Disentangling the complexity of globular clusters: a chemical approach

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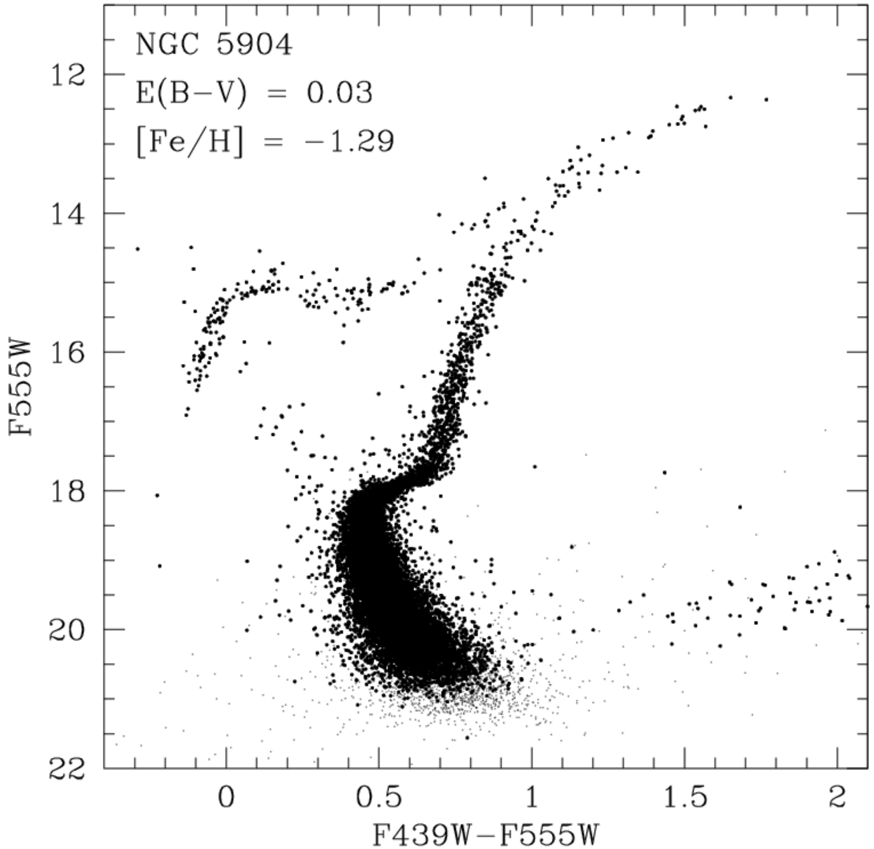
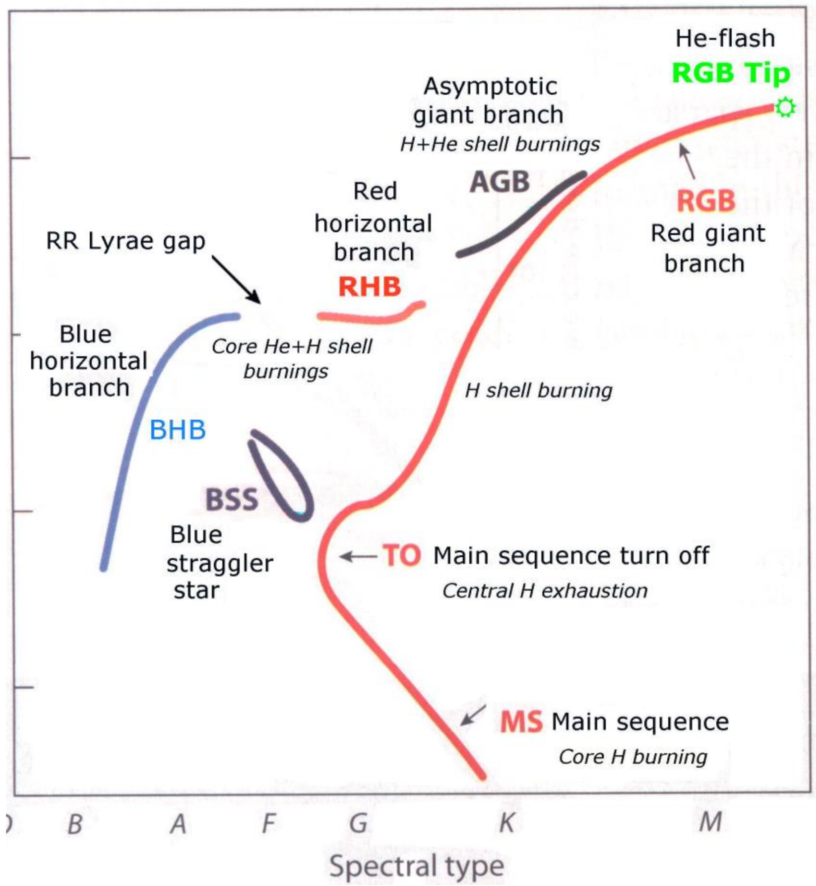
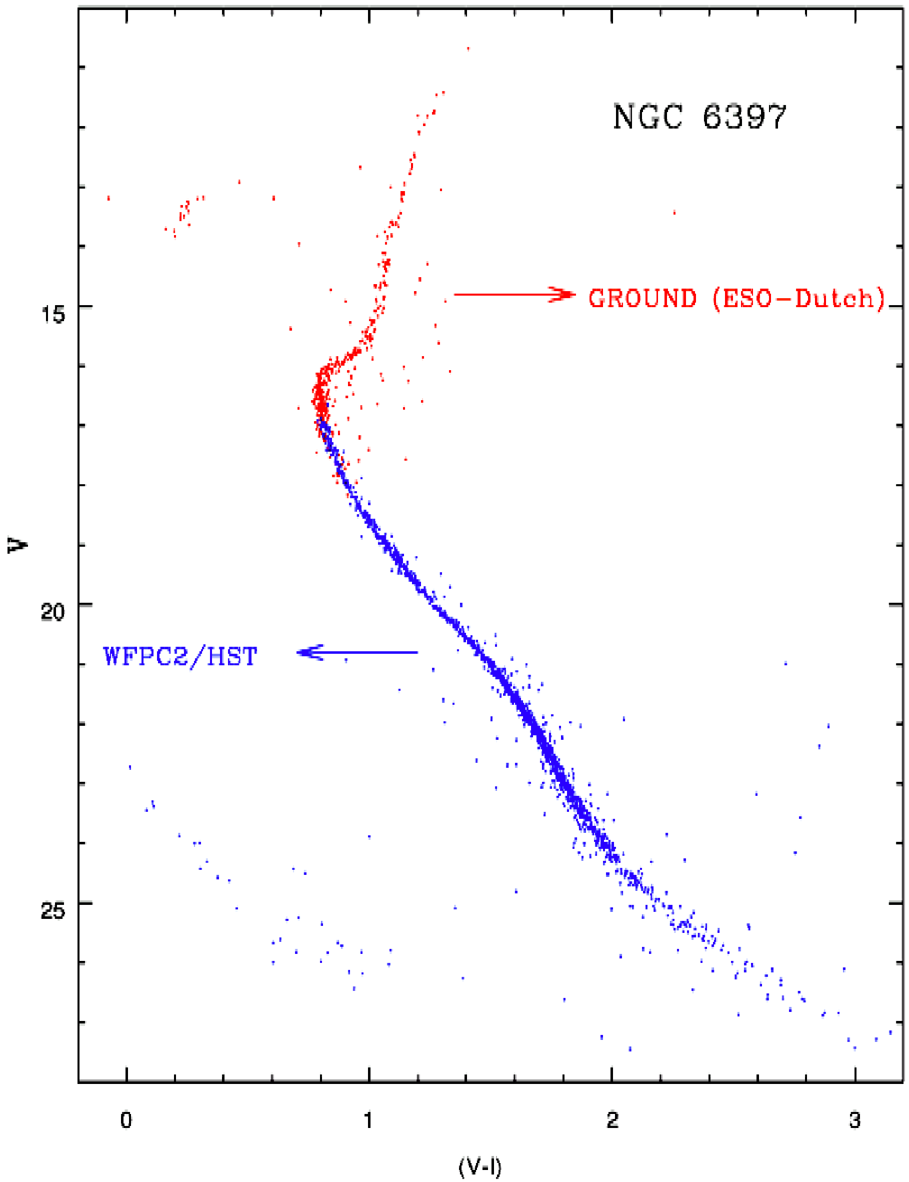
Per la guida, premere il pulsant

Globular Clusters: benchmark for stellar evolution





Globular Clusters look like an isochrone

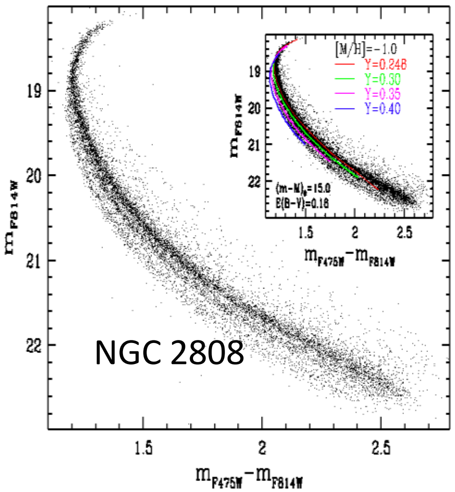


Simple stellar Population (SSP): aggregates of single, coeval stars with the same initial chemical composition

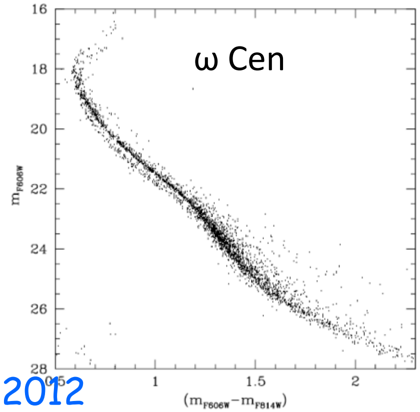
Location of stars in CMDs of globular clusters = function of the Mass and the chemical Composition of the star

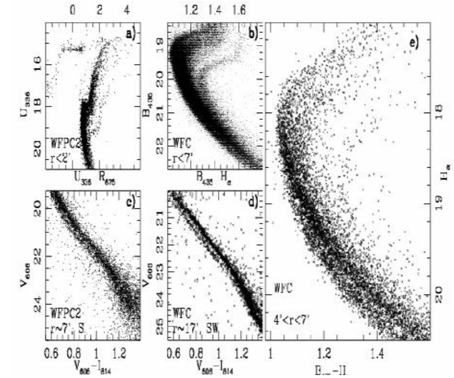
In nature, STELLAR CLUSTERS ARE THE BEST EXAMPLE of Simple Stellar Populations (Renzini & Buzzoni 1986)

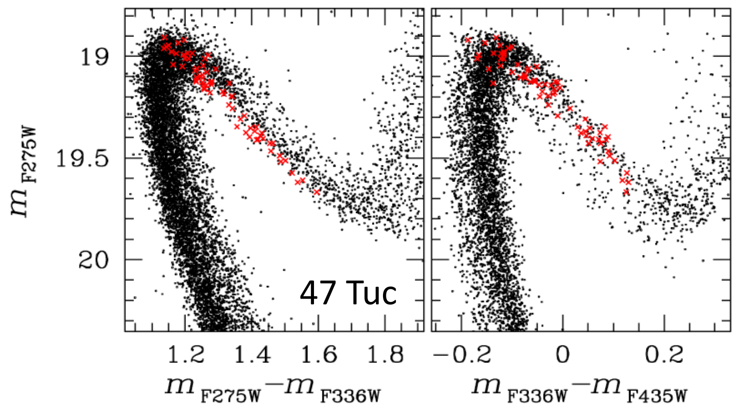
Globular Clusters are NOT SIMPLE: Multiple MSs, RGBs, SGBs

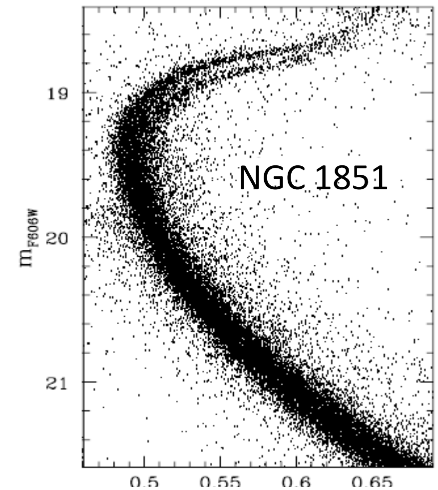


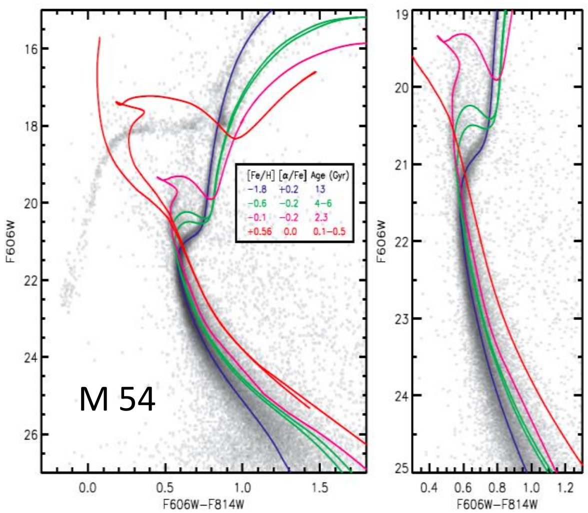
Lee et al. 1999
Pancino et al. 2000
Bedin et al. 2004
Piotto et al. 2005, 2007
D'Antona et al. 2005
Siegel et al. 2007
Zoccali et al. 2009
Anderson et al. 2009
Milone et al. 2008, 2011, 2012

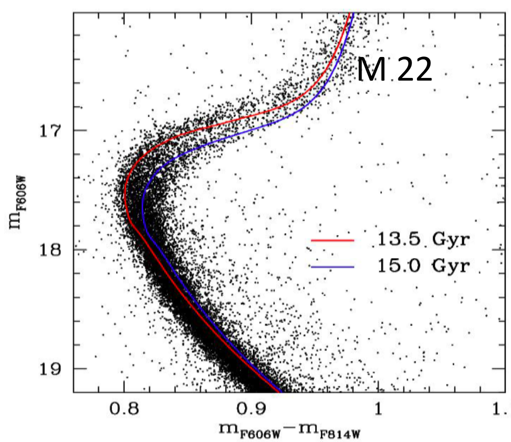


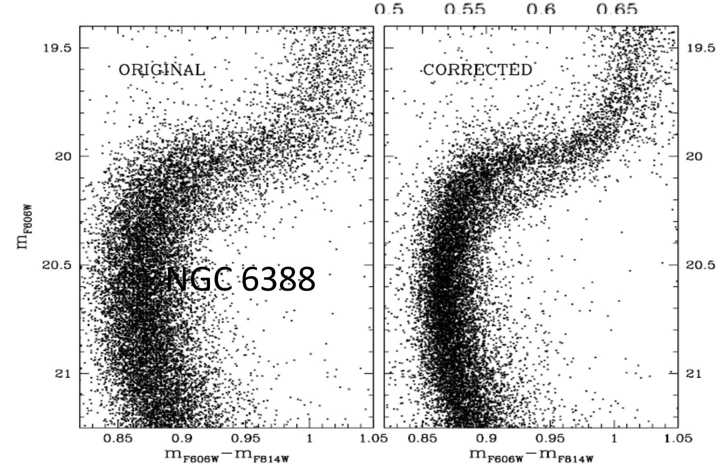






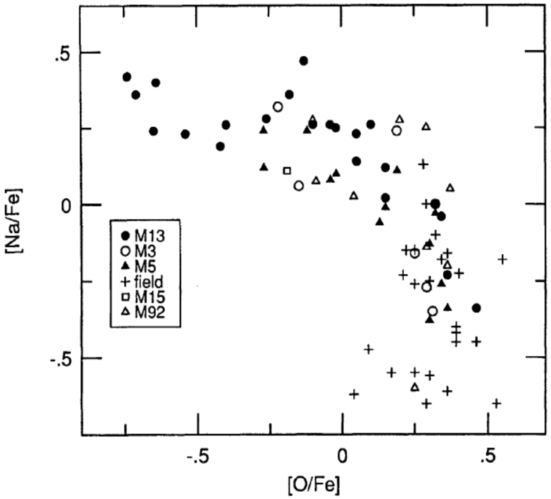




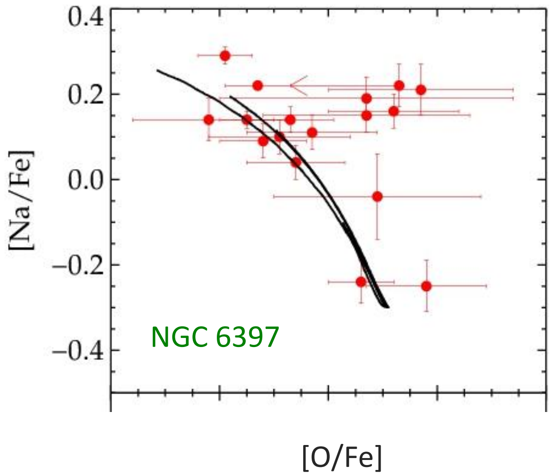


SPECTROSCOPY

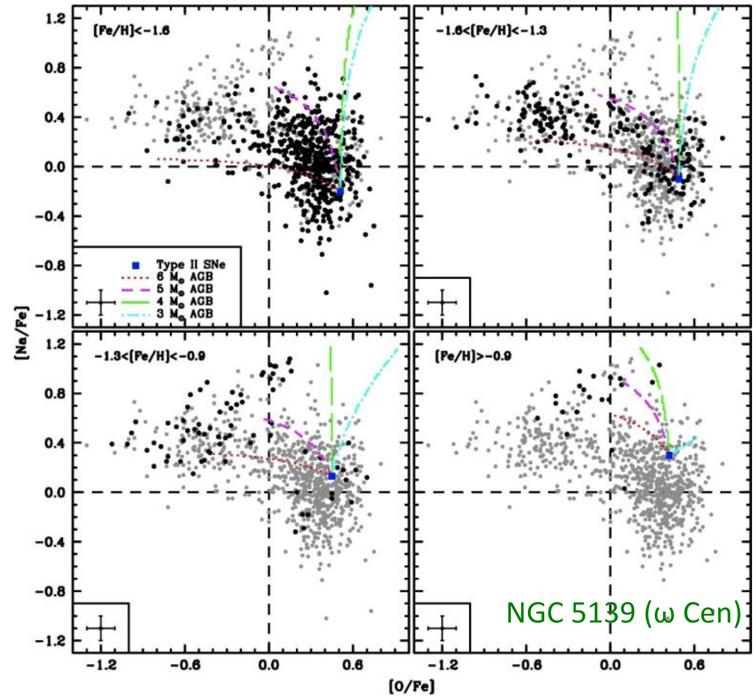
The Na-O anticorrelation



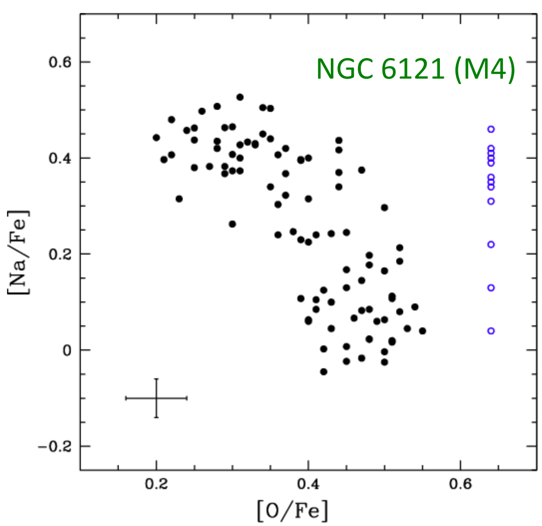
The Lick-Texas group (Kraft, Ivans, Sneden)



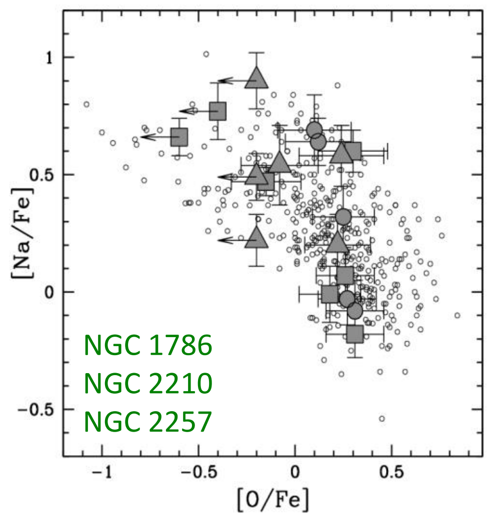
Lind et al. 2011



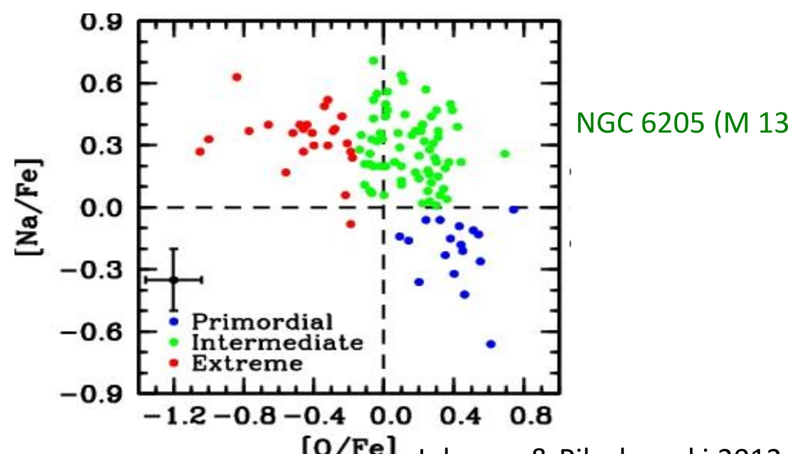
Johnson & Pilachowski 2010



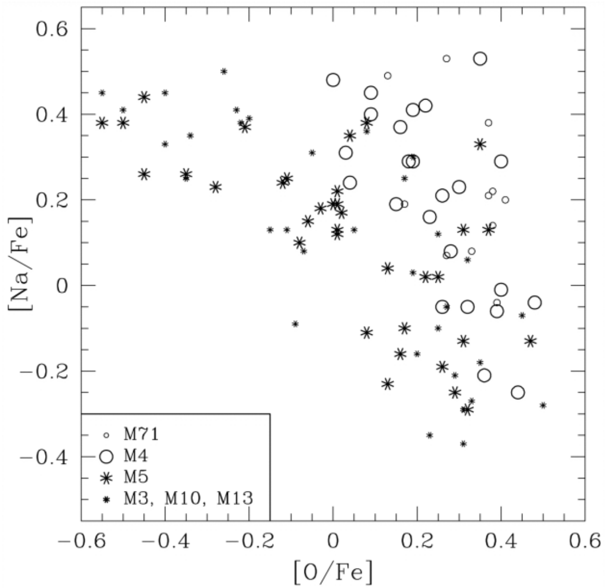
Marino et al. 2008



Mucciarelli et al. 2009



Johnson & Pilachowski 2012



Giants observed by Ivans et al. (2001)
and the Lick-Texas group (Sneden, Kraft, Langer)

Signature of the activation of high-temperature proton capture reactions

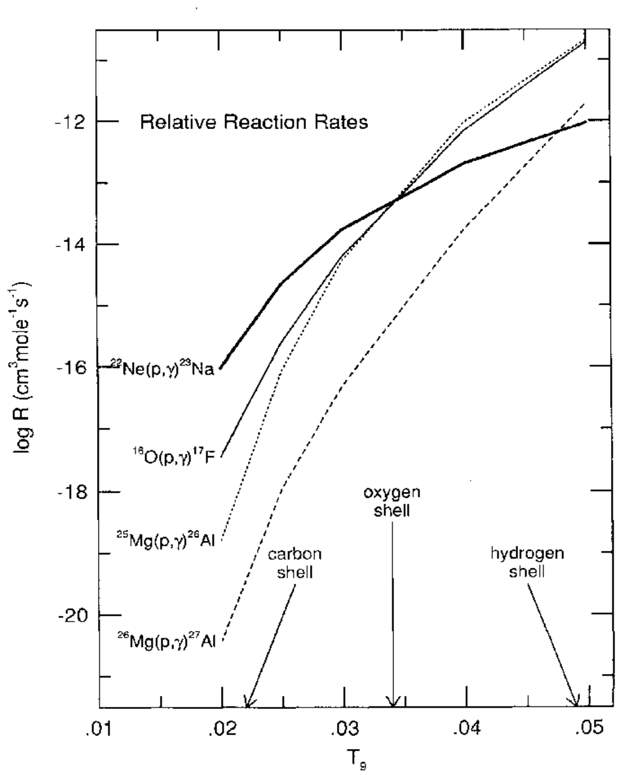


FIG. 1—Proton capture rates (in units of cm^3 $moles^{-1}$ s^{-1}) for temperatures found in the energy-generating regions of small-mass red giant stars.

The NeNa cycle that enhances Na, is expected to operate in the same fusion zones in which the ON part of the CNO cycle is fully operative
(Denisenkov & Denisenkova 1990; Langer et al. 1993).

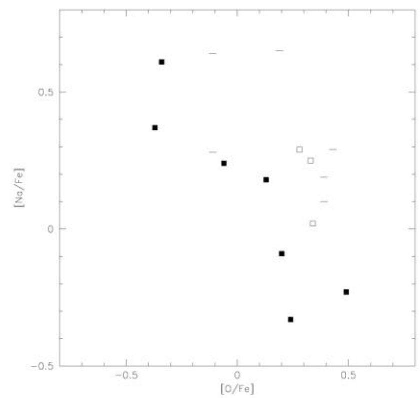
CNO: T > 20 MK
NeNa: T~ 35 MK
MgAl: T> 50 MK
^{24}Mg depletion: T~70 MK

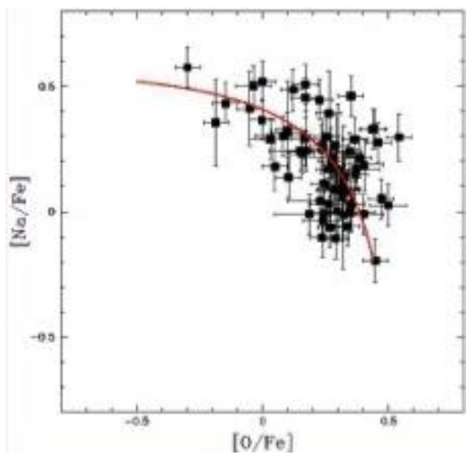
The smoking gun of the PRIMORDIAL NATURE:
The Na-O anticorrelation in GC dwarfs and subgiants

Internal mixing is ruled out:

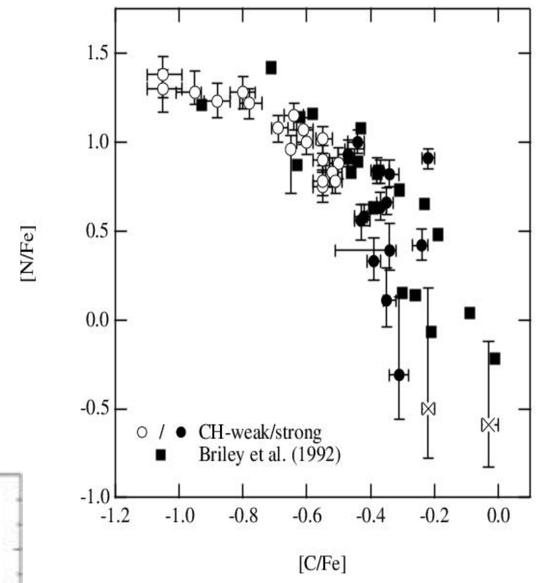
- ❑ negligible convective envelopes
- ❑ dominant H-burning cycle is p-p not CNO

Gratton et al. (2001)





Cohen et al. (2002)



D’Orazi et al. (2010a)

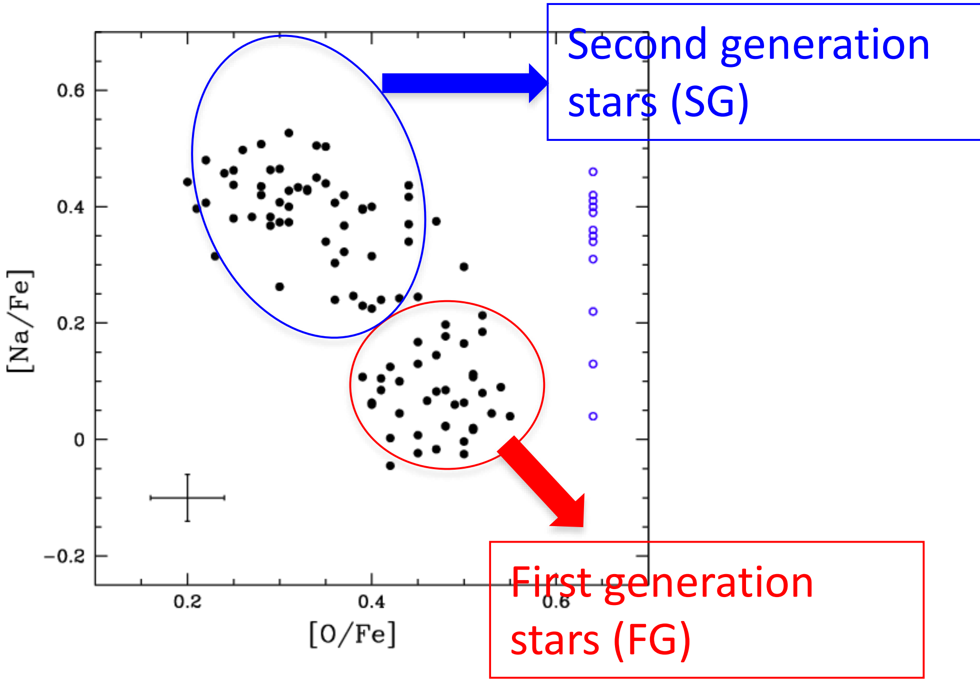
at least TWO stellar generations

A PREVIOUS GENERATION of stars which synthesised in their interiors proton-capture elements are RESPONSIBLE for these chemical signatures in GC stars

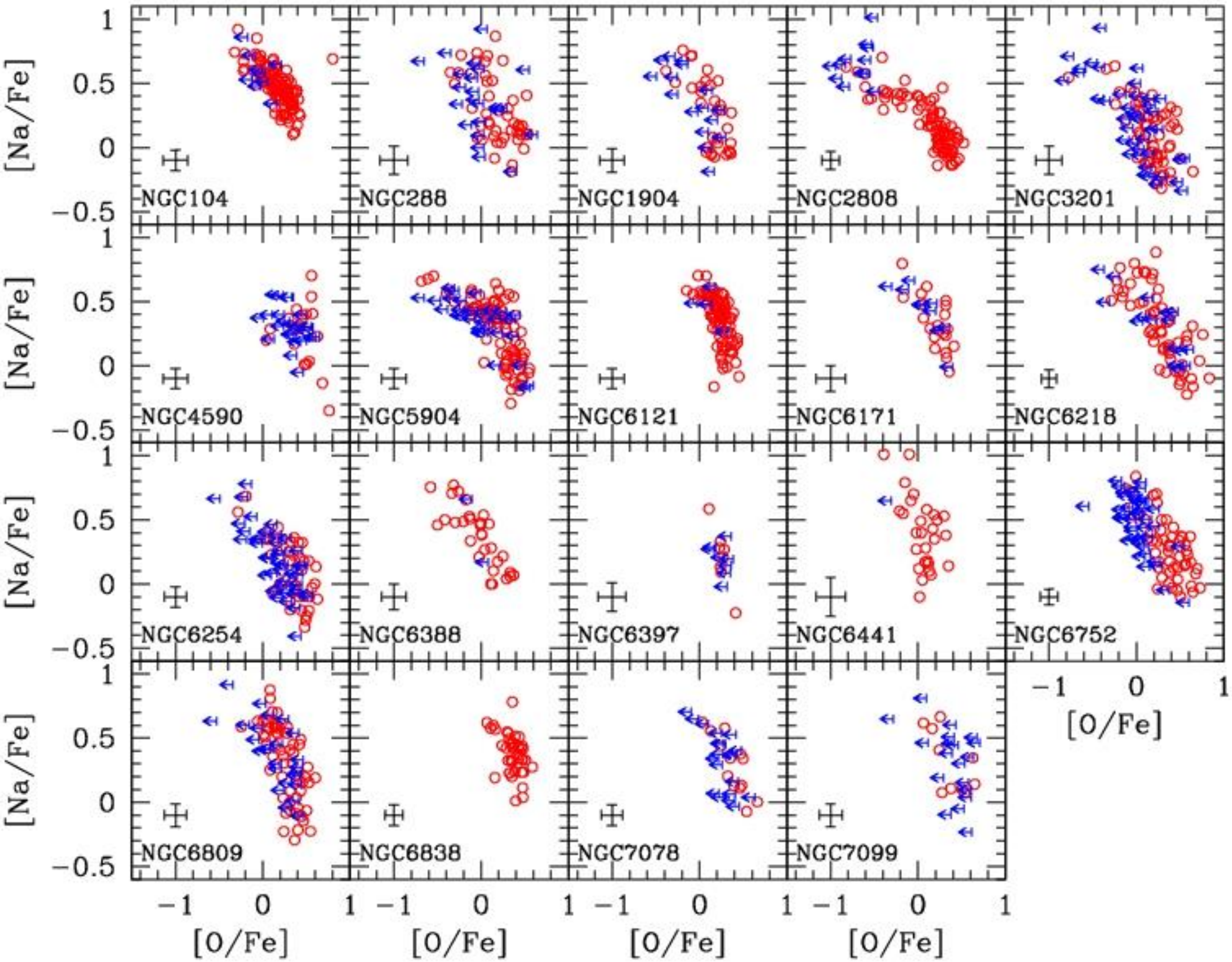
⬇

HOT hydrogen burning, where the ON, NeNa, and MgAl chains are operating - the ON reduces O, the NeNa increases Na (T ~ 30 million K), while the MgAl produces Al (T~65 million K)

In this picture a fraction of the first-generation stars (FG, O/Mg/C-rich and Na/Al/N-poor) underwent nucleosynthesis through the proton capture (CNO, NeNa, and possibly MgAl) cycles and polluted the interstellar medium with the processed material via stellar winds. The second stellar generation (SG, O/Mg/C-poor and Na/Al/N-rich) formed from this enriched material, probably within a few hundred Myr



Our Survey: Na-O abundances in 19 GCs

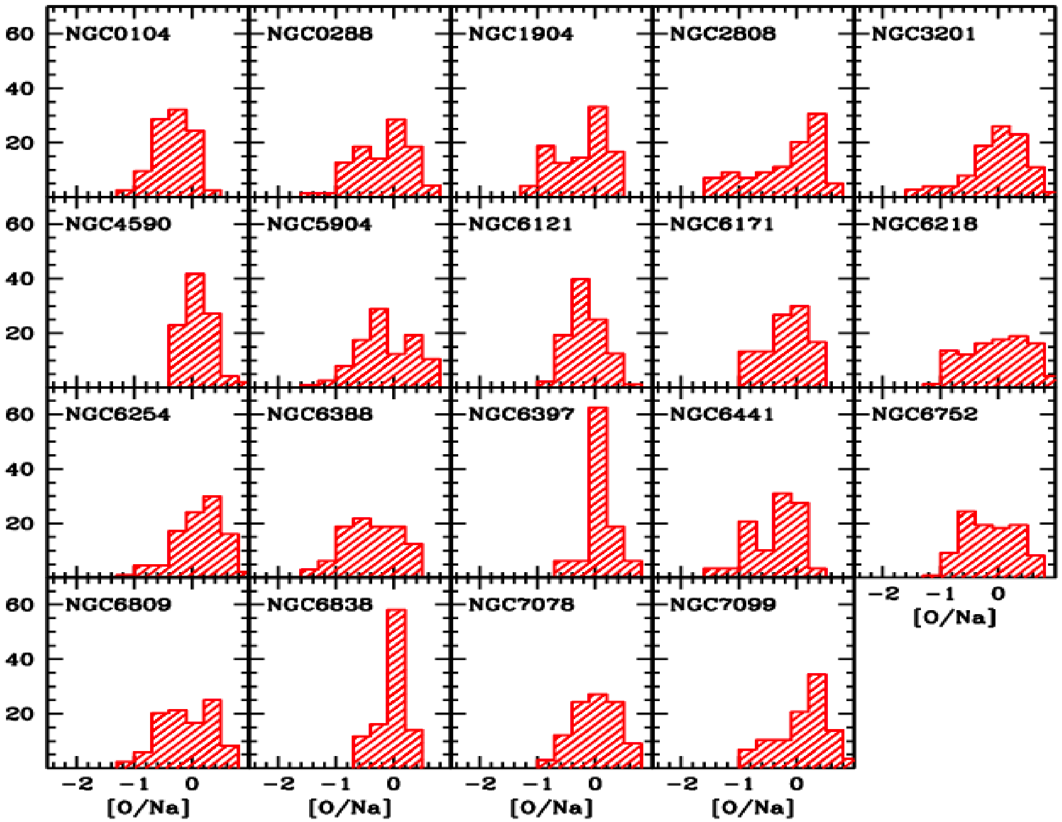


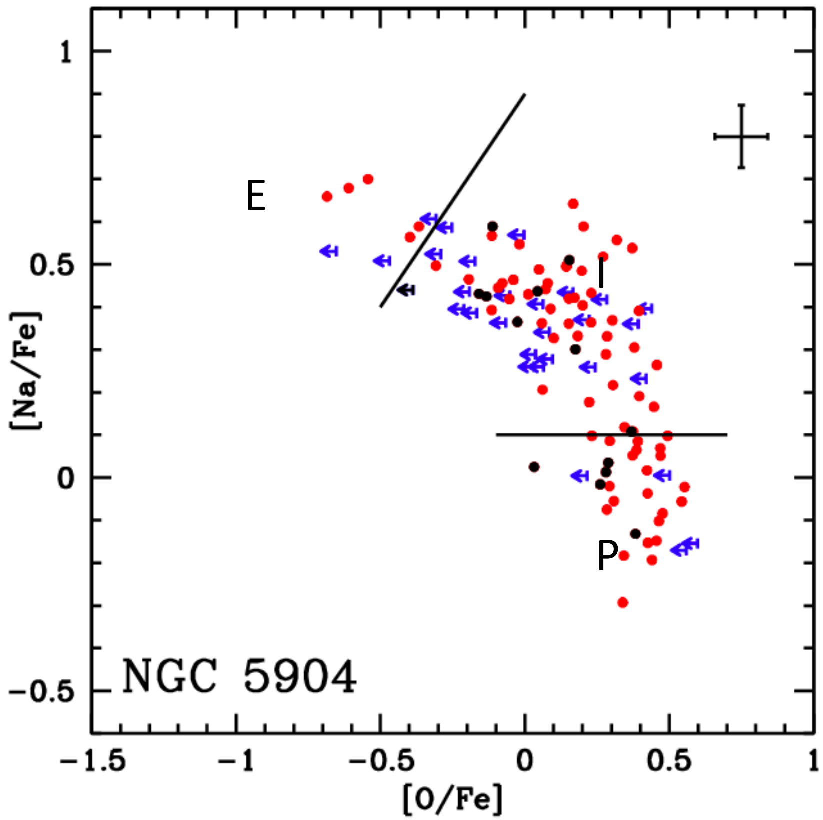
FLAMES@VLT (Giraffe+UVES): more than 100 hours

Fe-peak, Na, O, Mg,
Al abundances derived
for a grand total of about 1200 stars

Carretta et al. (2009a)

Stellar generations in GCs: PIE groups





Primordial Intermediate Extreme

P: [Na/Fe] < [Na/Fe]min+4σ I: [O/Na] > -0.9 E: [O/Na] >-0.9

SN nucleosynthesis Second-generation chemical composition

A feature so widespread among GCs must be related to their origin/formation mechanism (Carretta 2006)

↓

A NEW Definition:

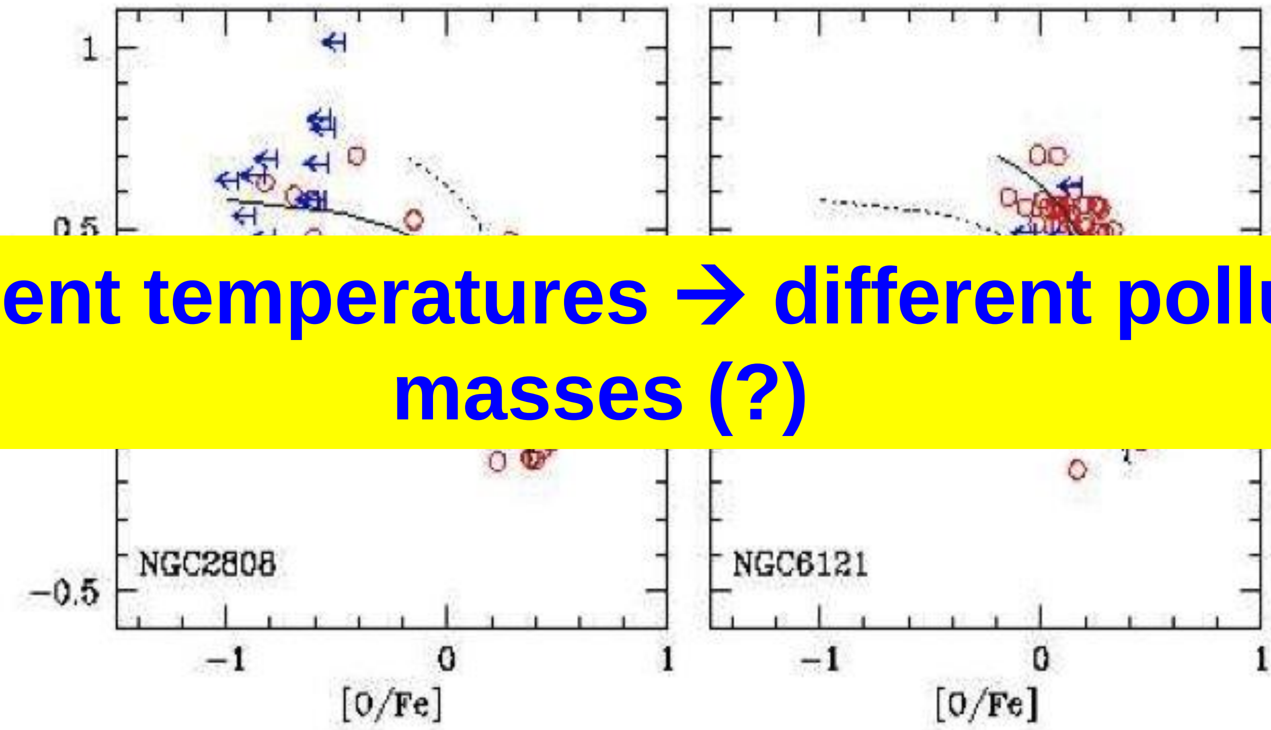
"A *bona fide* GC is a stellar aggregate showing the Na-O anticorrelation"

(Carretta et al. 2010)

↓

GCs contain multiple stellar generations born in *at least* two episodes of star formation

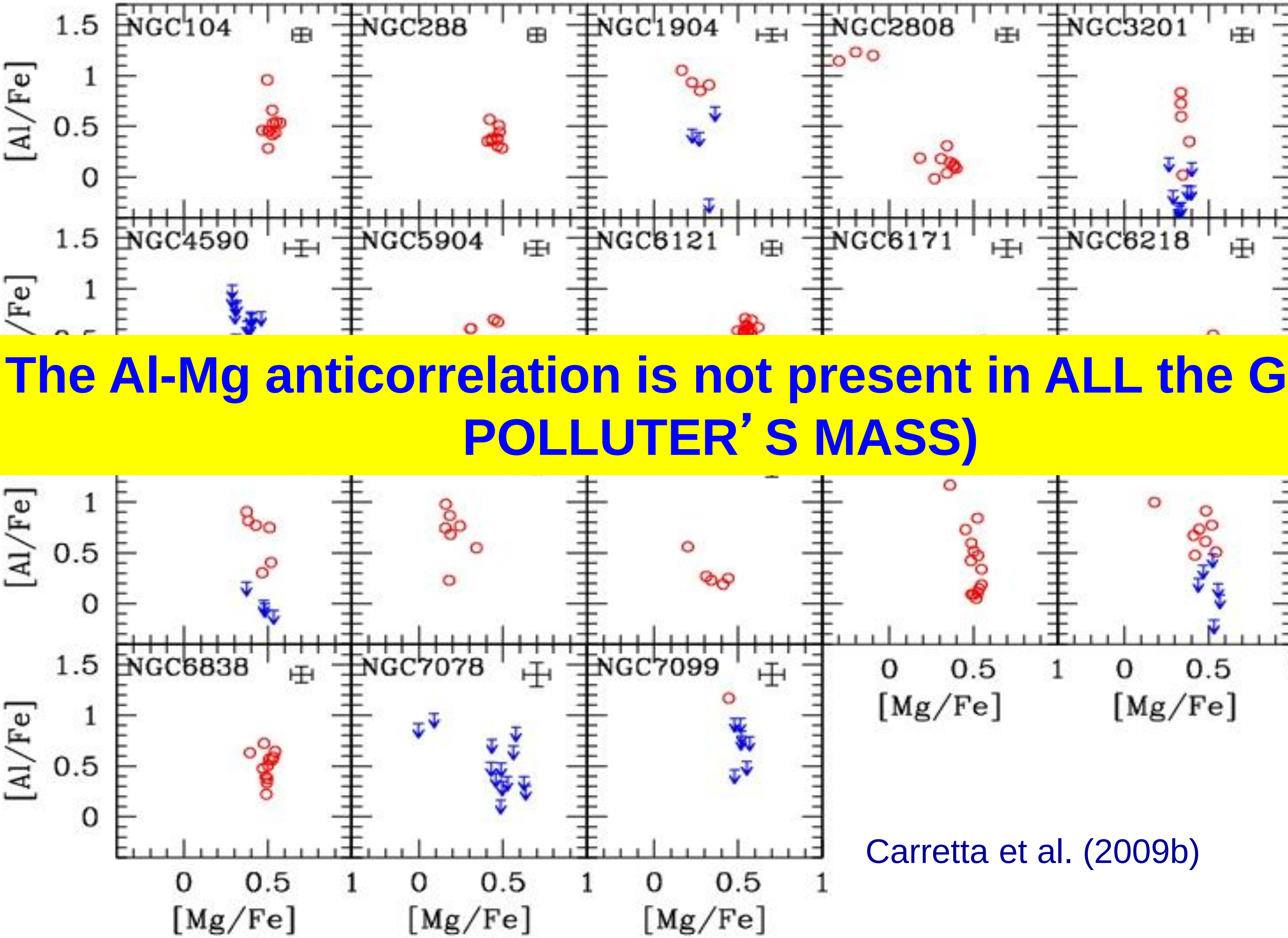
Different clusters have different Na-O anticorrelations



Different temperatures → different polluter masses (?)

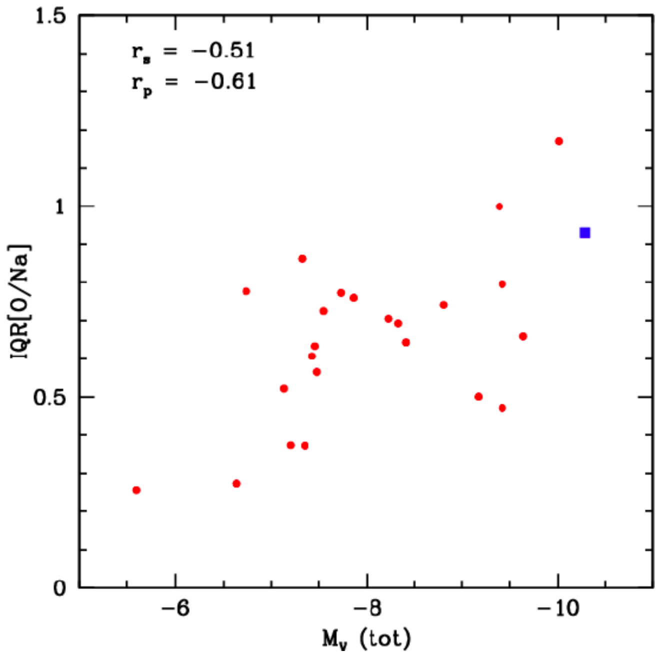
The shape and the extent of the Na-O anticorrelation vary from GC to GC

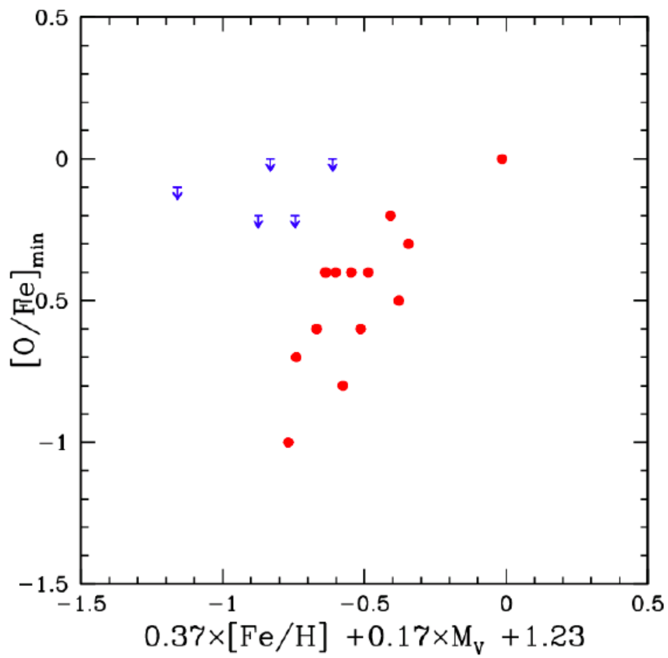
The Al-Mg anticorrelation



The Al-Mg anticorrelation is not present in ALL the GCs (→ POLLUTER'S MASS)

Carretta et al. (2009b)





The O_{min} = f ([Fe/H],M_V)

Different $[O/Fe]_{min}$ +
similar [Fe/H]

→$[O/Fe]_{min}$ depends on M_V (mass)

Larger average polluter mass..?

Most favourite candidate polluters

(alterations in light elements, heavier elements unmodified)

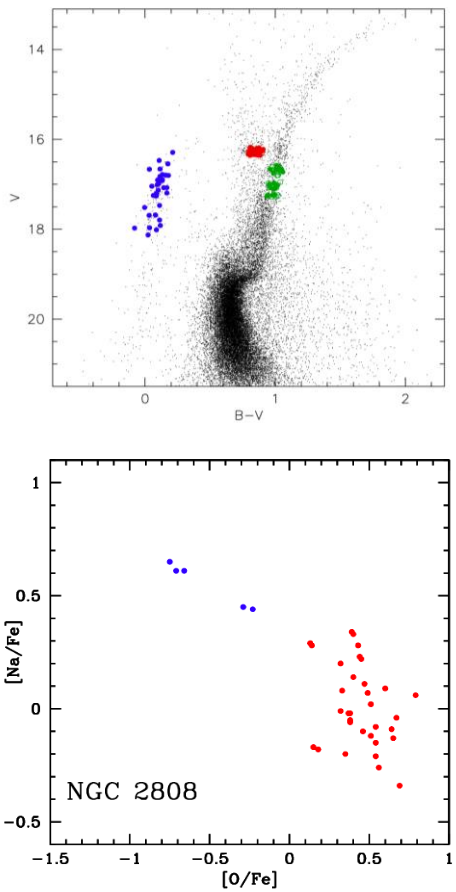
Candidate Polluter	**Location of H-burning**	**Mass involved**	**Pollution**
Intermediate Mass AGB stars (IM-AGBs, Ventura et al. 2001)	Hot Bottom Burning	4 – 8 $M_\odot$	Slow winds and envelope ejection
Fast Rotating Massive stars (FRMS, Decressin et al. 2006)	Core He-burning	20 – 120 $M_\odot$	Slow equatorial winds

Other suggestions: MASSIVE BINARIES (de Mink et al. 2009, Izzard et al. 2013); NOVAE (Maccarone & Zurek 2012)

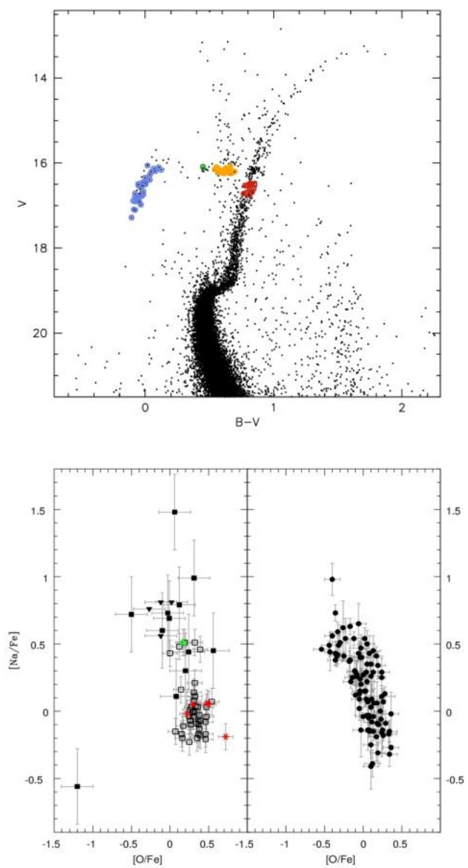
(Some) Open Issues

1. Relations of p-capture element variations with global GC parameters, e.g., the HB morphology ? (see Raffaele’s talk)

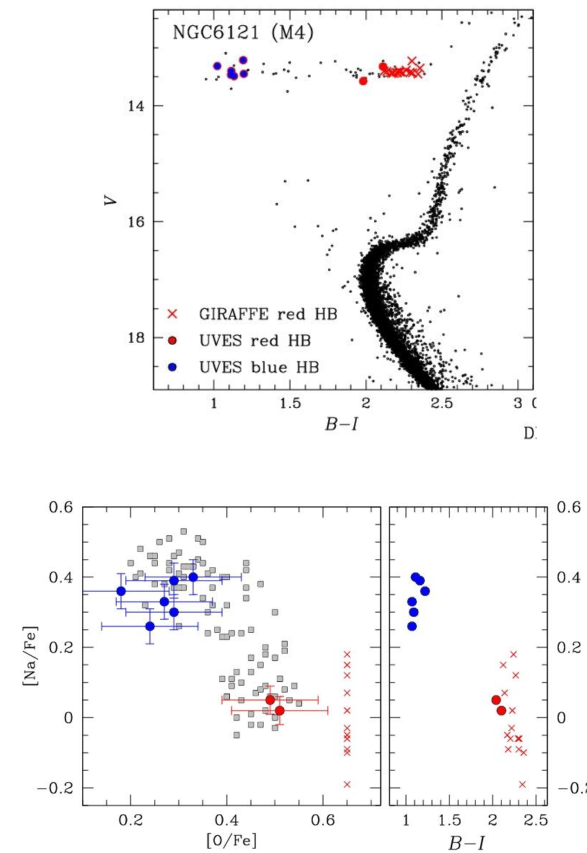
NGC 2808



NGC 1851



NGC 6121 (M4)



Gratton et al (2011, 2012)

Marino et al. (2011)

(Some) Open Issues

~~1. Relations with global GC parameters, e.g., the HB morphology ? (see Raffaele's talk)~~

2. The nature of the polluters

Fast Rotating Massive Stars	Intermediate-mass AGB stars
PRO: May produce Y up to Y~0.4 CON: Timescales close to SNII (how do we avoid Fe variation?) Yong et al. 2005) NO Li production	PRO: No close over-imposition with core-collapse SNe They can produce discrete values Hard to match the highest level of Na enhancement and/or O depletion unless fine-tuning of input physics (convection treatment + fast mass loss rate; Ventura & D'Antona 2005, D'Orazi et al. 2013a) Rb (s-process elements in general, D'Orazi et al. 2013a,b)

Both candidates require GCs were initially much more massive (preferentially lost of FG stars) or a very peculiar IMF

Ask lithium…

It is expected that at CNO/NeNa cycle temperatures occur NO Li is left

→ Polluting material (ejected from the first generation stars) has Li ~ 0

(under the assumption that there is NO Li production within the polluters)

Na-poor, O-rich stars (FG stars) should be Li-rich

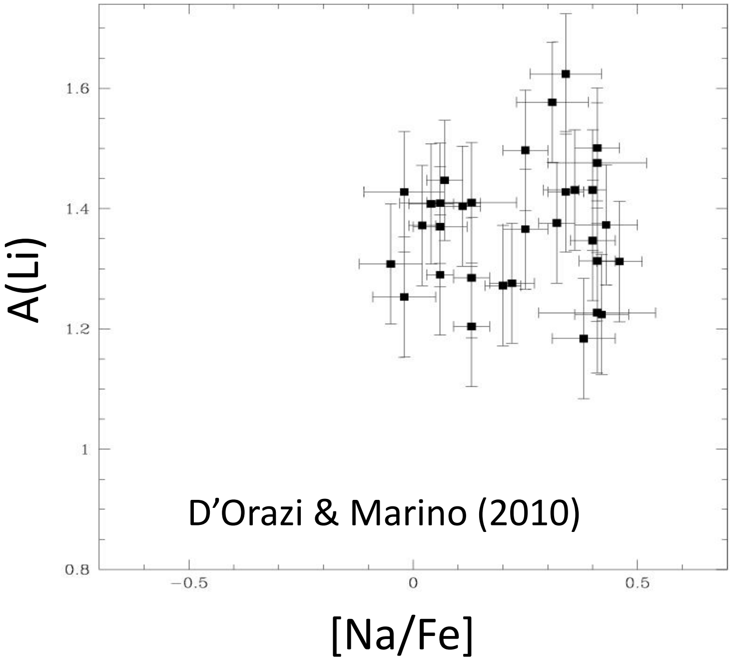
Na-rich, O-poor stars (SG stars, formed from gas progressively enriched by the ejecta of the first population) should be Li poor

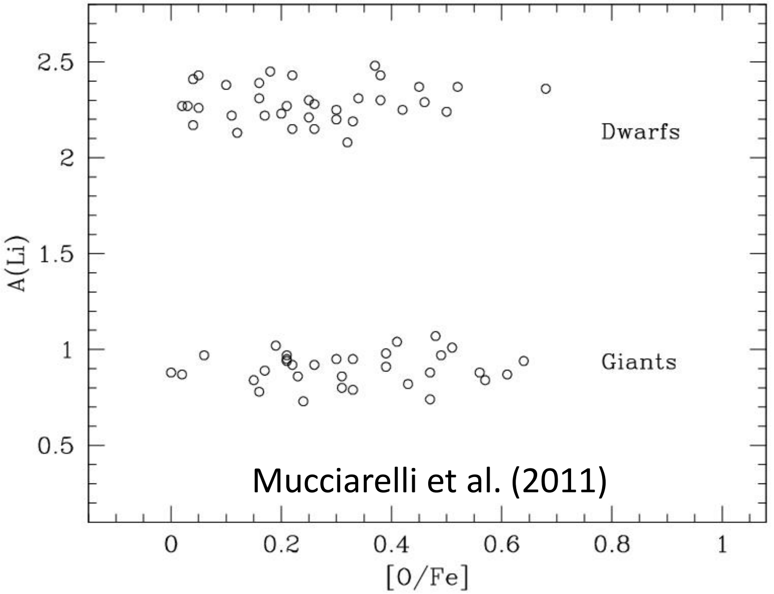
LITHIUM AND OXYGEN ARE EXPECTED TO BE CORRELATED, AND LITHIUM AND SODIUM ANTICORRELATED

While Fast Rotating Massive Stars can only destroy Li, the IM-AGB stars can also produce it via THE CAMERON-FOWLER MECHANISM ("^{7}Be transport" mechanism, Cameron & Fowler 1971)

Any production of Lithium tends to erase the Li–O(Na) (anti–)correlation

The case of M4





NO Li – O positive correlation and Li-Na anticorrelation:
FG Stars and SG stars SHARE the same Li abundances

Take-home message: Lithium has been produced between the First and the Second Generation (DILUTION is NOT the explanation!)

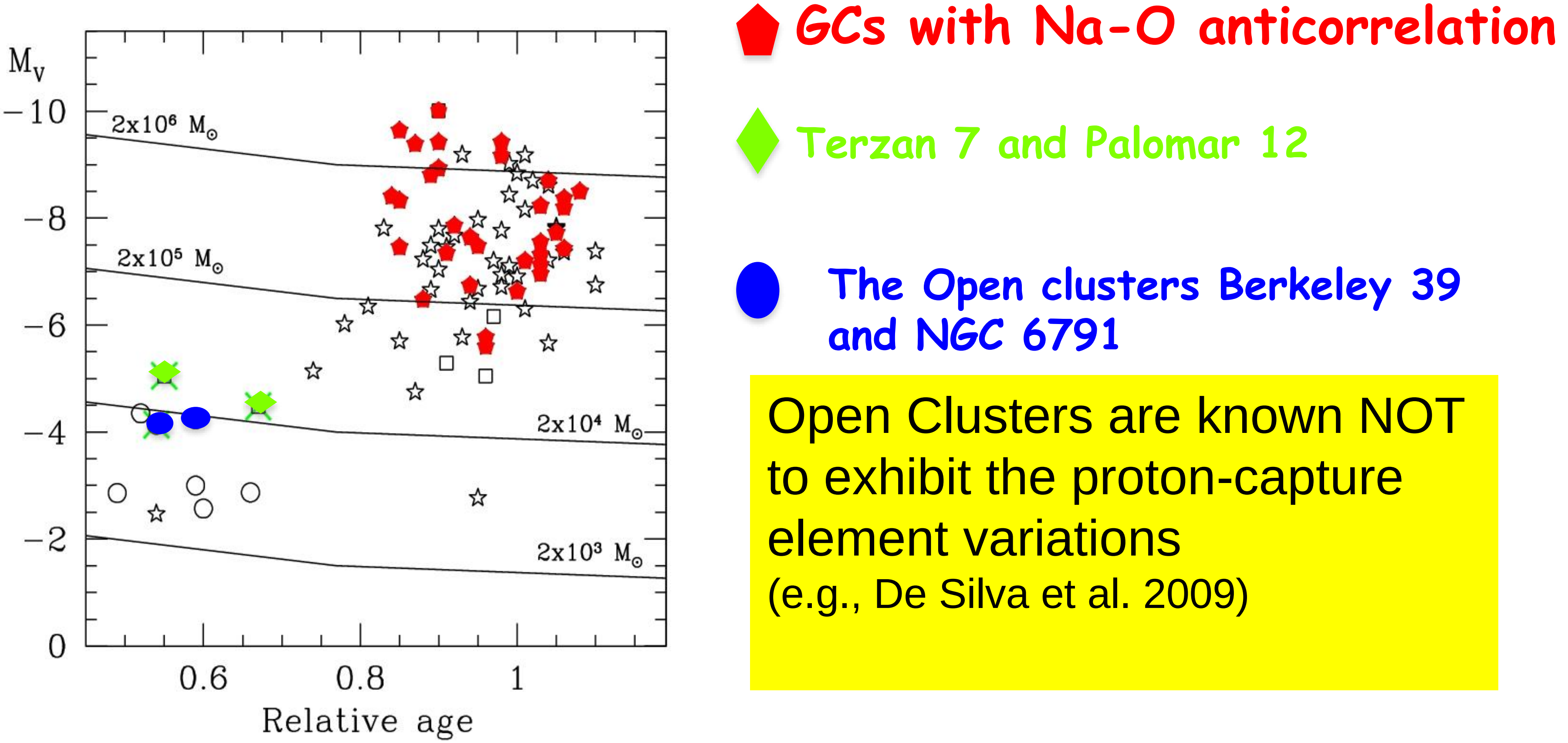
IM-AGB stars as internal POLLUTERS (?)

(Some) Open Issues

1. ~~Relations with global GC parameters, e.g., the HB morphology ? (see Raffaele's talk)~~

3. Does SIZE matter? Open Clusters *vs* Globulars

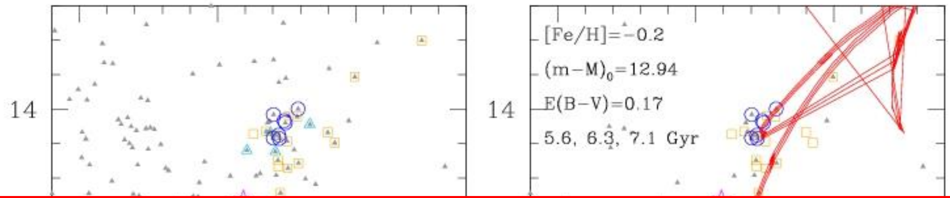
2. ~~The nature of polluters~~



Open Clusters are known NOT to exhibit the proton-capture element variations
(e.g., De Silva et al. 2009)

Gratton, Carretta, Bragaglia (2012, originally from Carretta et al. 2010)

Berkeley 39

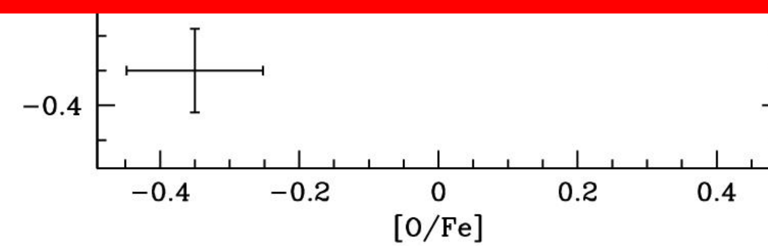


Bragaglia et al. (2012): FLAMES observations for 30 giants → Abundance analysis for several

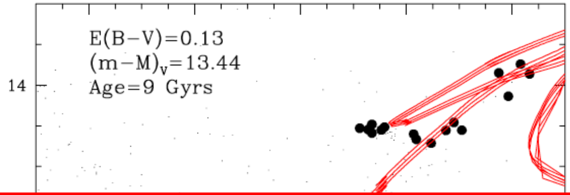
“The observations were optimised to look in particular for possible star-to-star variations in O and Na, which are indicative of the existence of multiple populations in this cluster, in analogy to what is is found for the higher mass, older GCs.

No such scatter or anti-correlation was found, and we conclude that Be 39 is a normal, homogeneous, single-population cluster”

[Ti/Fe] II	5.07	0.12	0.05		
[V/Fe] I	3.97	-0.08	0.04	-0.16	0.08
[Cr/Fe] I	5.67	-0.15	0.05	-0.13	0.08
[Mn/Fe] I	5.34	0.00	0.02		
[Ni/Fe] I	6.28	0.04	0.04	0.07	0.03
[Ba/Fe] II	2.18	0.14	0.08	0.30	0.09



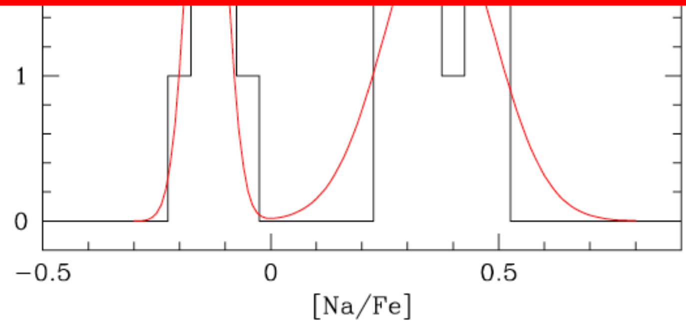
NGC 6791

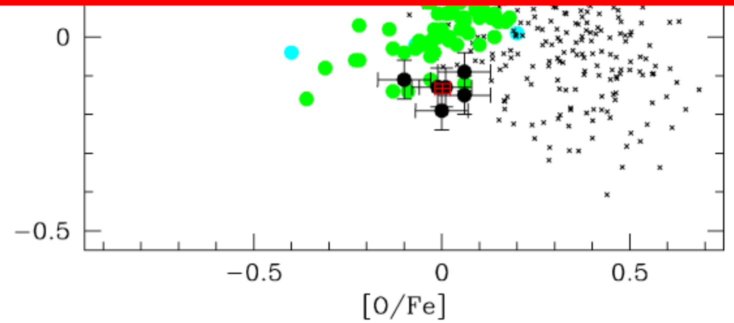


Geisler et al. (2012): HIRES @Keck I observations for 5 early RGB stars + Hydra@WYIN for 19 stars in the upper

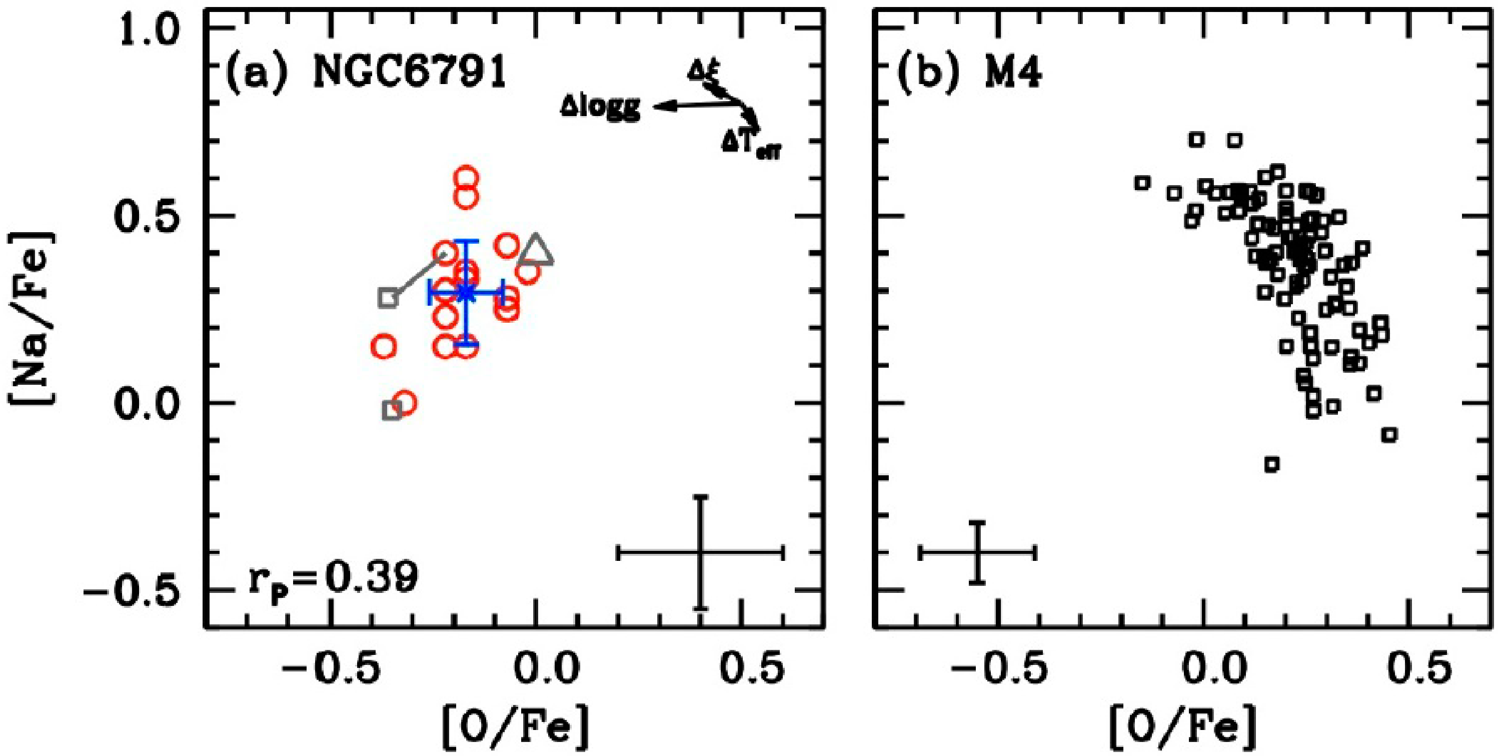
"We found a homogeneous [Fe/H]=+0.42±0.01. Surprisingly, stars are divided into two subpopulations with different mean O and especially Na contents.

Thus, NGC 6791 becomes the first OC to display an intrinsic dispersion in any element and the first presumed OC discovered with multiple populations."





NO Na-O anticorrelation NGC 6791 according to Bragaglia et al. (2013, subm.)



[Na/Fe]=0.28±0.03 (rms=0.15)
[O/Fe]=-0.18±0.02 (rms=0.08)

(Some) Open Issues

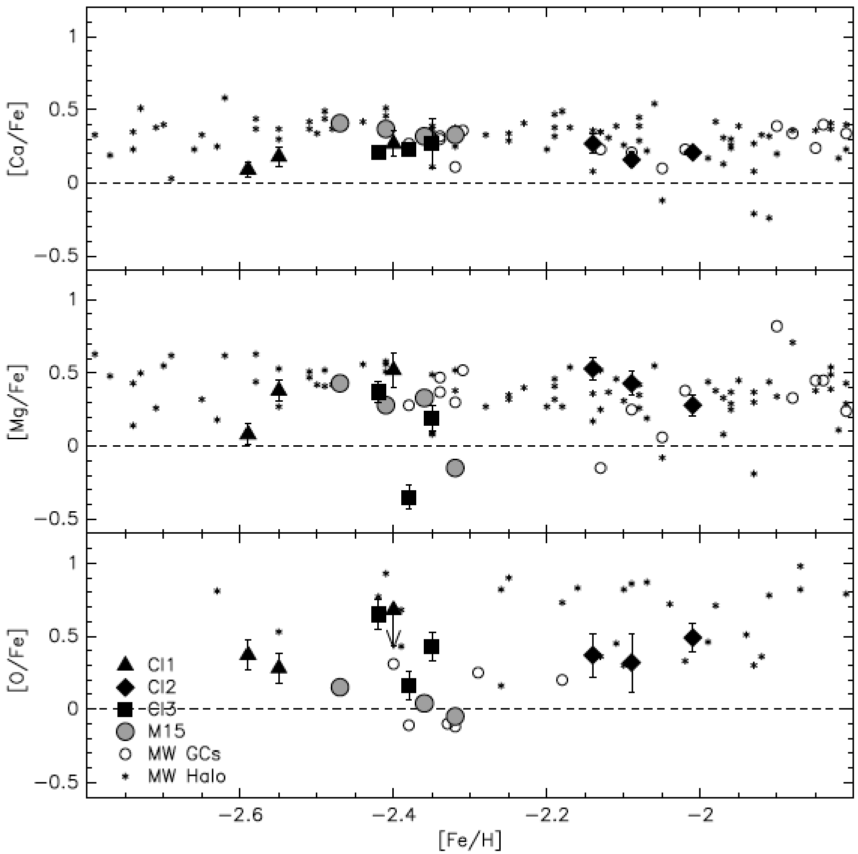
~~1. Relations with global GC parameters, e.g., the HB morphology ? (see Raffaele's talk)~~

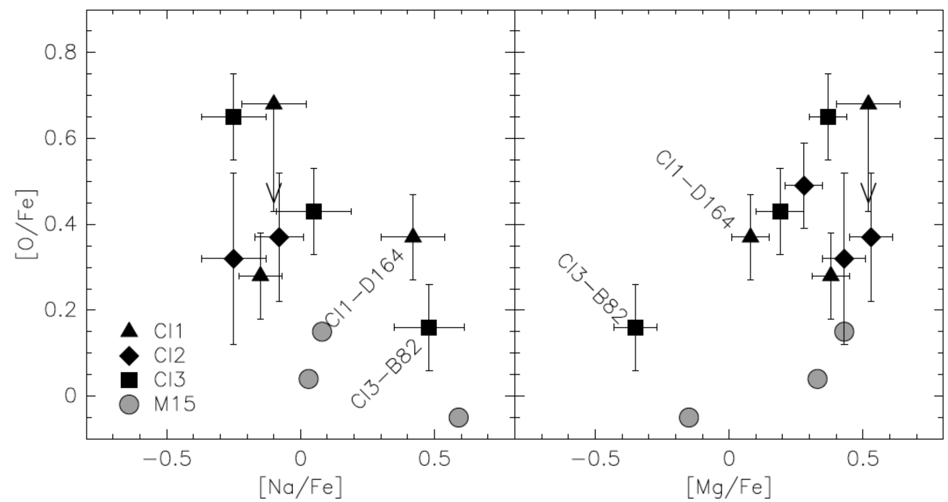
4. Environmental effect

Galactic vs extra-galactic GCs

~~2. The nature of polluters~~

The Fornax globular clusters

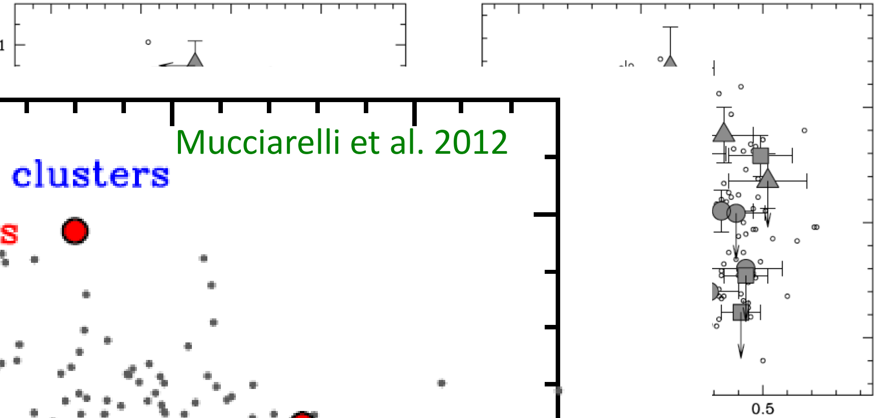


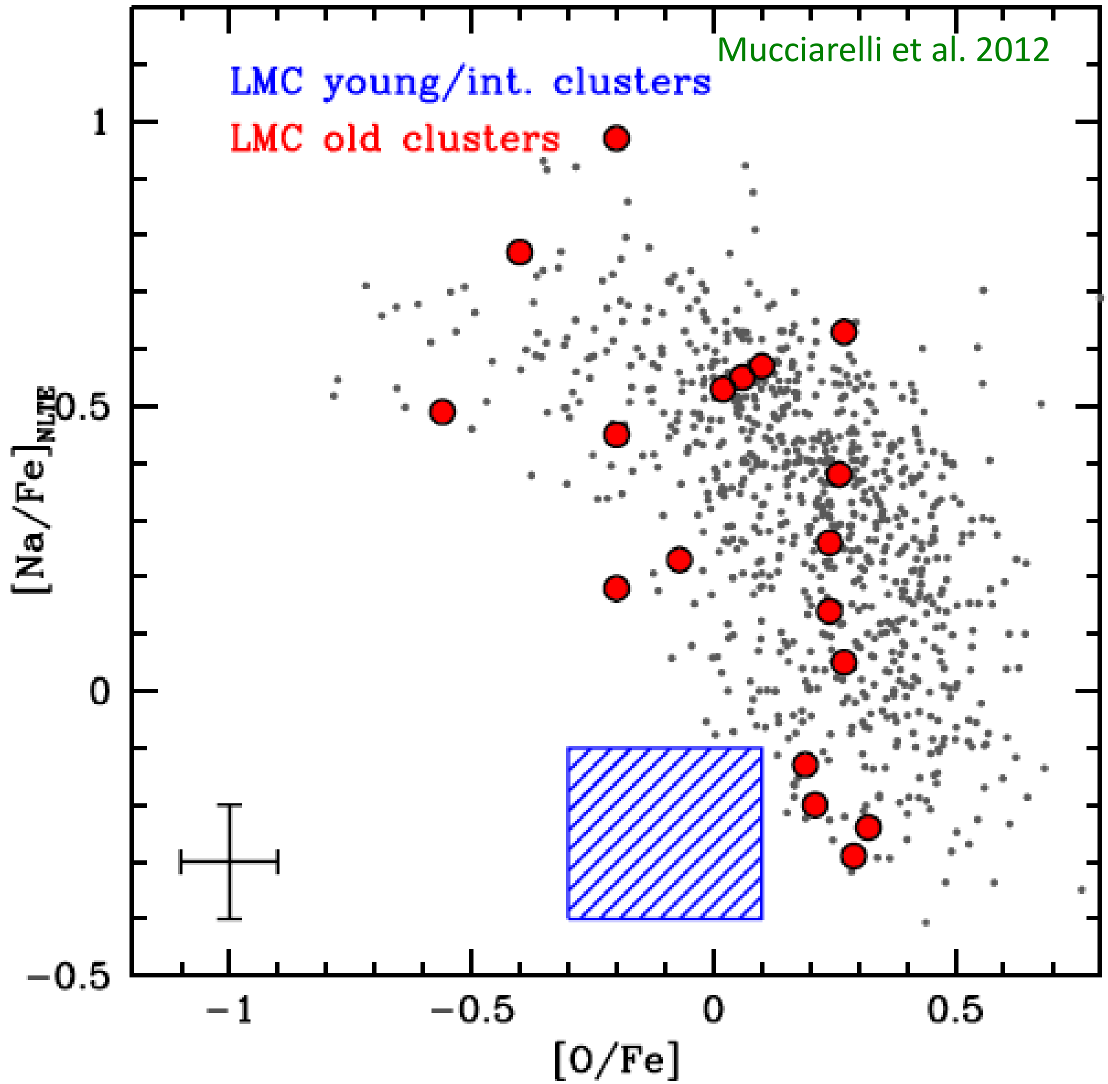


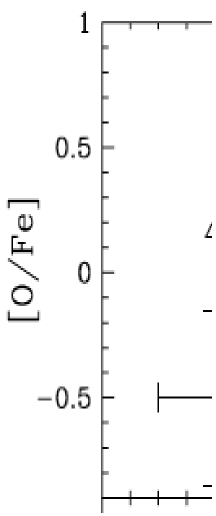
Letarte et al. (2006): 2 out of 9 stars classified as SG (one in Fornax Cl1 and one in Fornax Cl3)

The LMC globular clusters

Mucciarelli et al. (2009):
Na-O antico
GCs
(NGC 1786, N







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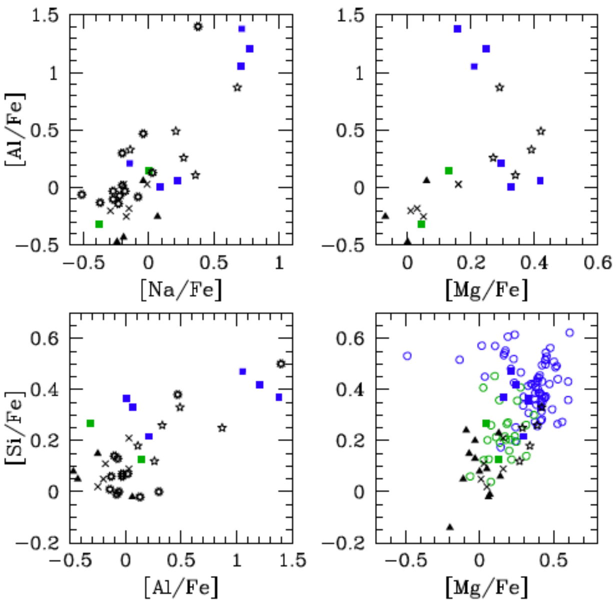
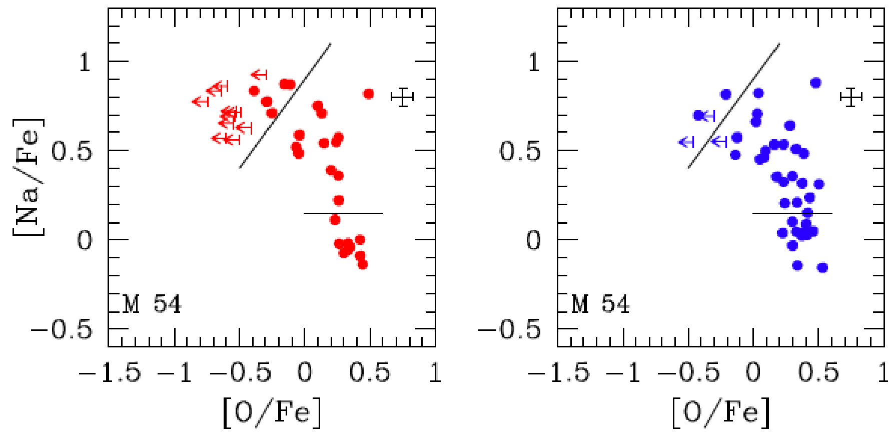
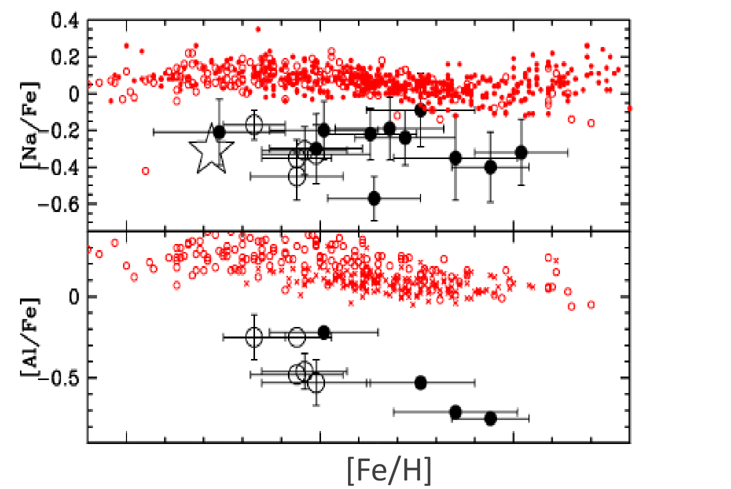
The Sagittarius dSph globular clusters

Carretta et al. 2010:
Na-O + Al-Mg anticorrelations in the (massive) GC M54



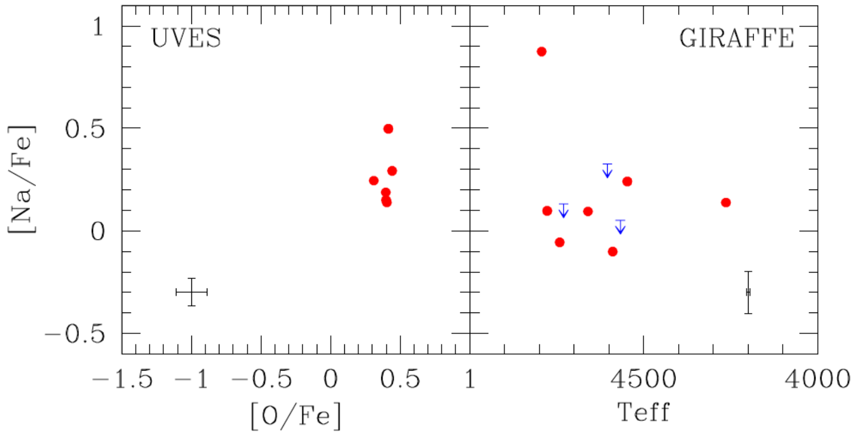


Tautvaiŝienė et al.(2004),
Sbordone et al. (2007):
No variation in Na,O, Al in Ter 7



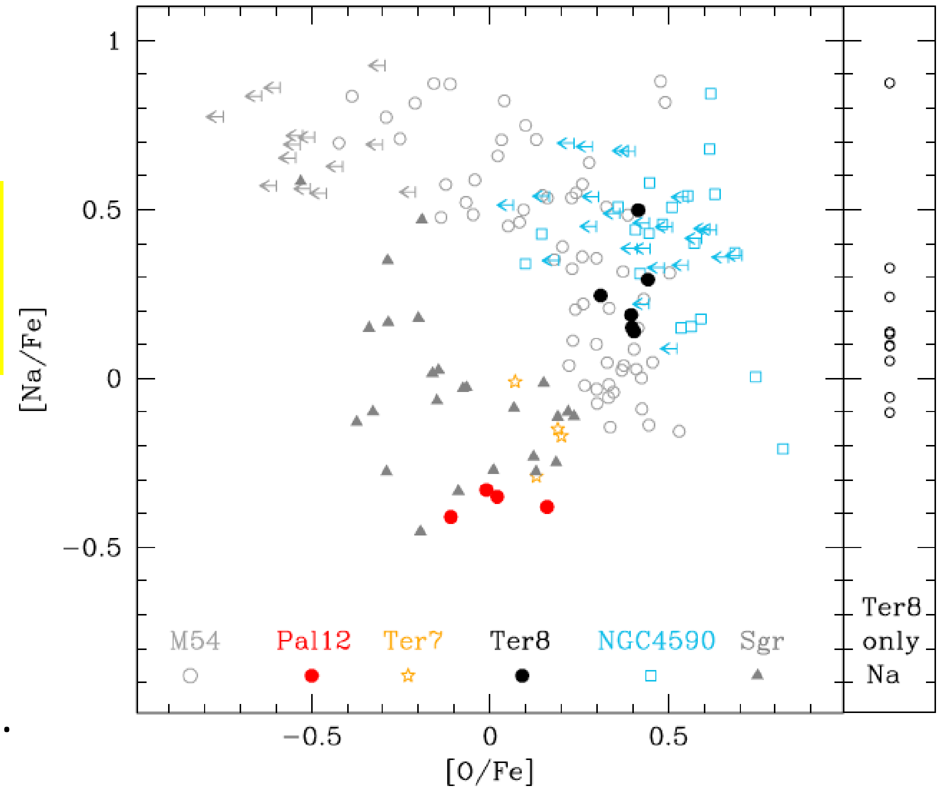
Cohen et al. (2004): Homogeneous Na and O abundances in four giants in Palomar 12

Ion	S1 [X/Fe] (dex)	S1 σ^a (dex)	S1 No. Lines	1118 [X/Fe] (dex)	1118 σ^a (dex)	1118 No. Lines	1128 [X/Fe] (dex)	1128 σ^a (dex)	1128 No. Lines	1305 [X/Fe] (dex)	1305 σ^a (dex)	1305 No. Lines
O I	0.04	0.04	2	0.21	0.19	2	−0.06	0.21	2	0.07	0.13	2
Na I.........	−0.47	0.18	4	−0.52	0.16	4	−0.55	0.20	4	−0.49	0.16	4



Carretta et al. (2013, subm.):
Giraffe spectra for 10 giants (Fe, Na)+UVES for six RGB (Fe, Na, O) in Terzan 8

None of the stars show O depletion and only one exhibits Na overabundance

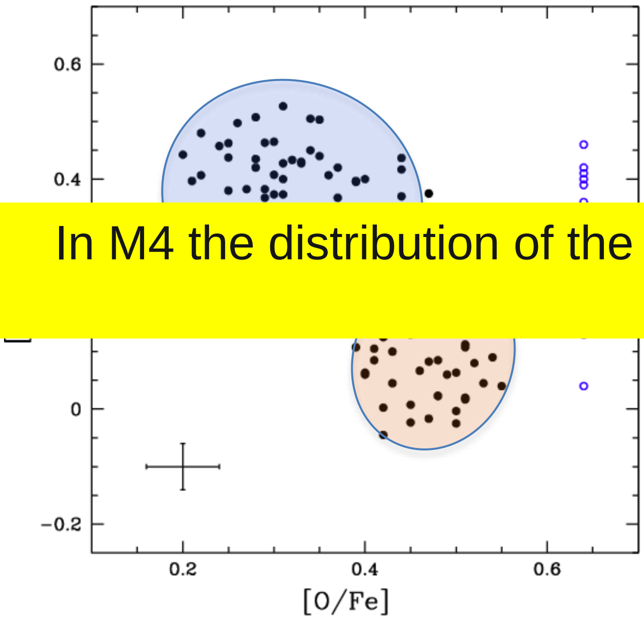


Ter 8 seems to host SG stars (actually, only one within our sample), although as a minority fraction, the opposite of what is found for higher mass MW clusters, and also at variance with other low-mass Sgr GCs, Pal 12 and Ter 7 (where no significant Na and O spread).

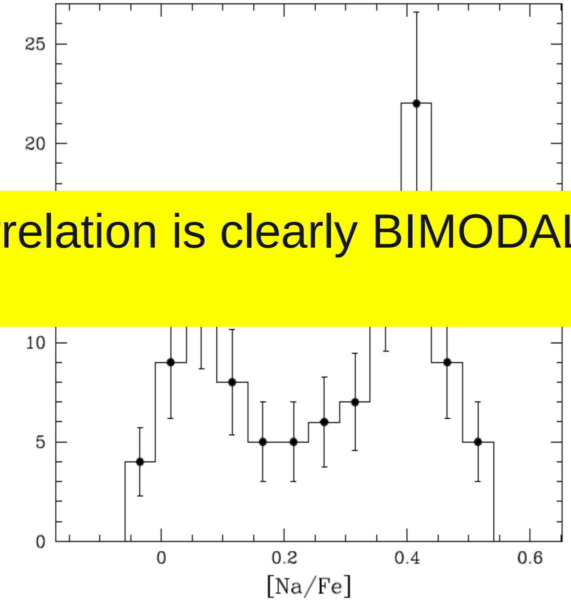
Ter 8 may represent a candidate for the class of <u>mainly-FG cluster</u>, while the two other GCs can be considered as good candidates for FG-only clusters (Caloi & D'Antona 2011), (but keep in mind that only a very few stars were analysed in the last two clusters)

Other issues include (BUT, unfortunately, are not limited to)

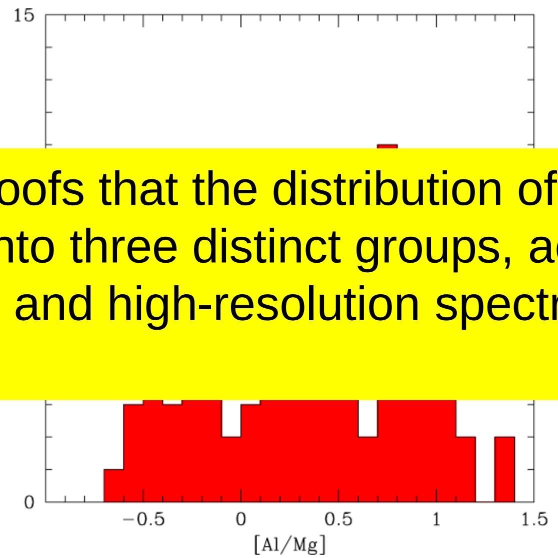
5. Continous vs discrete distributions in Na-O and/or Al-Mg planes?



NGC 6121 from Marino et al. 2008



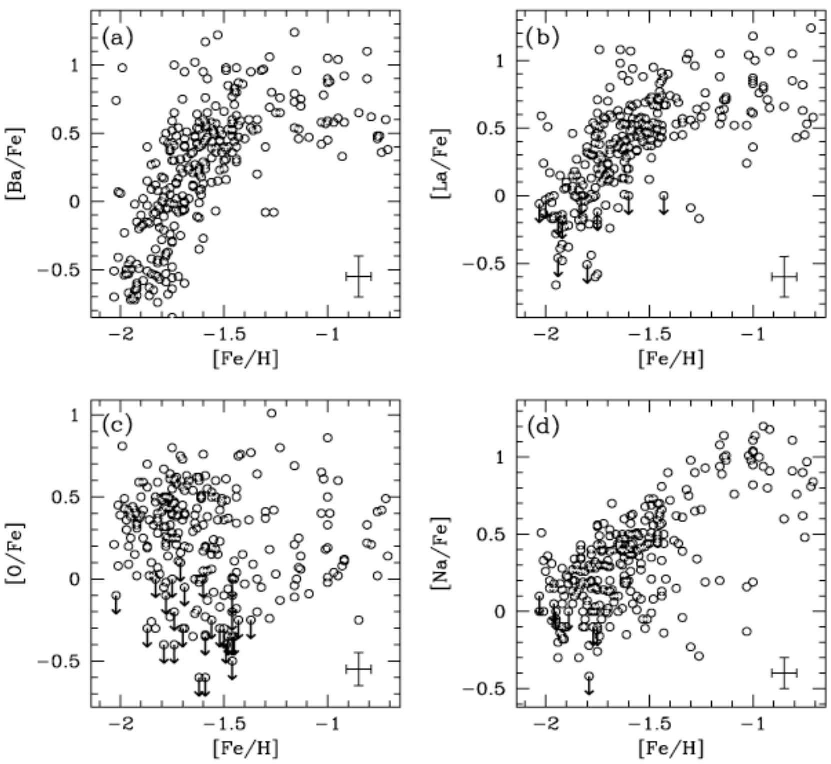
In M4 the distribution of the objects on the Na-O anticorrelation is clearly BIMODAL



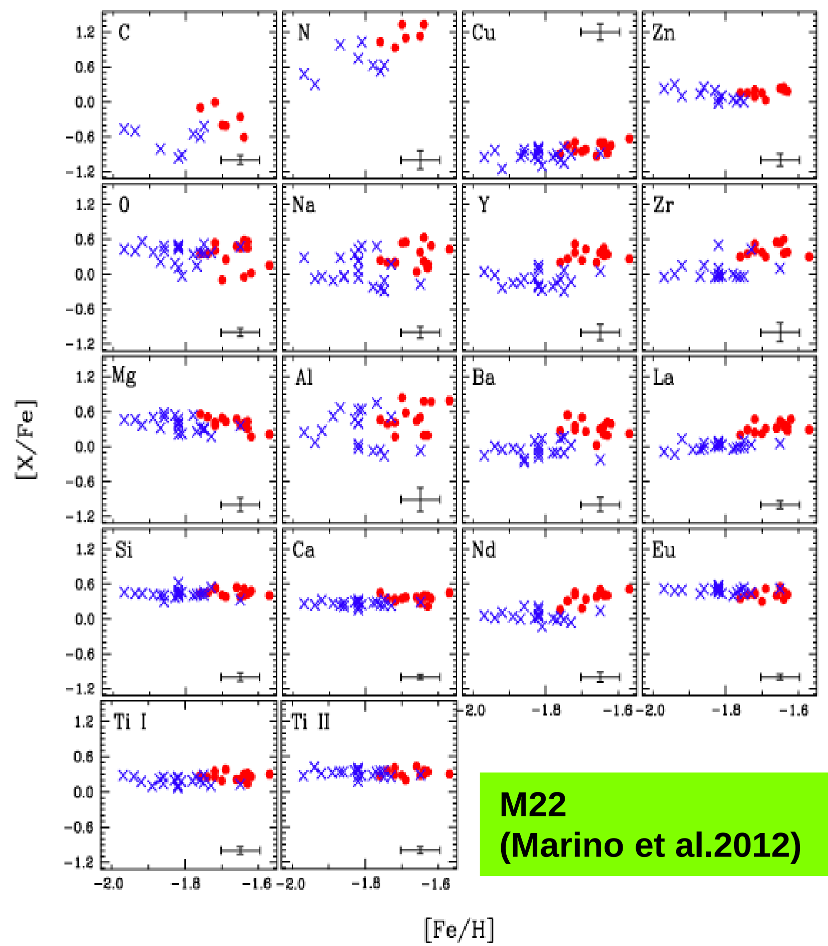
We provide two independent proofs that the distribution of giants in NGC 6752 is multi-modal, with stars segregated into three distinct groups, according to both Strömgren photometry and high-resolution spectroscopy.

6. The *exotic* Globular Clusters: ω Centauri, M22, NGC 1851, M54..

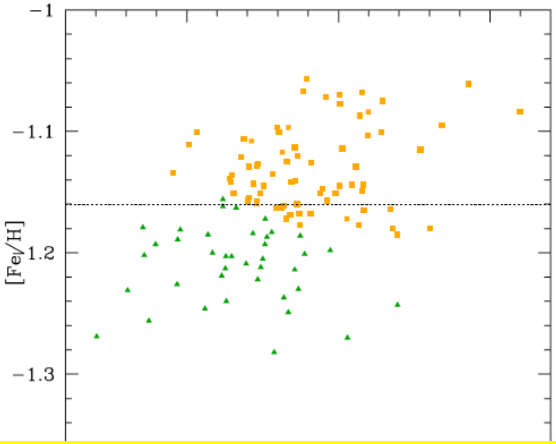
Along with the the usual variations in elements affected by p-capture we detect significant variations in: [Fe/H], α-elements, *s*-process elements (to a different extent)

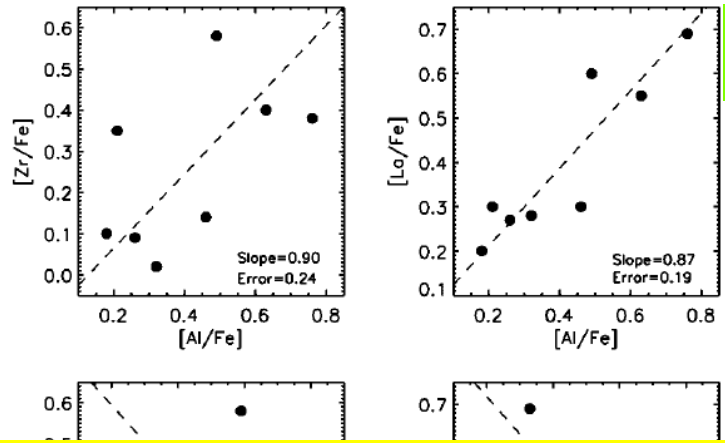


ω Centauri (Marino et al. 2011)



M22 (Marino et al.2012)

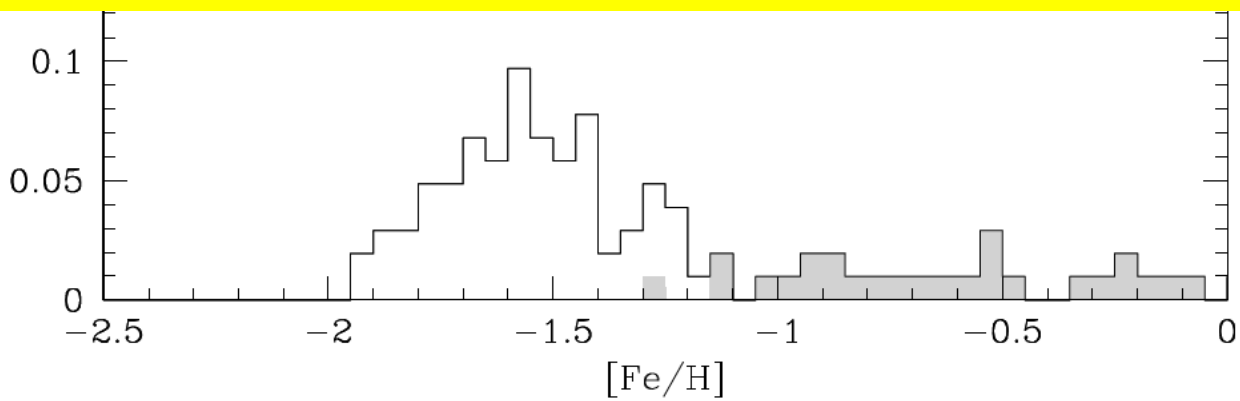




NGC 1851
(Yong & Grundahl 2008)

In this peculiar GCs several episodes of star formation are required

Much more complex star formation histories: different timescales → different (kind of) polluters involved



M54
(Carretta et al. 2010)

That's NOT all folks !

- What about young massive star clusters?

  (Portegies-Zwart 2004; Vinko et al. 2009; Larsen et al.2011; Neguerela et al. 2011)

- Binary fraction and density environment

  (Milone et al. 2008; D'Orazi et al. 2010; Vesperini et al. 2011)

- The GC formation scenarios

  (D'Ercole et al. 2008, 2010; Bekki et al. 2007, 2011; Conroy & Spergel 2010, Valcarce & Catelan 2011)

- The different behaviour of AGB stars

  (Norris et al. 1981; Sneden et al. 2000; Gratton et al. 2010, Campbell et al. 2010, 2013)

- The GC – Milky Way connection

  (Martell & Grebel 2010; Carretta et al. 2010; Sarah's talk)

The road is long and bendy……

BUT WE CARRY ON…