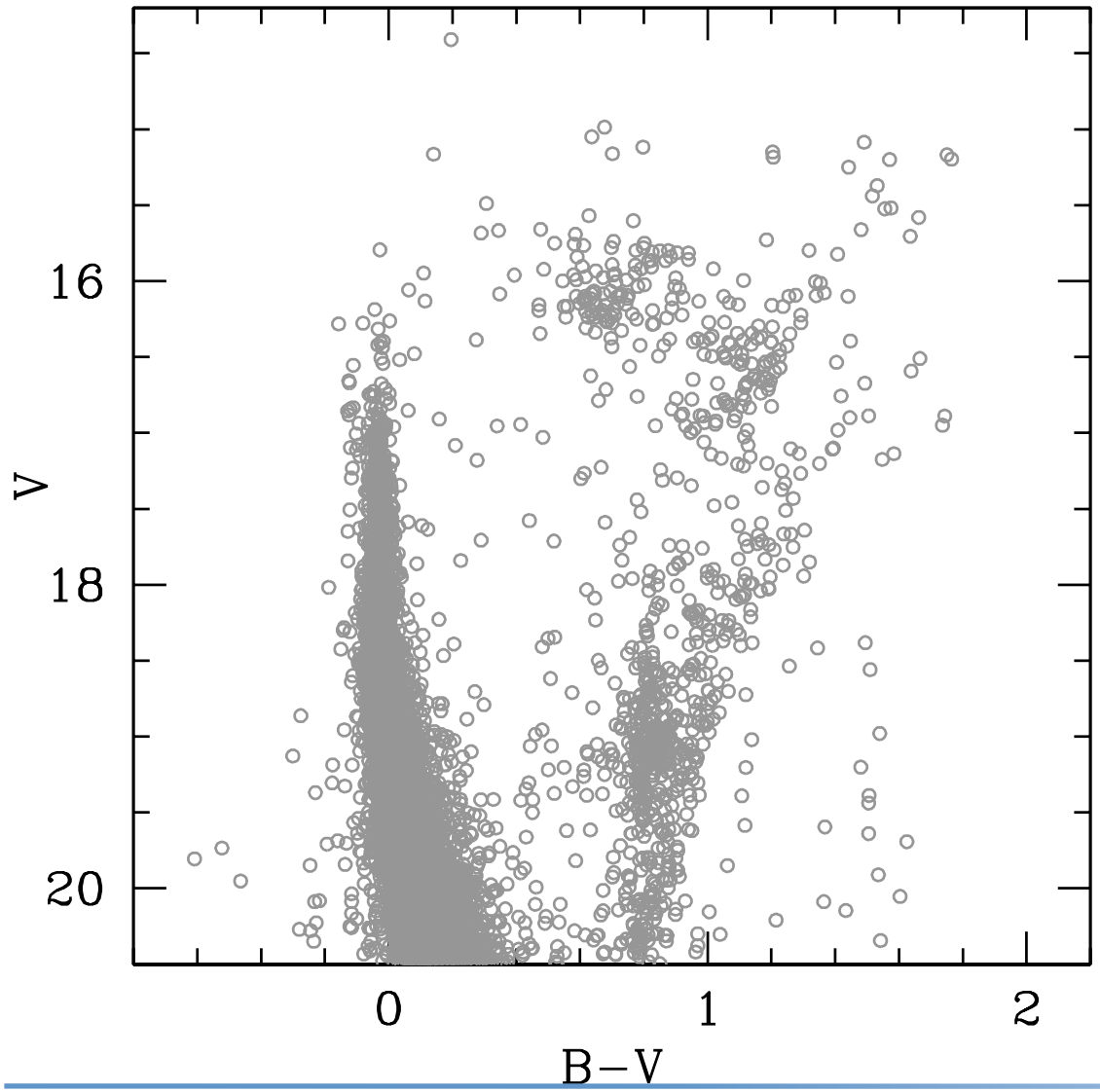
All the stars in NGC1806 share the same chemical composition

No (chemically distinct) multiple populations in the cluster

Broad/double MSTO clusters ≠ **Old clusters with NaO anticorrelation**

Other mechanisms must be invoked to explain broad MSTO GCs:
- Merging between binary clusters
- Collision between GC and giant molecular clouds
- Fast-rotating MS stars

Young clusters: the case of NGC1866

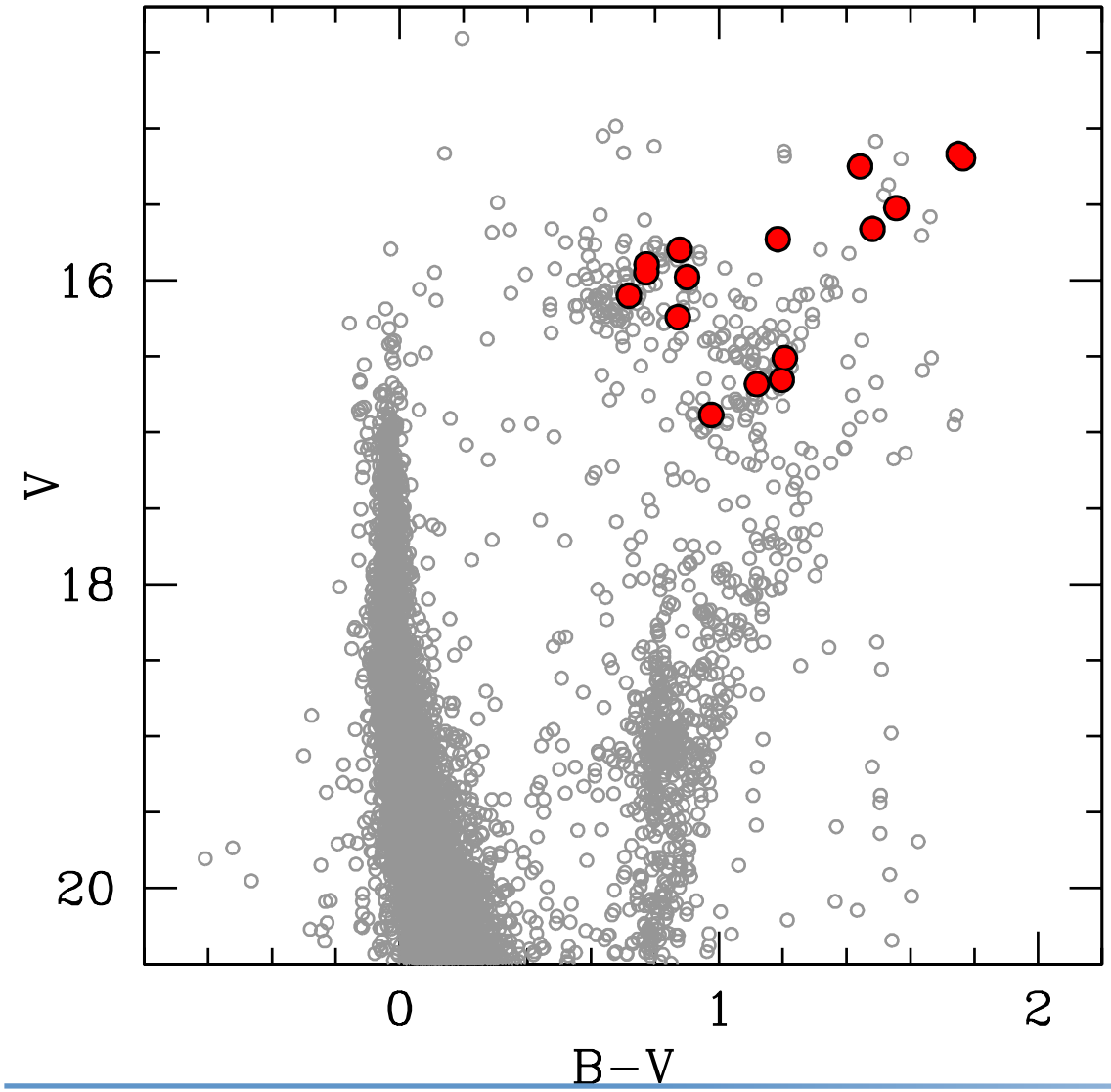


Young
(150-250 Myr, Brocato+03)

$M_{TO} \sim 4.5\ M_{SUN}$

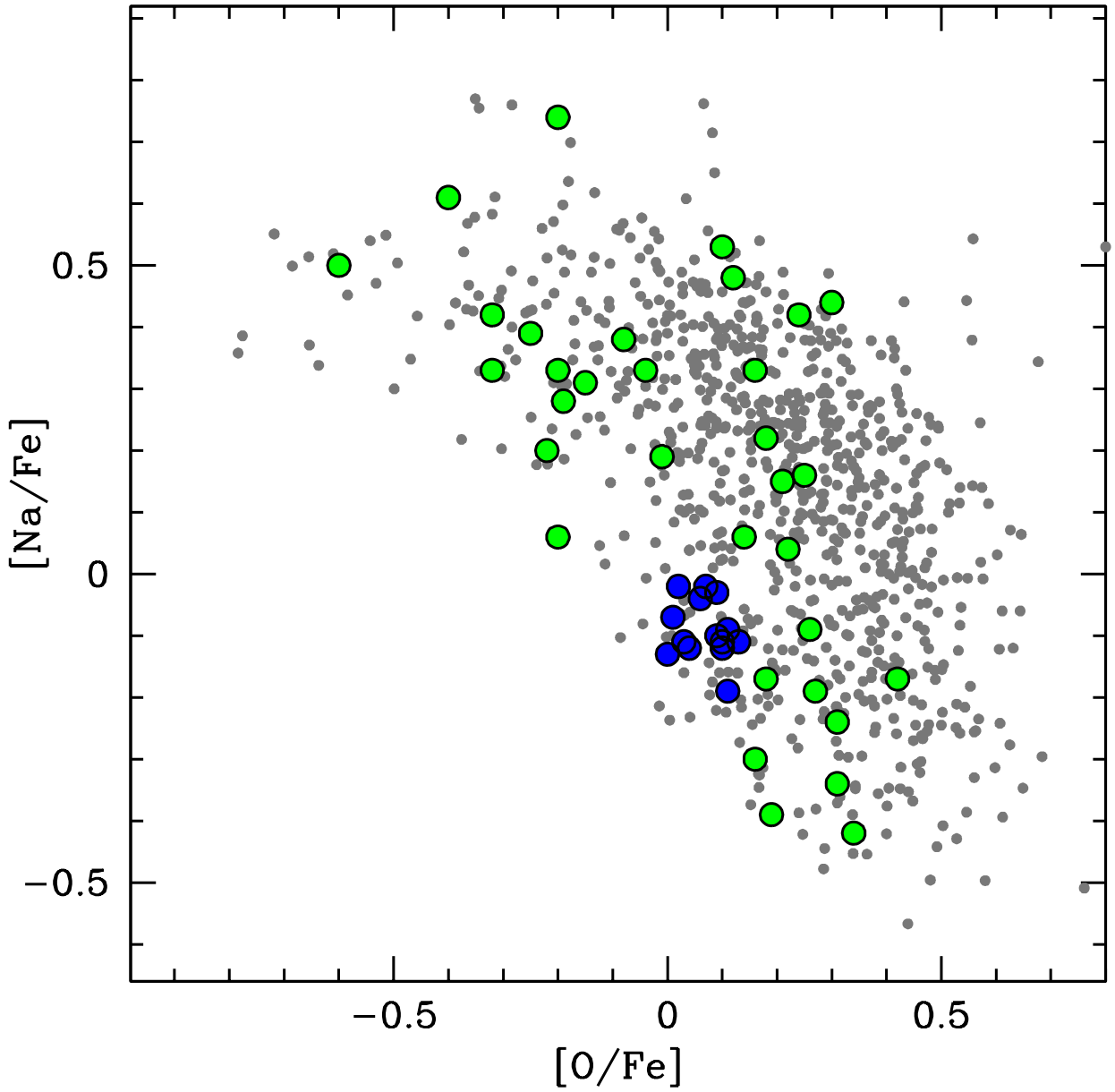
Massive ~$5 \times 10^4\ M_{SUN}$

Young clusters: the case of NGC1866



FLAMES observations
14 member stars

[Fe/H]=-0.43±0.01 dex


0.5
0
−0.5
[Na/Fe]
−0.5
0
0.5
[O/Fe]

Conclusions

Old LMC GCs:
- NaO anticorrelations like those observed in MW GCs
- No differences with respect to the old MW GCs

Young/intermediate-age LMC GCs:
- homogeneous in all the abundance ratios
- the dual MSTO cluster NGC1806 does not show anomalies (ruling out the scenario proposed by Keller+11)
- not massive enough to retain the gas