Multiple stellar populations in Globular Clusters: the cases of M22 and Omega Centauri

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OVERVIEW:

- ***“Normal Globular Clusters”***:

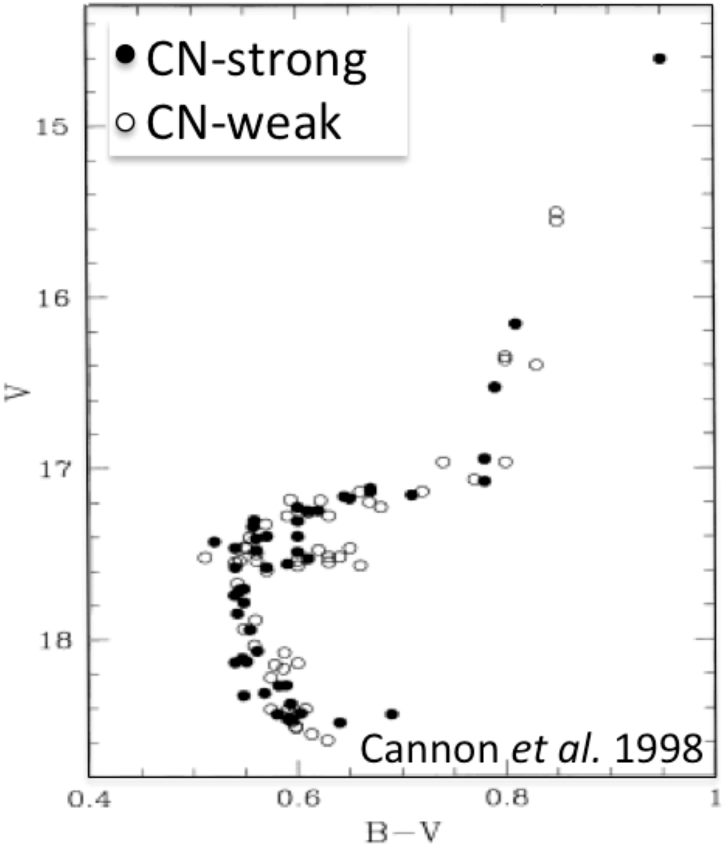
  Na-O anticorrelation

- ***“Peculiar Globular Clusters”***:
  - Metallicity, heavy elements variations
  - Na-O anticorrelations
  - The cases of M22
  - Peculiarities on the CMD

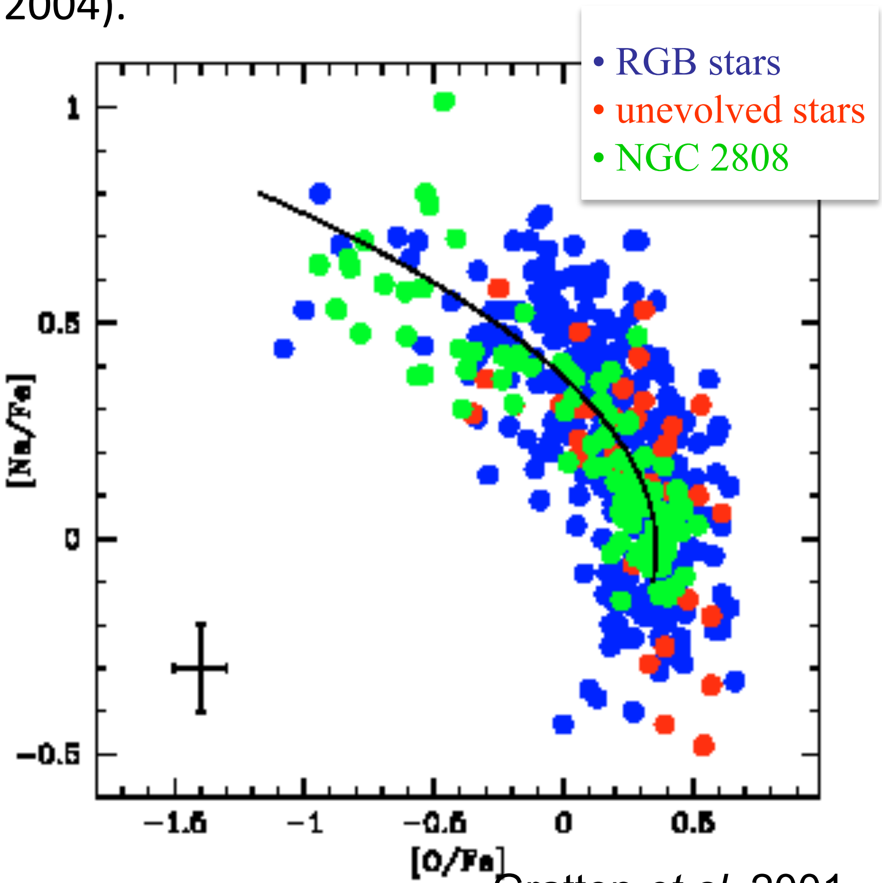
- ***“Omega Centauri”***:
  - Na-O (anti)correlations

Light elements variations and anticorrelations in GCs

Light element abundance variations occurr also in unevolved MS stars and less-evolved RGB stars. The Na-O anticorrelation was found at the level of the MSTO and SGB in M13 (Cohen & Meléndez 2005), NGC 6397 and NGC 6752 (Carretta et al. 2005; Gratton et al. 2001), NGC 6838 (Ramírez & Cohen 2002) and 47 Tuc (Carretta et al. 2004).

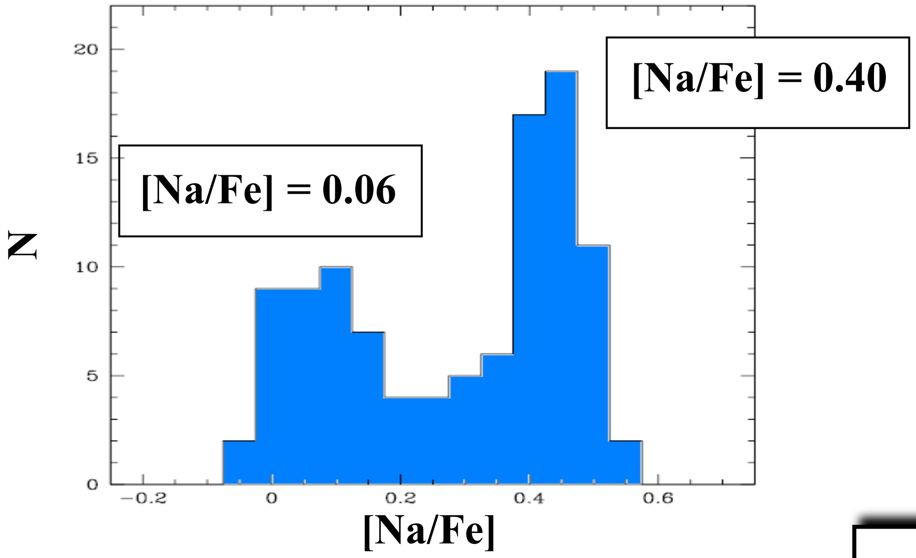


Cannon *et al.* 1998

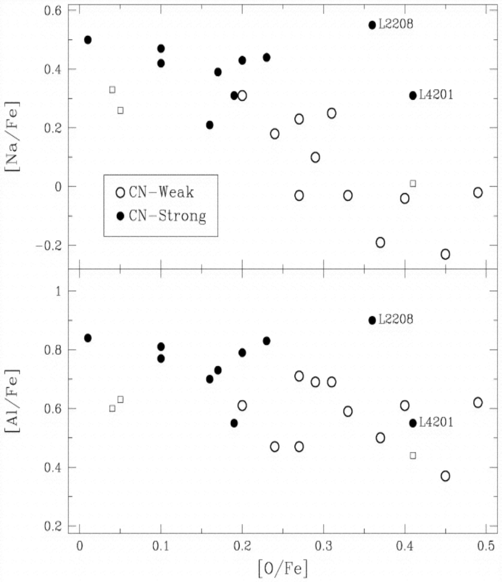


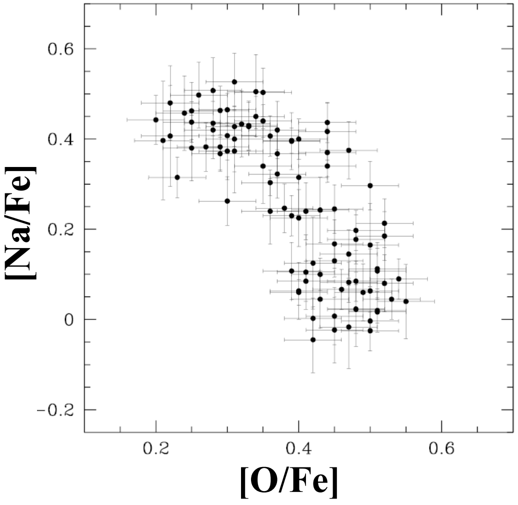
Gratton *et al.* 2001
Carrretta *et al.* 2009

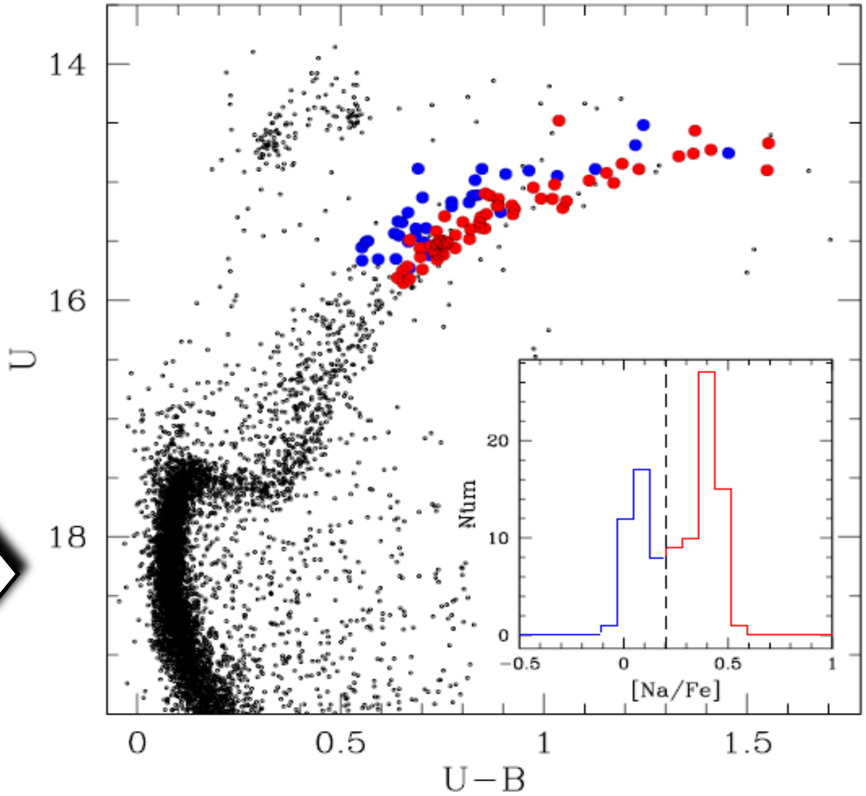
Na-O anticorrelation in GCs: The Na bimodality in M4

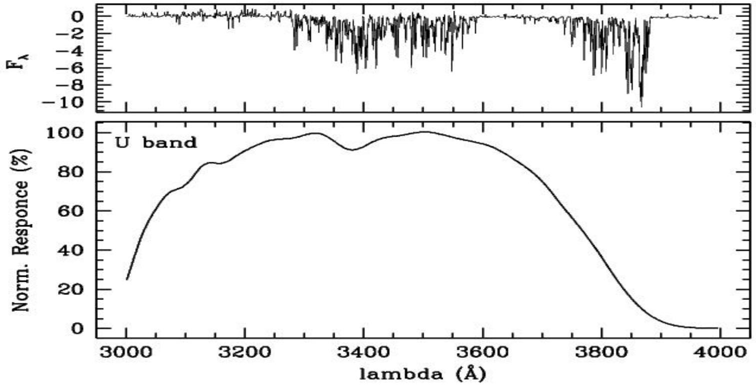


Ivans *et al.*1999, AJ,118, 1273





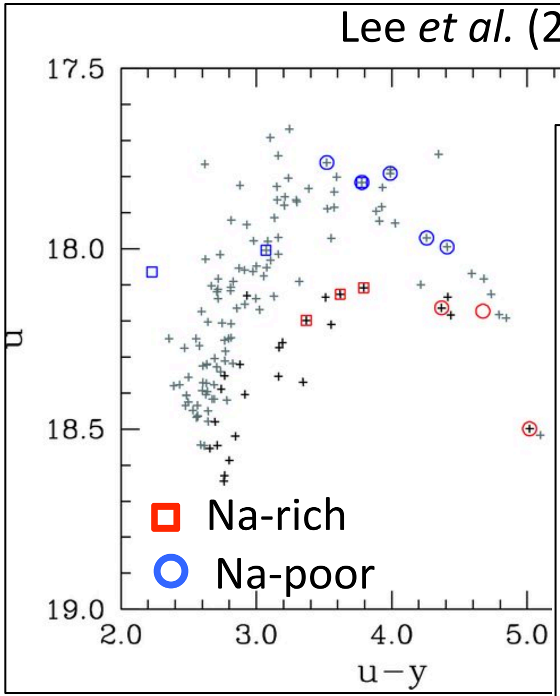




Marino *et al.* 2008, A&A, 490, 625

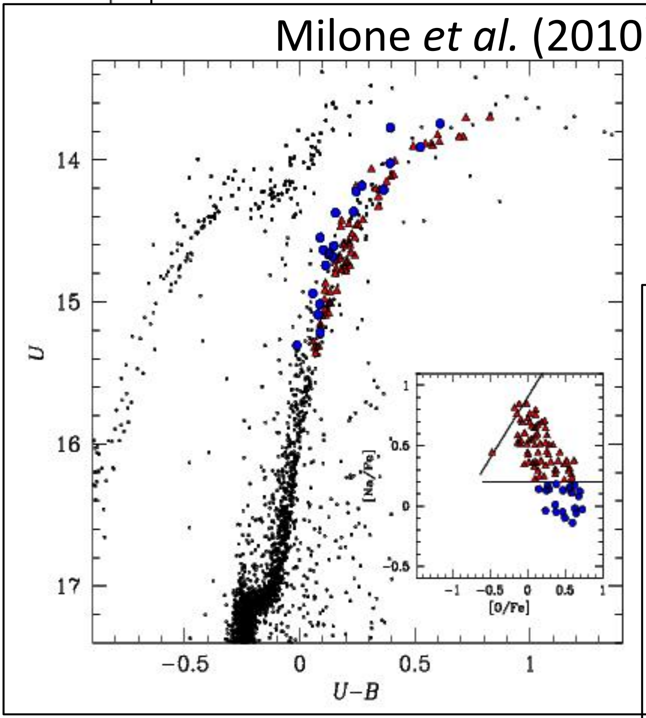
Multiple RGB and the Na-O anticorrelation:

NGC1851:



Lee *et al.* (2009)

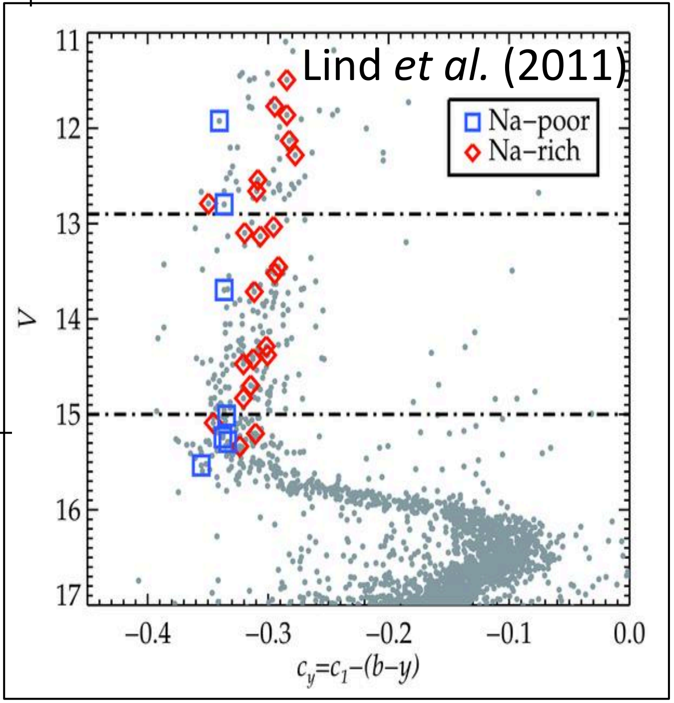
NGC6752:



Milone *et al.* (2010)

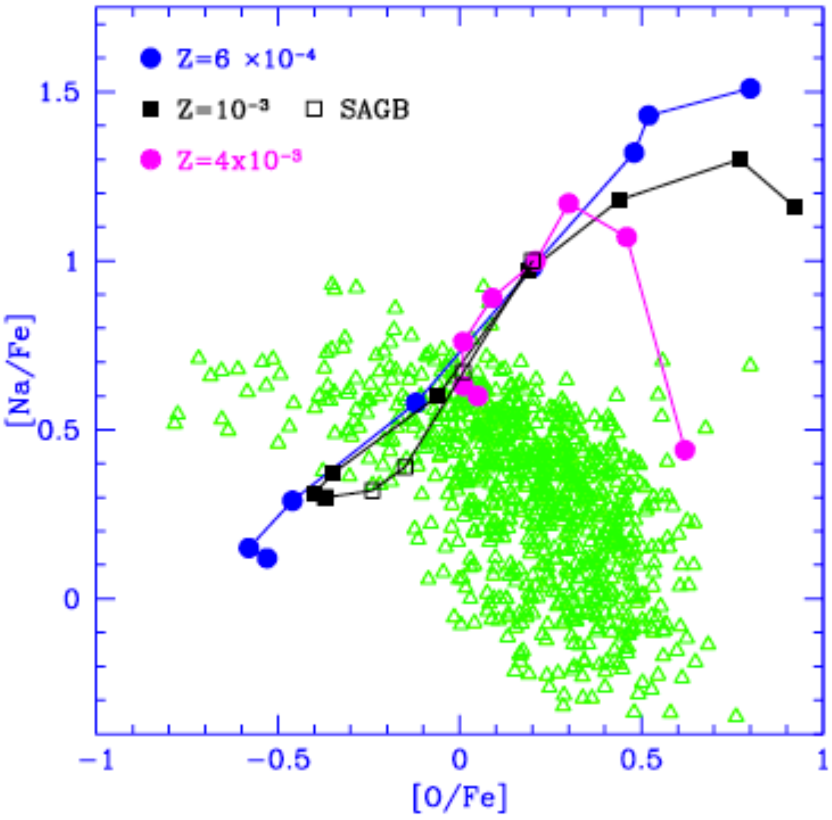
(See also Yong *et al.* 2008)

NGC6397:



Lind *et al.* (2011)

Intermediate mass AGB pollution



from D'Antona *et al.* (2011)

Hydrodinamical models for the formations of Na-O anticorrelation in *normal* GCs:
(D'Ercole et al. 2008, 2010)

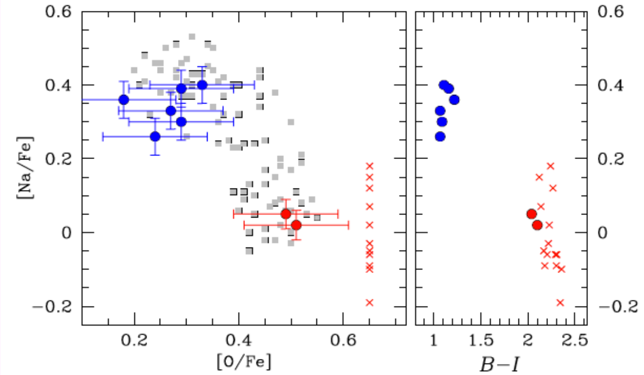
The most O-poor stars could born directly from the pure ejecta of the IM-AGBs of the FG, after the SN II epoch, that has cleared the cluster from the residual gas.

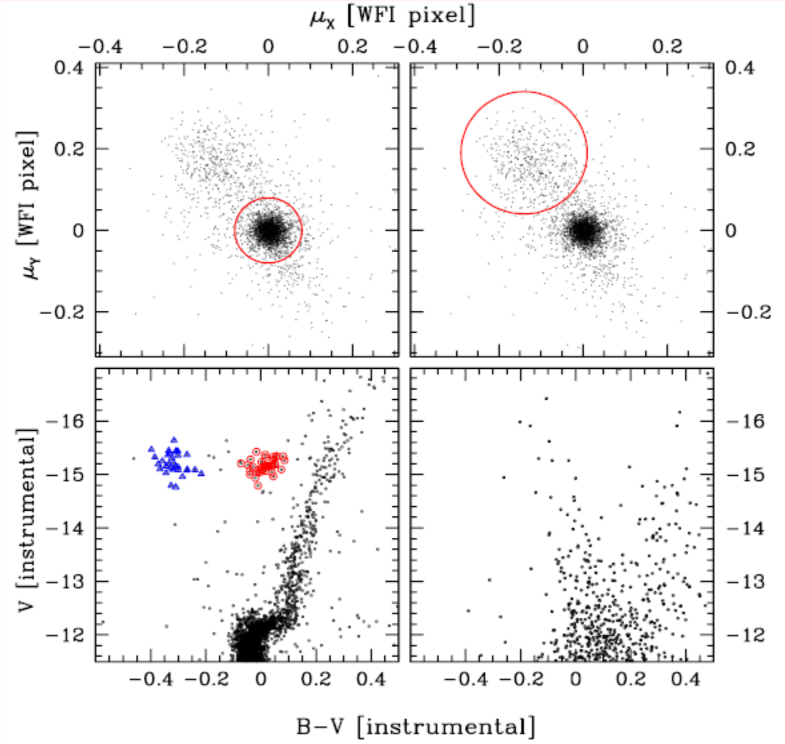
Cooling flow sets in and brings to the core the low velocity winds of the AGBs, so that stars can form directly from their very rich hot–CNO processed material.

Then a phase of mixing of the AGB ejecta with pristine gas follows, giving origin to the stars, with milder oxygen depletion.

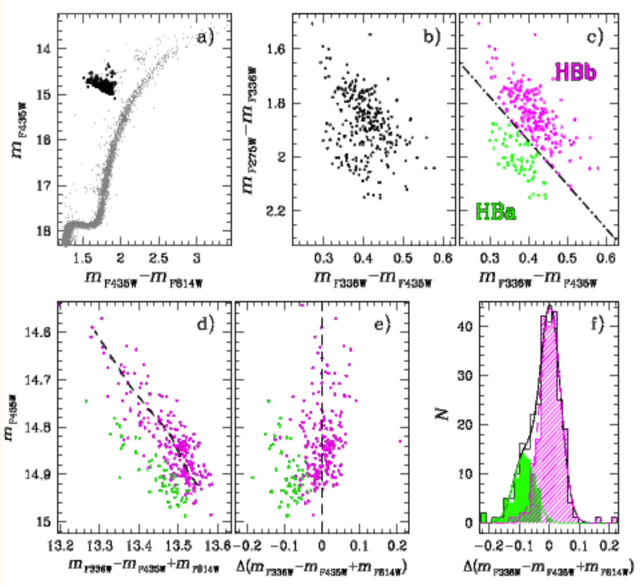
Horizontal branches and the second parameter problem

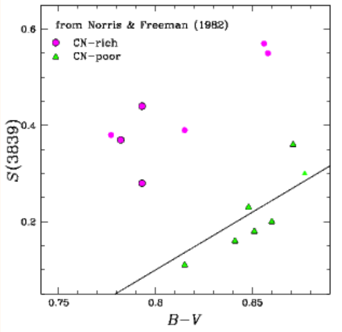
M4 (from Marino et al. 2011, ApJL, 730, 16)

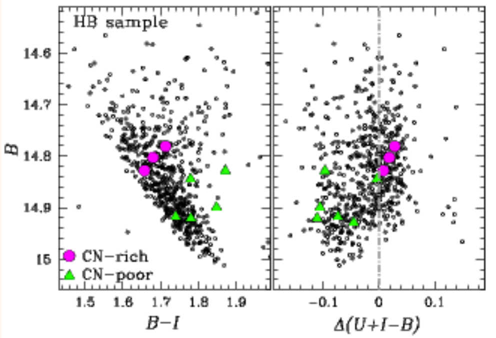




47 Tuc (from Milone et al. submitted)







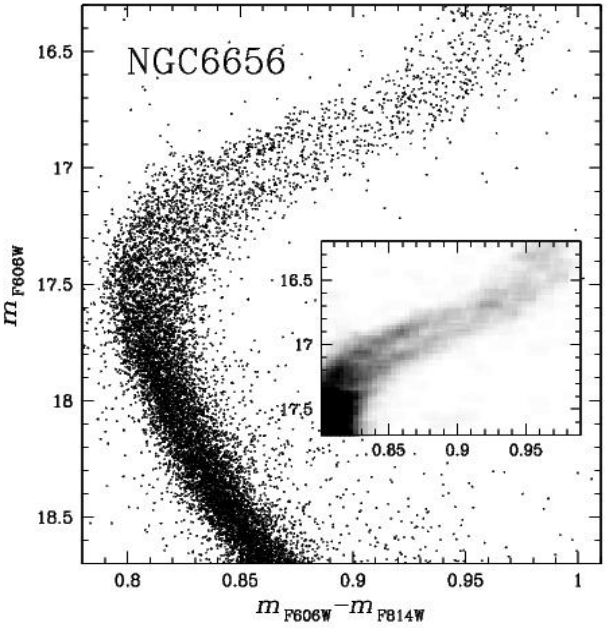
The HB morphology of 47 Tuc is not consistent with a SSP.

(Spectroscopic data from Norris & Freeman 1982)

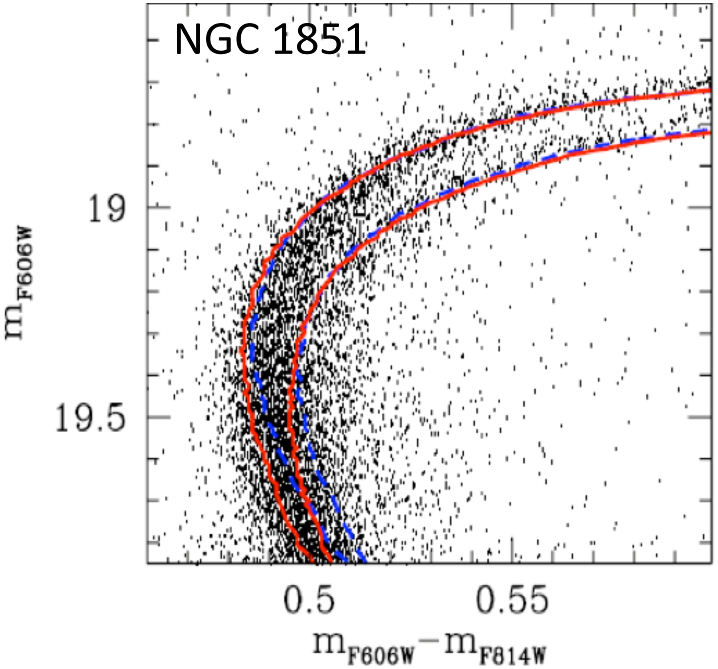
The peculiar GCs

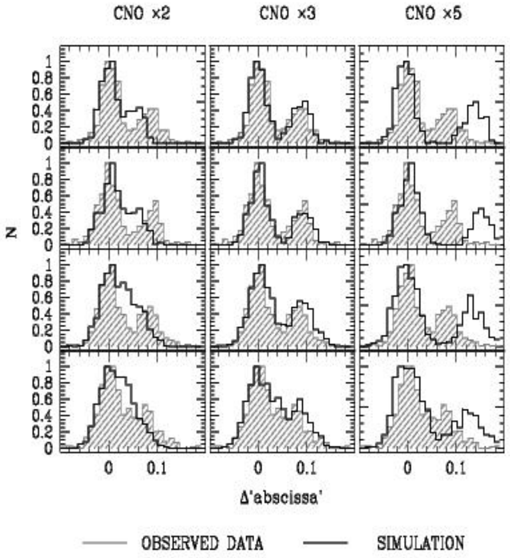
SGB splits:

Marino et al. 2009, A&A 505, 1099



Milone et al. 2008, ApJ 673, 241

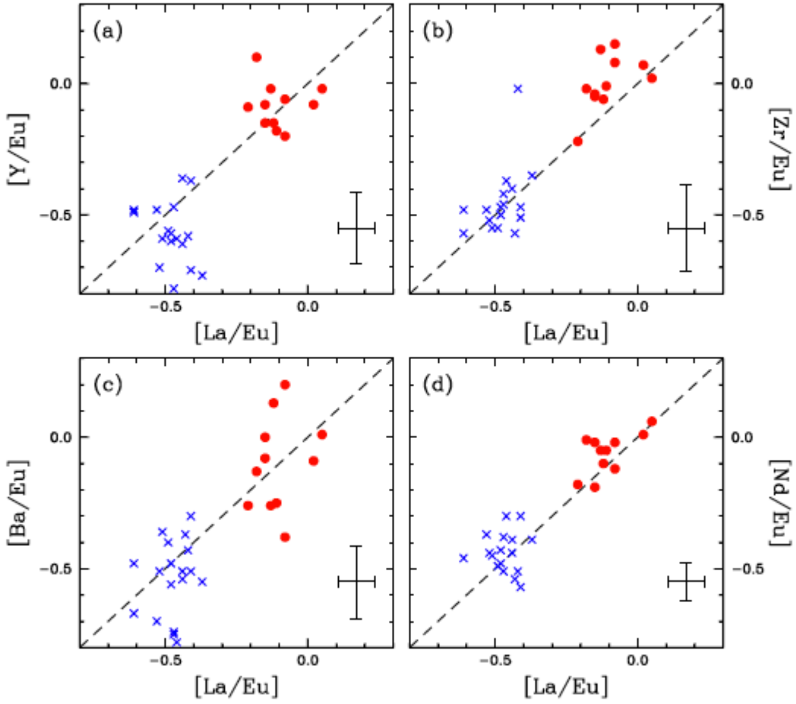


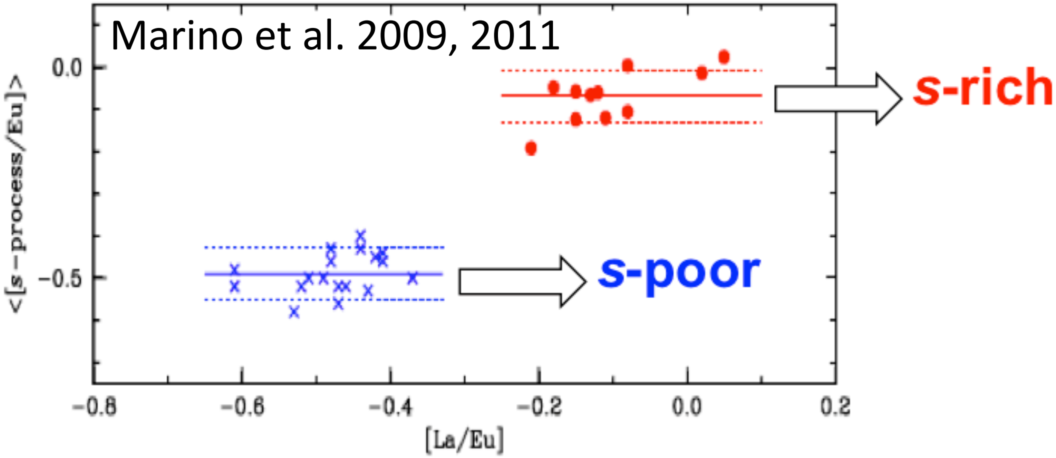


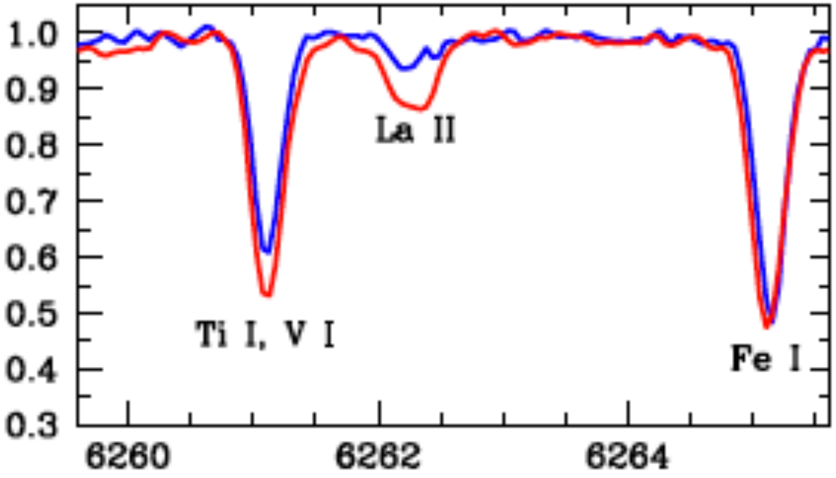
Cassisi et al. (2008) and Ventura et al (2009) showed that the split SGB could be due to the presence of two stellar populations, with the second generation enriched in the total CNO abundance by a factor of ~3.

In such a case, the age difference between the two groups may be very small (10^7-10^8 years).

The peculiar GCs: M22





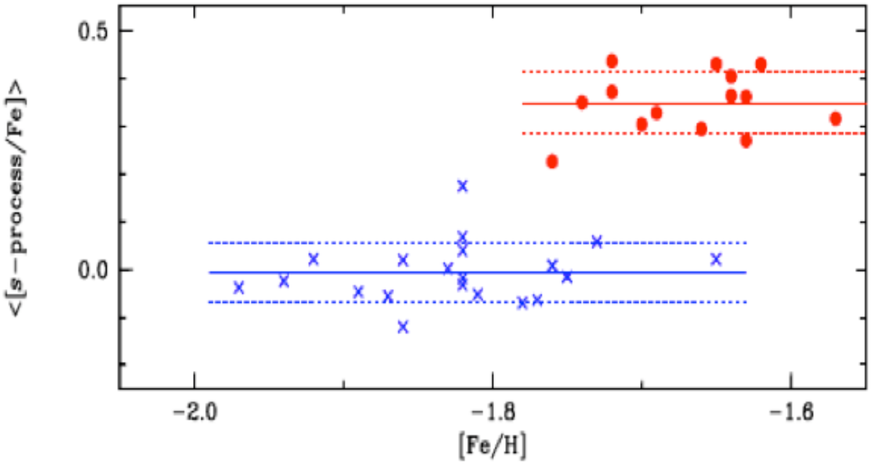


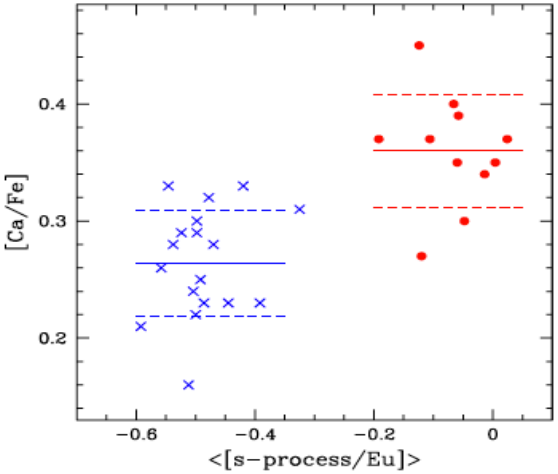
We identified two distinct stellar populations with different content of *s*-process elements.

A similar bimodality in *s*-process elements was first found also in the other split-SGB GC NGC 1851 by Yong & Grundahl (2008)

Marino et al. 2011, arXiv:1105.1523

The chemical properties of the 2 *s*-groups in M22





1. Iron: by dividing stars on the basis of their *s*-process element content, the mean [Fe/H] turns out to be ~0.15 dex higher in the s-rich stars

2. Calcium: similarly to iron, the calcium abundance is higher for the *s*-rich stars

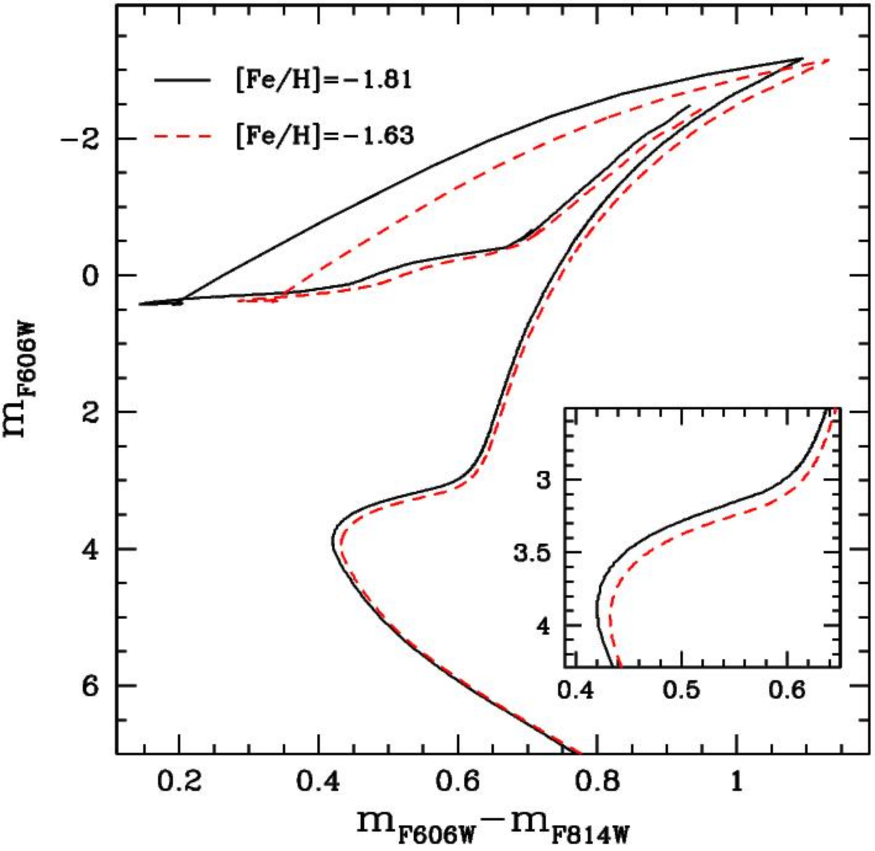
M22 has a confirmed spread in metallicity, but significantly smaller than that in ω Centauri.

Spread in metallicity were successively found also in the other GCs:

1. M22 (Marino et al. 2009, Da Costa et al. 2009)
2. M54 (Carretta et al. 2010)
3. Terzan 5 (Ferraro et al. 2010)
4. NGC2419 (Cohen et al. 2010)

The SGB split of M22

Fainter SGB stars are very likely the progenie of *s*-elements rich, iron rich RGB stars

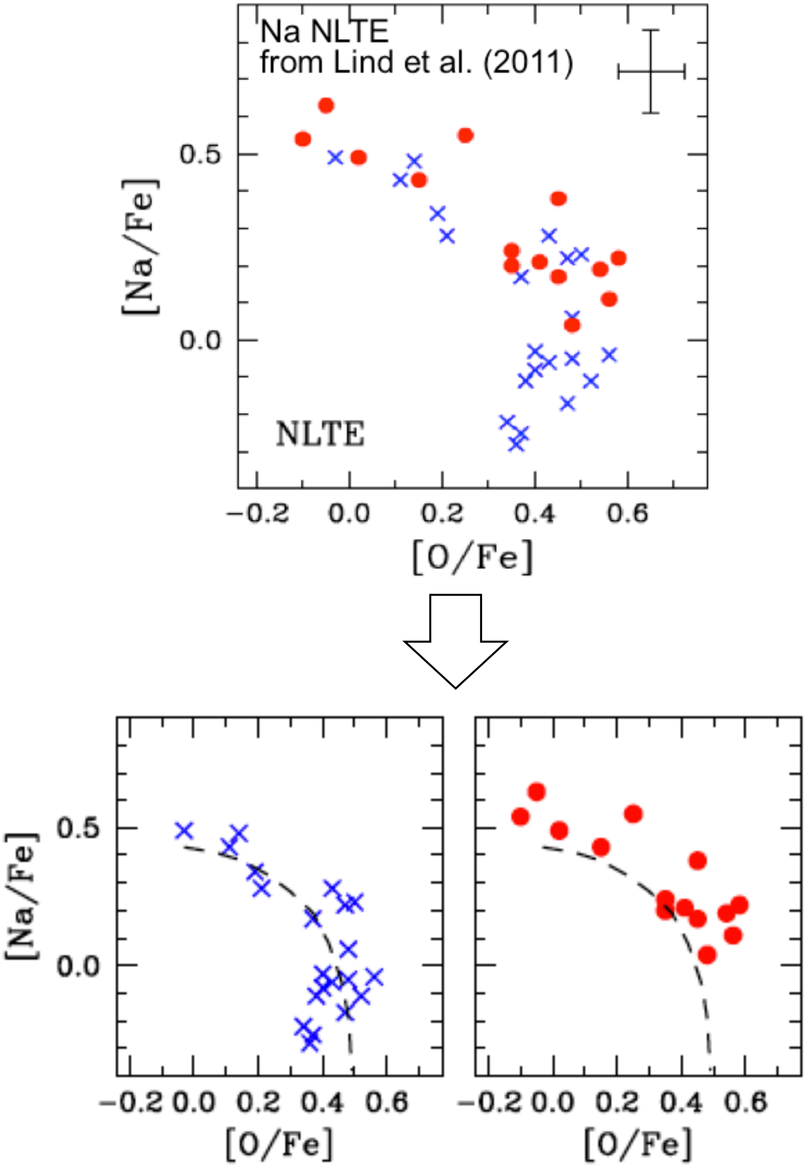


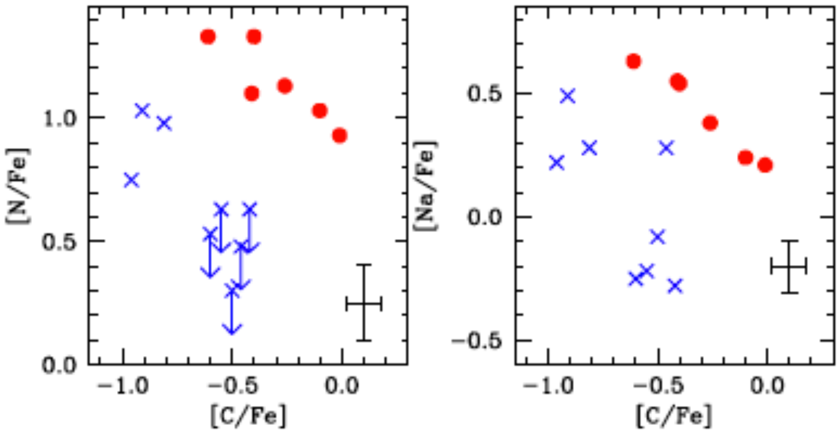
from Marino et al. (2009)

Iron difference alone is not enough to explain the SGB split

The reason of the SGB split may be more complicated and also involve the CNO abundances, as suggested by Cassisi et al. (2008) and Ventura et al. (2009) for NGC1851

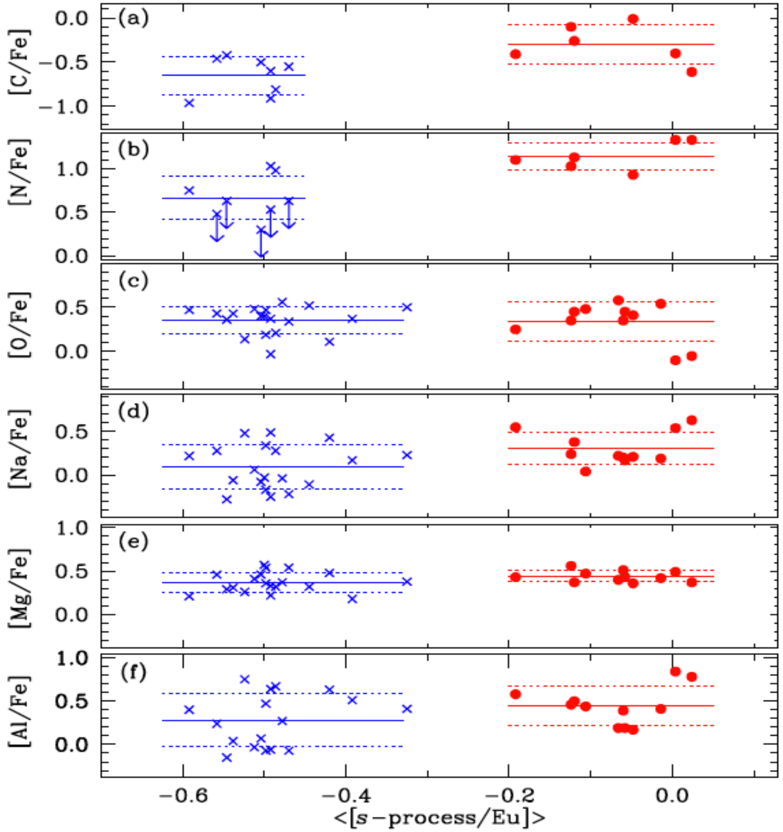
Na-O and C-N anticorrelations in M22

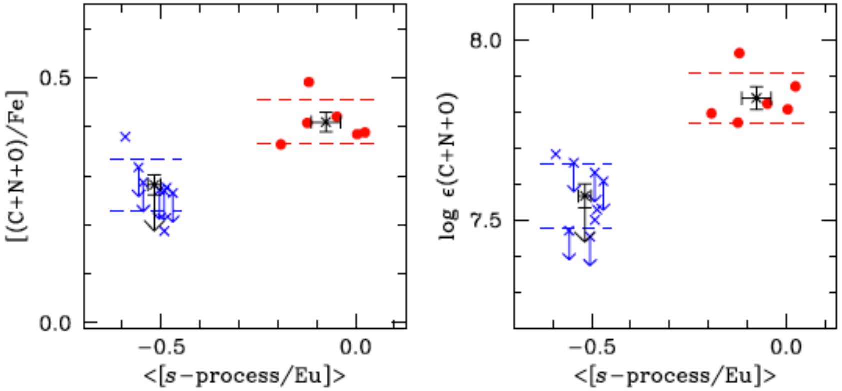


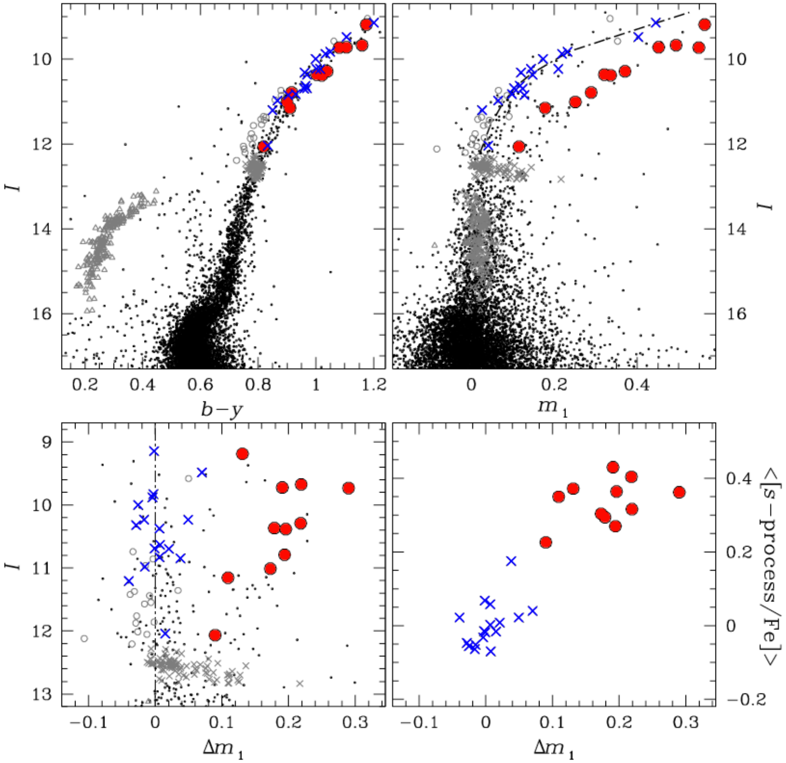


- Both the *s*-elements/iron rich and the *s*-elements/iron poor population exhibit a Na-O and a C-N anticorrelation.
- A tight AlNa correlation is present, but there are no evidence for a MgAl anticorrelation
- On the Na-O plane *s*-rich and *s*-poor stars span a similar range in O while the level of Na is higher for *s*-rich stars

C+N+O variations



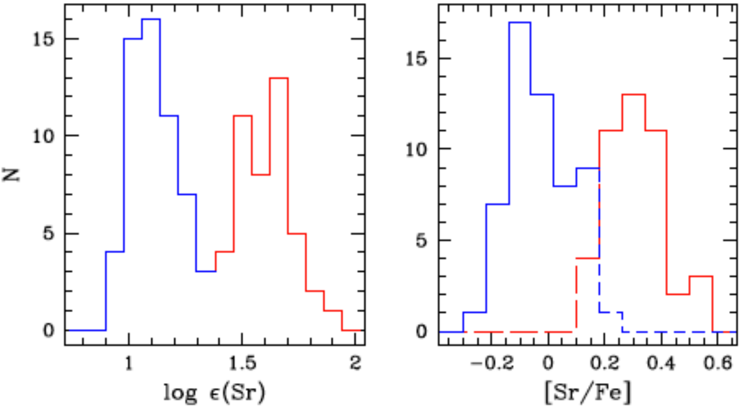


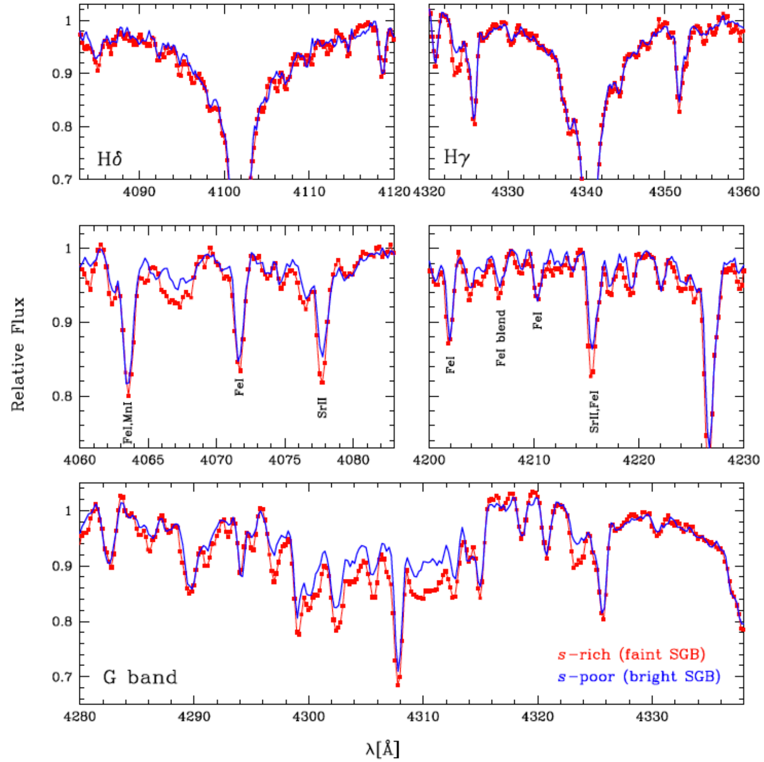


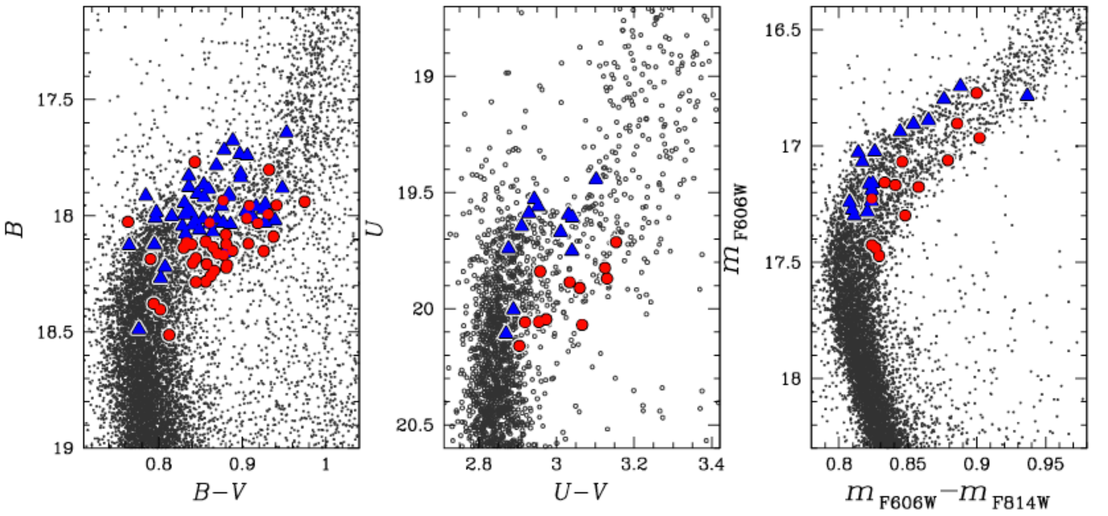
- *Normal* GCs: The total C+N+O content is constant within observational errors (Ivans et al. 1999)
- NGC 1851: Evidence for a large variations in this SGB split GC (Yong et al. 2009).
- M22 seems to behave similarly to NGC1851, but in this case the difference in the CNO among the two *s*-groups is lower.

from Marino et al. (2011), arXiv:1105.1523

The SGB split of M22:







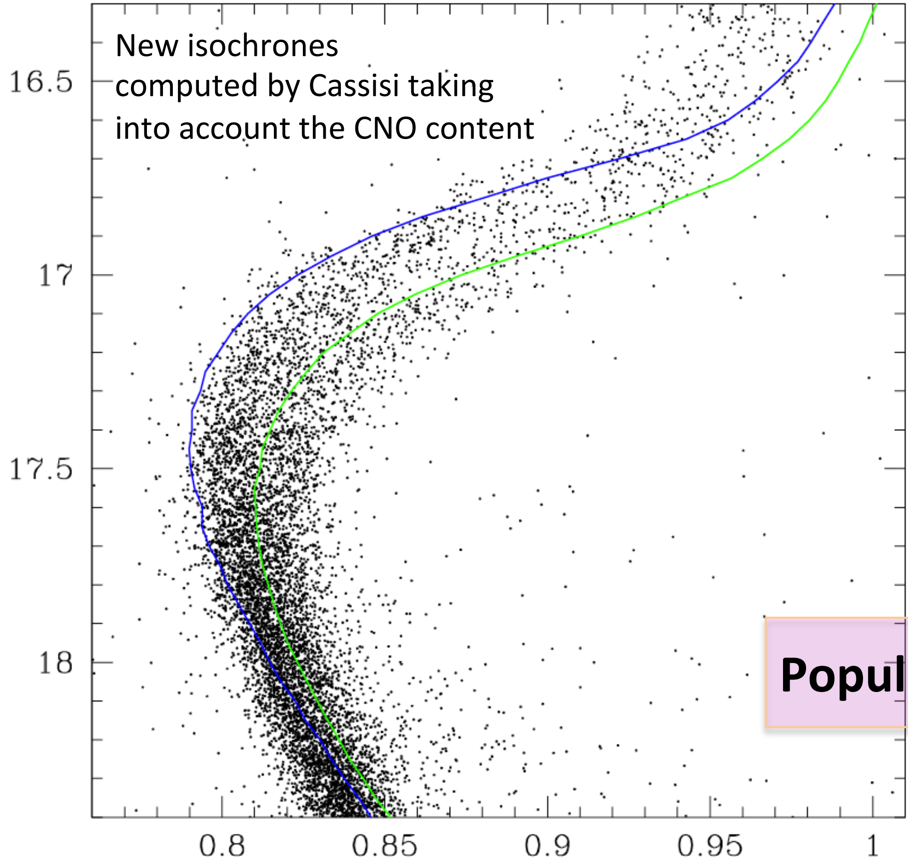
At the light of our previous results on the RGB stars, we can charachterize the two SGBs in M22 in terms of chemical composition:

- **faint-SGB**: *s*-rich stars, with higher metallicity, α-element Ca, and enhanced C+ N+ O abundance
- **bright-SGB**: *s*-poor stars, with lower metallicity, α-element Ca, and depleted C+ N+ O abundance

Pop.	[Fe/H]	[s/Fe]	[CNO/Fe]	[Ca/Fe]	[Eu/Fe]
SGB-f	−1.67	+0.35	+0.41	+0.36	+0.42
SGB-b	−1.82	−0.03	+0.28	+0.26	+0.49

Marino et al. in prep.

Dating the SGB populations:


New isochrones computed by Cassisi taking into account the CNO content

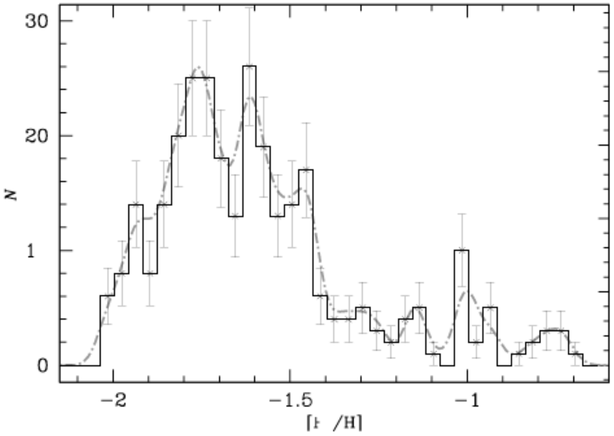
By taking into account the C+N+O variations the two *s*-groups are coeval. The result is valid within the errors of ±0.3 Gyr that affect the determination of relative ages from the turnoffs' location.

Note however that each group of stars with different metallicity and *s*-content behaves separately as a *normal* GC, i.e. its stars are mono-metallic and show a Na-O anticorrelation

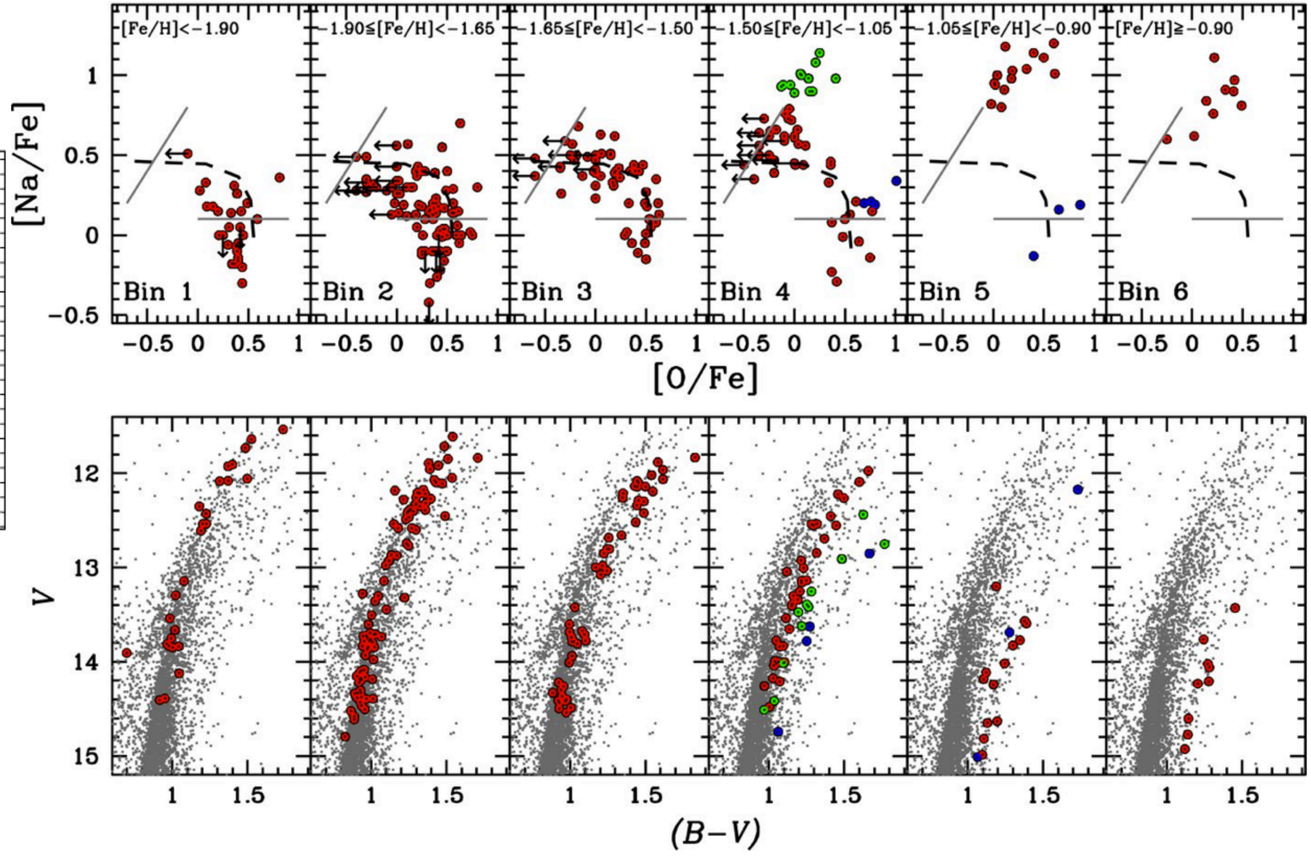
Populations coeval within 300 Myrs

Marino et al. in prep.

Omega Cen Na-O (anti)correlations:

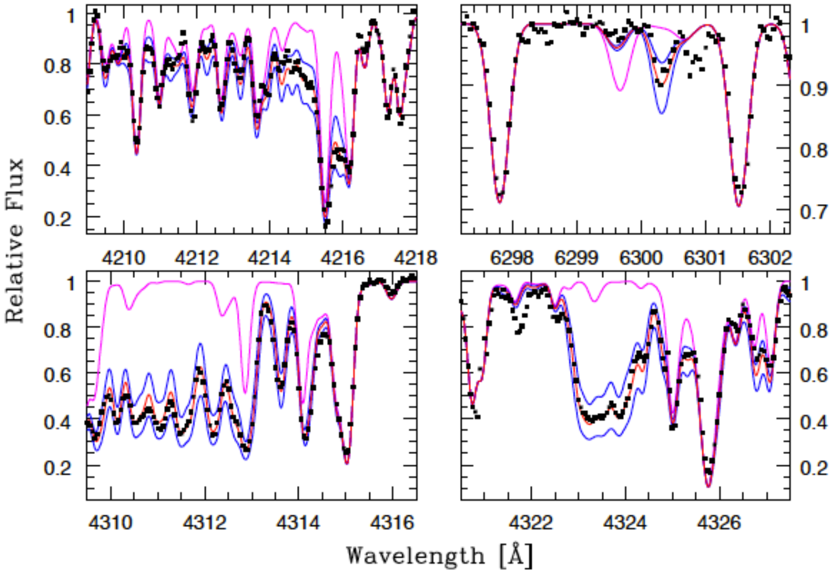


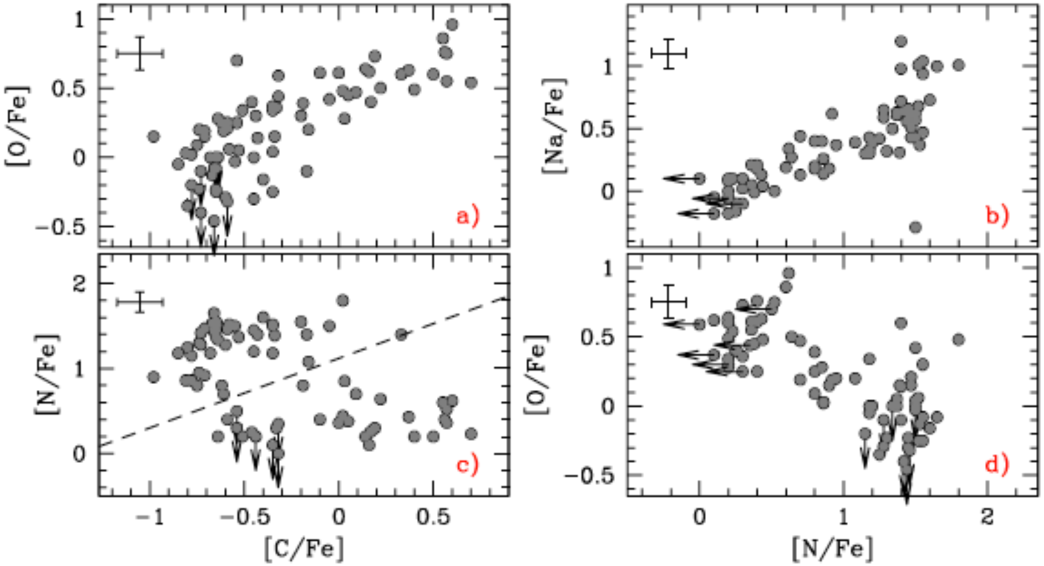
from Marino et al. (2011), ApJ 731, 64



See also Johnson & Pilachowsky (2010), ApJ 722, 1373

C, N, O abundances in Omega Cen:



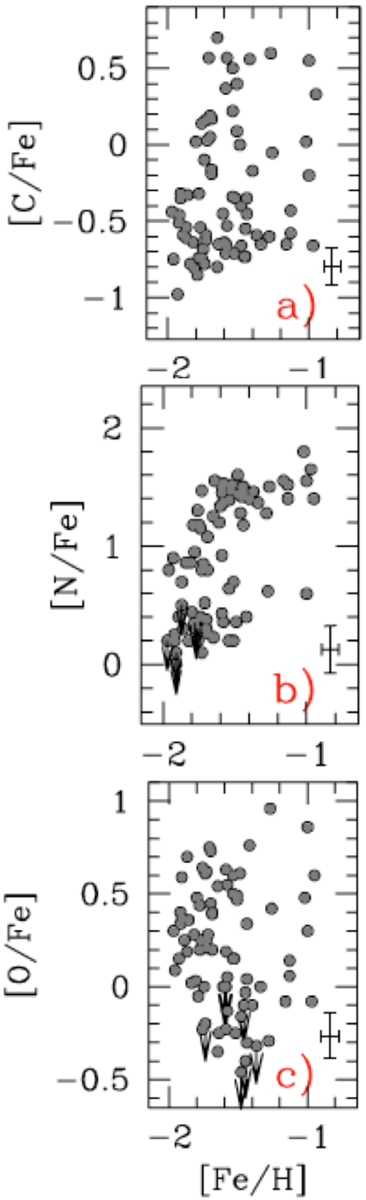


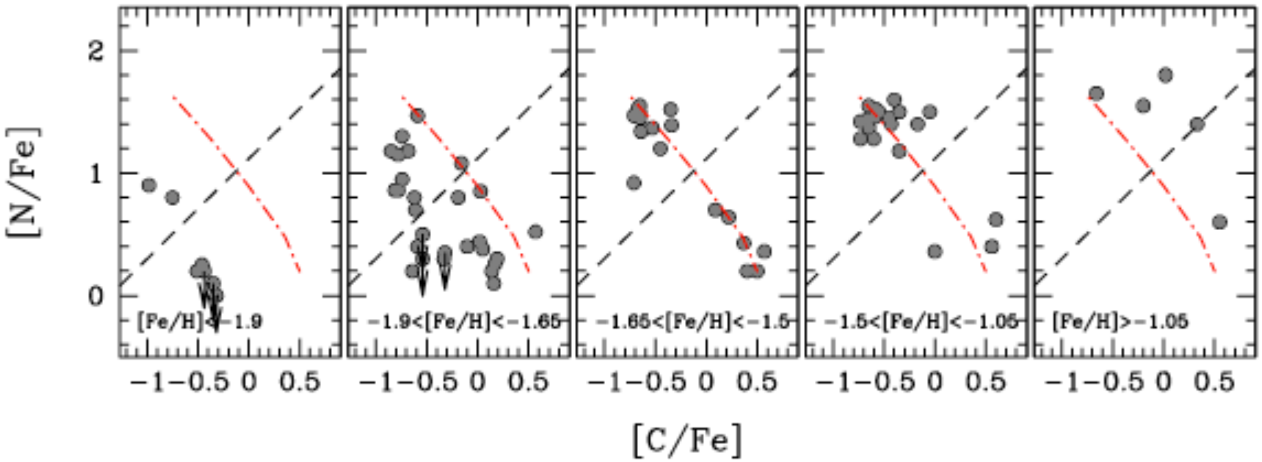
Our results clearly show:

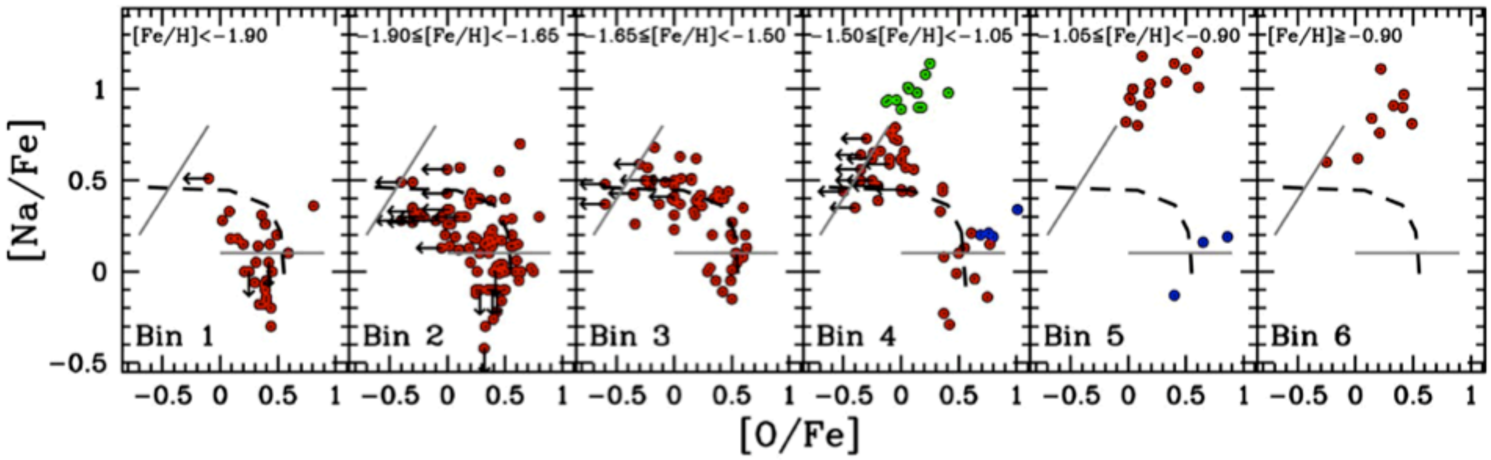
- **the existence of well-defined patters between C and N with O and Na: positive correlation among O and C, and Na and N, and N anticorrelates with O**
- **a C-N anticorrelation is not obvious**

from Marino, et al. Subm.

C-N, Na-O patterns:



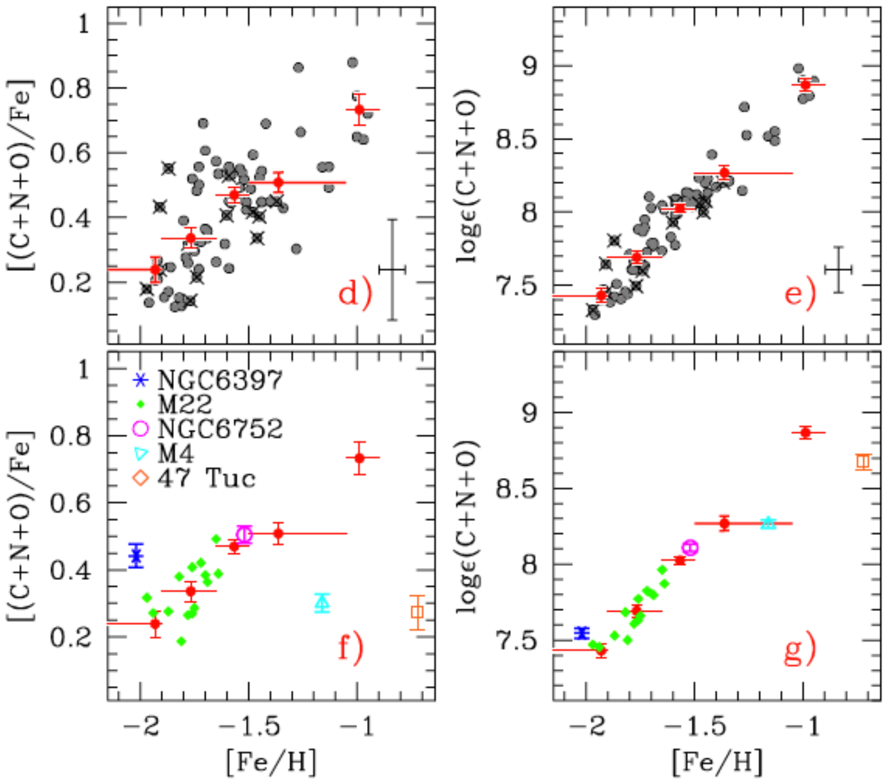




The shape of the C-N anticorrelation for different metallicities recalls the one of the Na-O anticorrelation, with the most metal-rich groups hosting also a larger fraction of N-rich (Na-rich, O/C-poor) stars.

from Marino, et al. Subm. to ApJ

C+N+O variations in Omega Cen:



M4 (Ivans et al. 1999)
NGC 6397, NGC 6752, 47 Tuc (Carretta et al. 2008)
M22 (Marino et al. 2011)

- **The overall CNO abundance varies significantly from star to star**
- **Correlation between C+N+O and [Fe/H], with the most metal-rich stars enhanced in [(C+N+O)/Fe] by 0.7 dex with respect to the metal-poor population.**
- ***Normal* mono-metallic GCs, regardless of metallicity, show all [(C+N+O)/Fe] in the range 0.2-0.5 dex.**
- **A trend with metallicity, nevertheless in a much lower range, is shown in the [(C+N+O)/Fe] of M22.**
- **Stars with higher CNO have also higher *s*-element abundance in close analogy with M22**

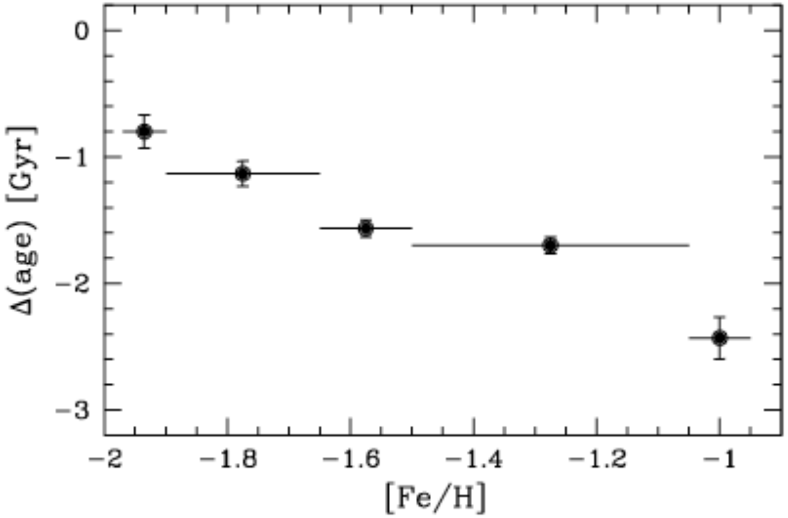
from Marino, et al. Subm. to ApJ

Dating the ω Cen populations:

Ferraro et al. (2004)
Sollima et al. (2005)
fast star formation

Stanford et al. (2006)
Hilker et al. (2004)
2-4 Gyrs

Hughes & Wallerstein (2000) ≥3 Gyrs
Hilker & Richtler (2000) 3–6 Gyrs
Villanova et al. (2007) 5 Gyrs
prolonged star formation



Role of the CNO in dating stellar populations:

$$\frac{\delta\ \text{age}}{\delta\ [\text{CNO}]} = -3.3\text{Gyr/dex}$$

[Fe/H]	[(C+N+O)/Fe]	Δ(age) [Gyr]
−1.97<[Fe/H]<−1.90	0.24±0.04	−0.8±0.1
−1.90<[Fe/H]<−1.65	0.34±0.03	−1.1±0.1
−1.65<[Fe/H]<−1.50	0.47±0.02	−1.6±0.1
−1.50<[Fe/H]<−1.05	0.48±0.04	−1.6±0.1
−1.05<[Fe/H]<−0.95	0.75±0.12	−2.7±0.4

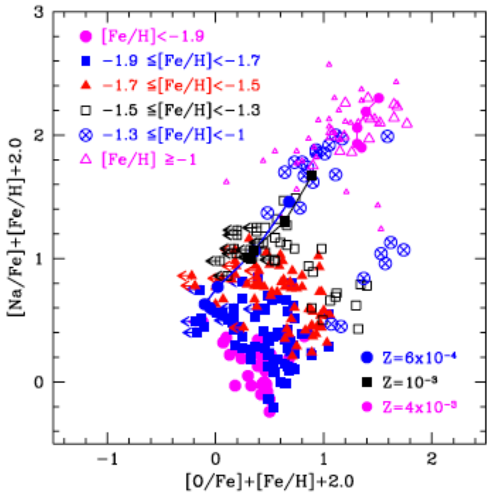
Star formation history in peculiar GCs:

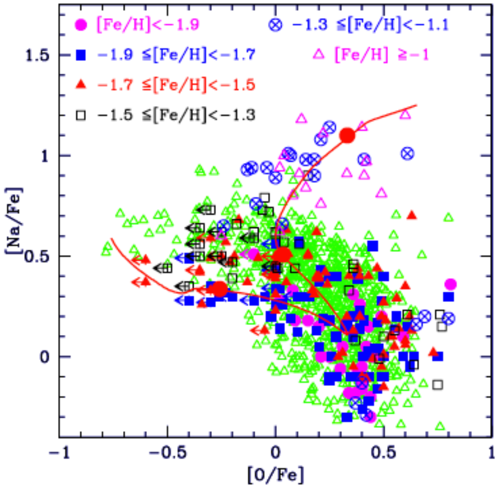
Self-enrichment

Can we extend the self-enrichment scenario proposed by D’Ercole et al. (2008, 2010) for simple GCs to ω Centauri?

Hydrodynamical simulations by D’Ercole et al. suggests that the second generation (Na-rich/O-poor) in *normal* GCs could form in the central GC regions after a cooling flow of material from first generation, diluted with pristine gas

D’Antona et al. (2011) scenario fro ω Cen:





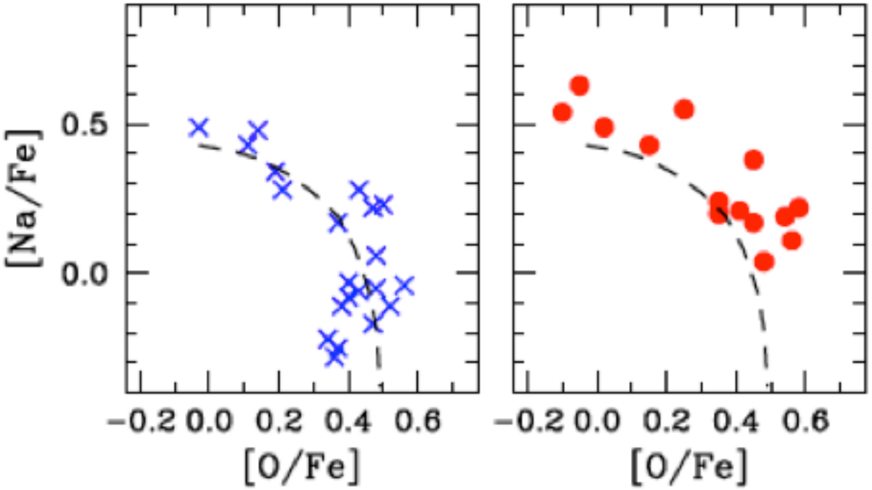
The predicted yields from AGB of various masses agree with the Na-O data in ω Cen.

Successive generations of increasing metallicity form from massive AGB ejecta diluted with the infalling iron-enriched pristine matter, until the diluting material is exhausted, and the most metal rich stars in the cluster are formed directly from the massive AGB ejecta, preserving their chemical composition, and the direct O-Na correlation of the models.

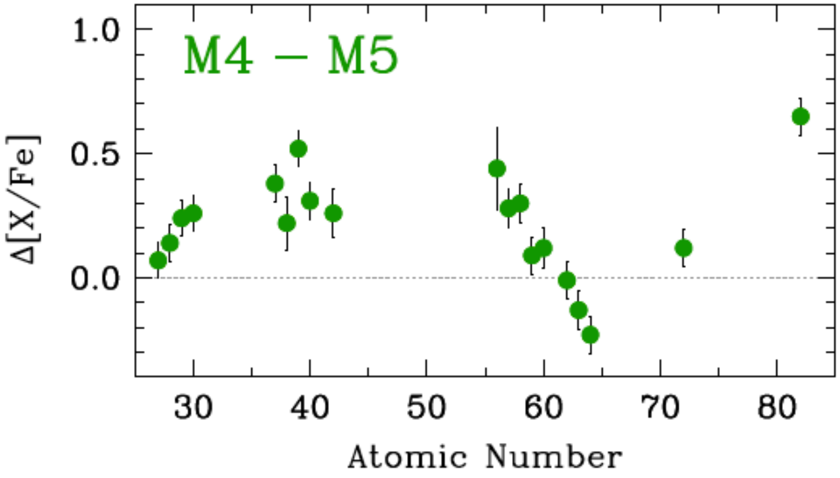
Mergers of different GCs?:

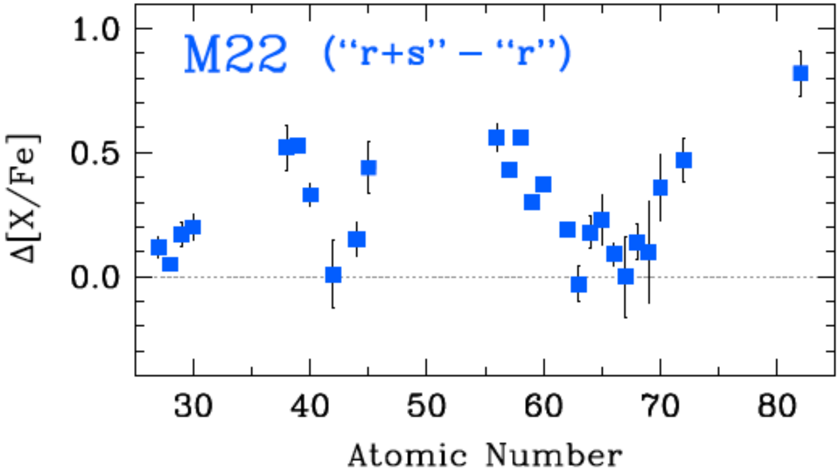
Mergers

- ☐ the subgiant branch shows two distinct sequences;
- ☐ there is a metallicity offset between the two groups;
- ☐ each group independently exhibits the O-Na anticorrelation;
- ☐ there are clearly distinct n-abundance patterns in the two groups.



from Roederer et al. in prep.





Abundances for M4 and M5 taken from Yong et al. 2008 and Ivans et al. 1999, 2000

Conclusions:

- ***"Normal GCs"*:**
  1. mono-metallic
  2. unique Na-O anticorrelation
  3. homogeneous heavy elements
  4. multiple RGBs if proper filters are used

- ***"Peculiar GCs"*:**
  1. intrinsic variations in metallicity
  2. multiple Na-O anticorrelations
  3. variations in n-capture elements
  4. complex CMDs: multiple RGB and SGBs

- ***Omega Cen:***
  1. Huge metallicity variations
  2. complex Na-O (anti)correlations
  3. large variation in s-process elements with metallicity
  4. multiple sequences along the entire CMD