On the Multiple Stellar Populations Phenomenon in Galactic Globular Clusters:

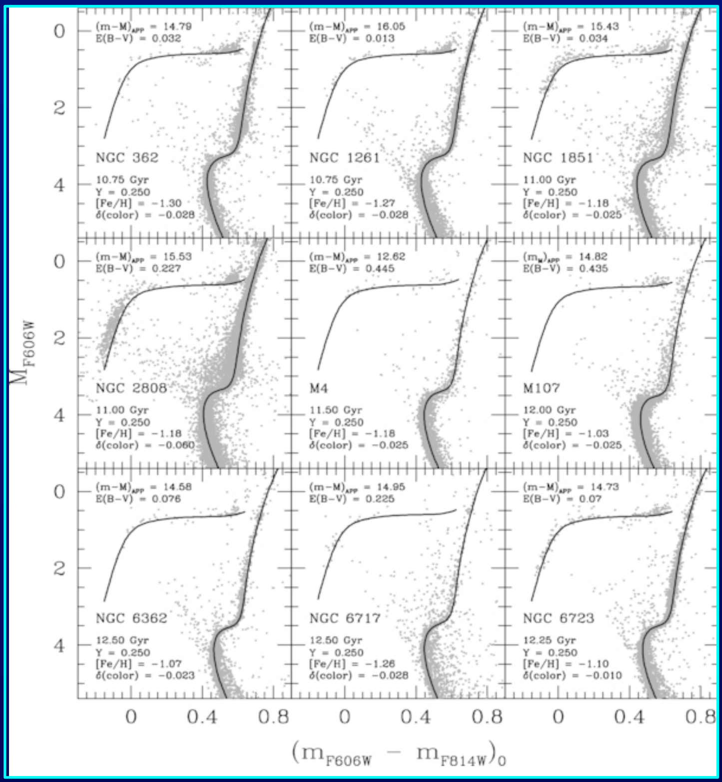
a (possible) link with the Galaxy formation process(es)

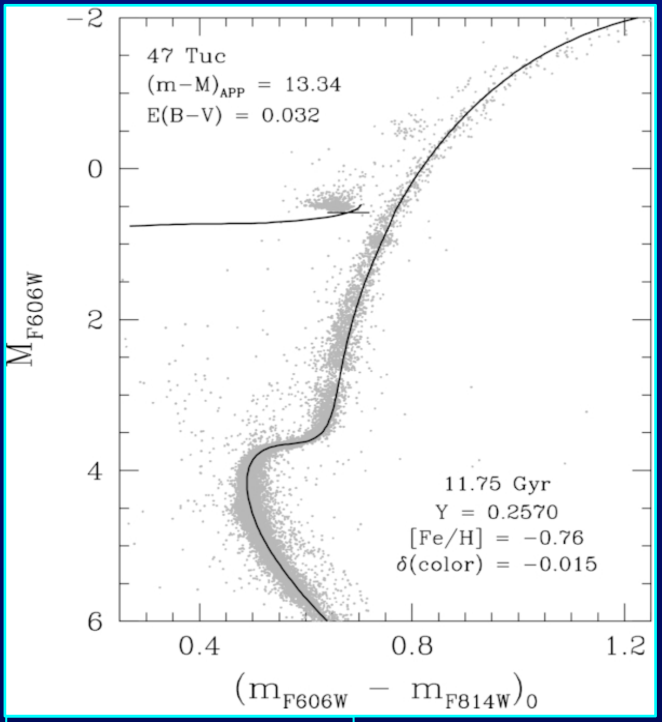
Santi Cassisi
INAF - Astronomical Observatory of Teramo

Globular Clusters: "simple" objects?

GCs represent an ideal laboratory for testing and calibrating stellar evolutionary models, as well as for dynamical studies…

Since long time, the comparison between empirical - mainly photometric - evidence and theoretical predictions supported the view of GCs as SIMPLE objects:



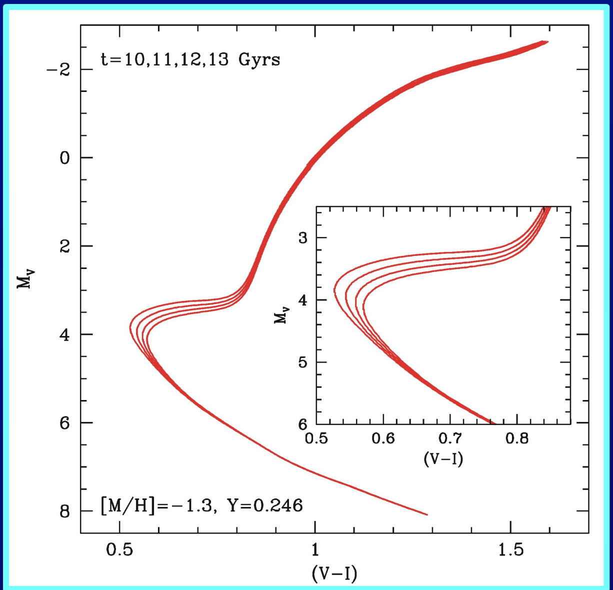


Vandenberg et al. (2013)

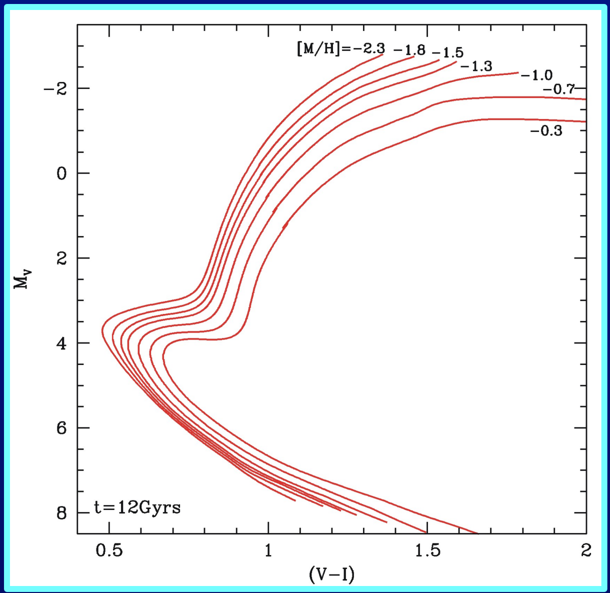
The GCs paradigma: they host single-simple stellar populations

The stellar evolution prescriptions

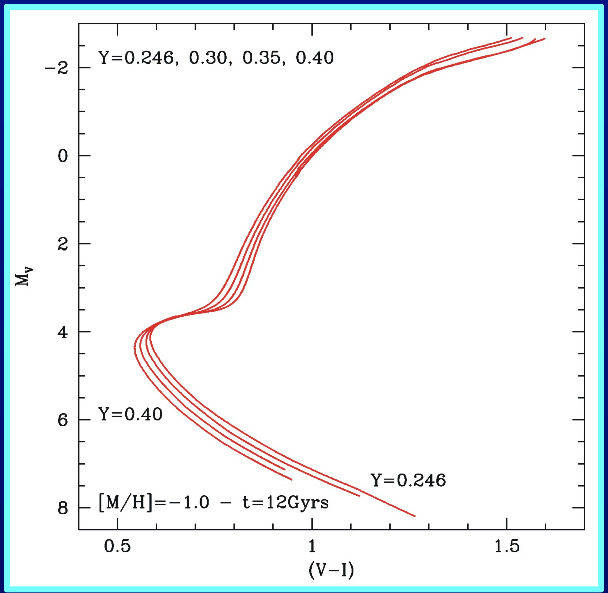
The age effect



The metallicity effect



The Helium effect



With “good” observations, we should be able
to detect the presence of sub-populations in a star cluster

spectroscopical evidence: a short summary

- Some GCs show a CN-bimodality on the RGB

- The C & N abundances in GCs are very different than in field giants

  → **The GC enviroment HAS to play a rôle**

- The O-Na anticorrelation in RGB stars

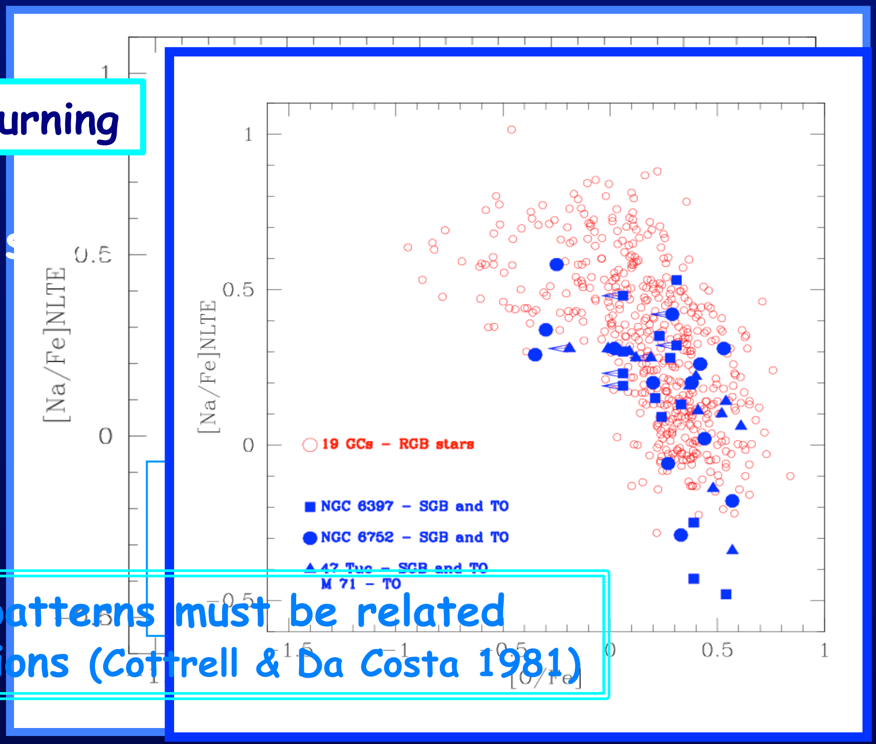
- The Mg-Al anticorrelation in RGB stars

  → **Clear signature of high-Temperature H-burning**

- These anticorrelations also in unevolved

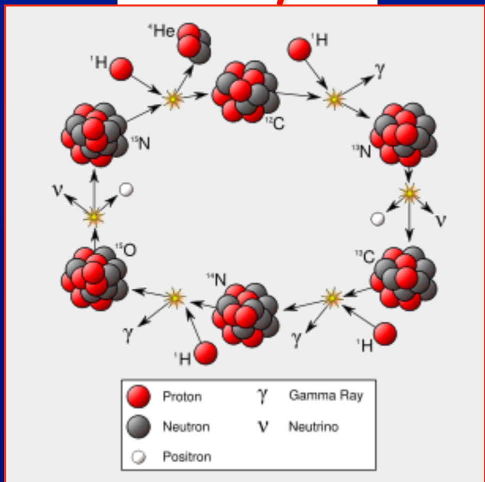
  → **These properties can NOT be due to evolutionary effects…**

  No "simply" surface pollution…



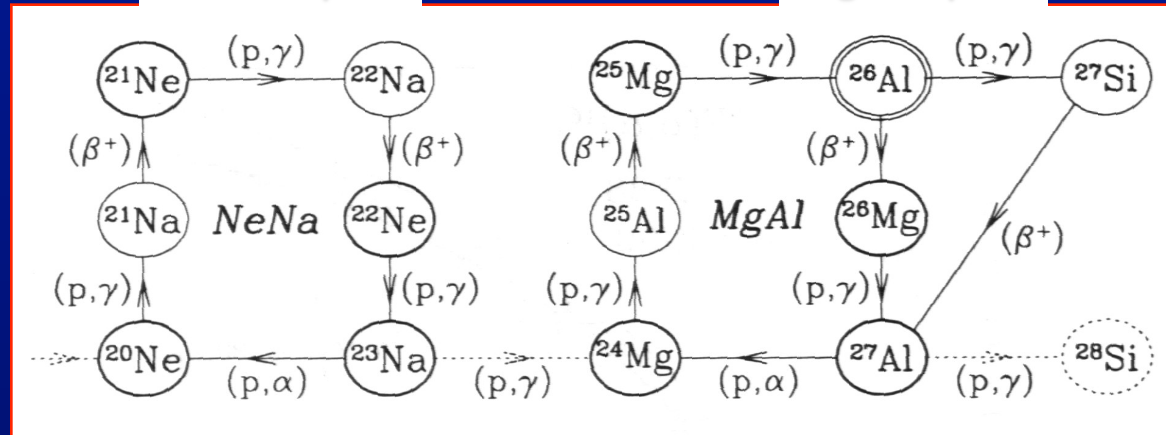
These peculiar chemical patterns must be related to primordial chemical variations (Cottrell & Da Costa 1981)

CNO cycle



NeNa cycle

MgAl cycle



T~20MK

T~35MK

T~50MK

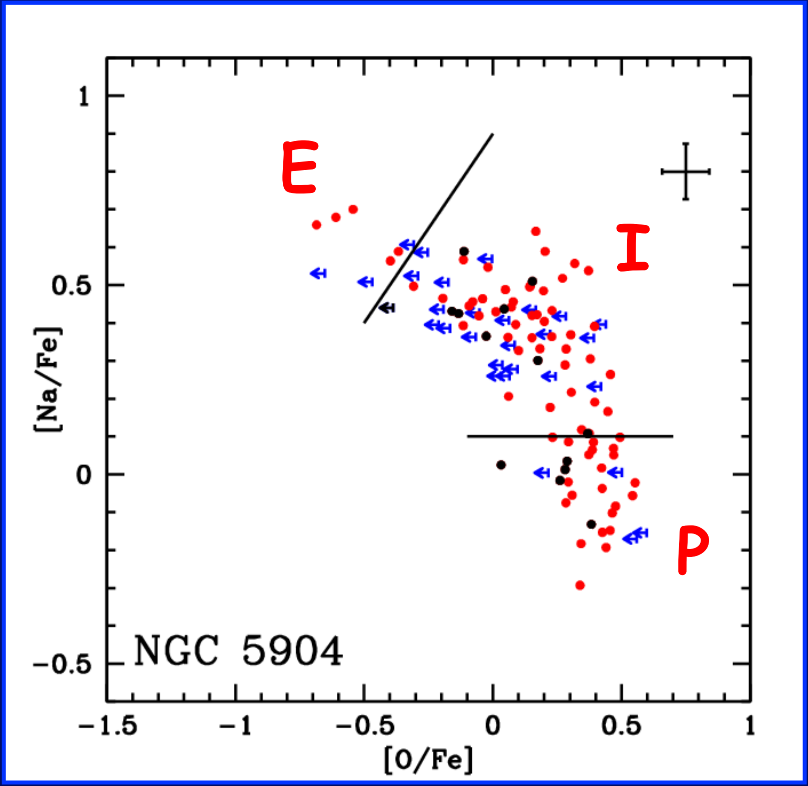
Significant ^{24}Mg depletion → T~70MK

The NeNa cycle which enhances Na, is expected to operate in the same fusion zones in which the ON part of the CNO cycle is fully operative

The MgAl cycle which enhances Al, is expected to operate at very high temperature…

In the same zones where CNO, NeNa, MgAl cycles, are expected to operate, a significant amount of Helium is present…

The O-Na anticorrelation



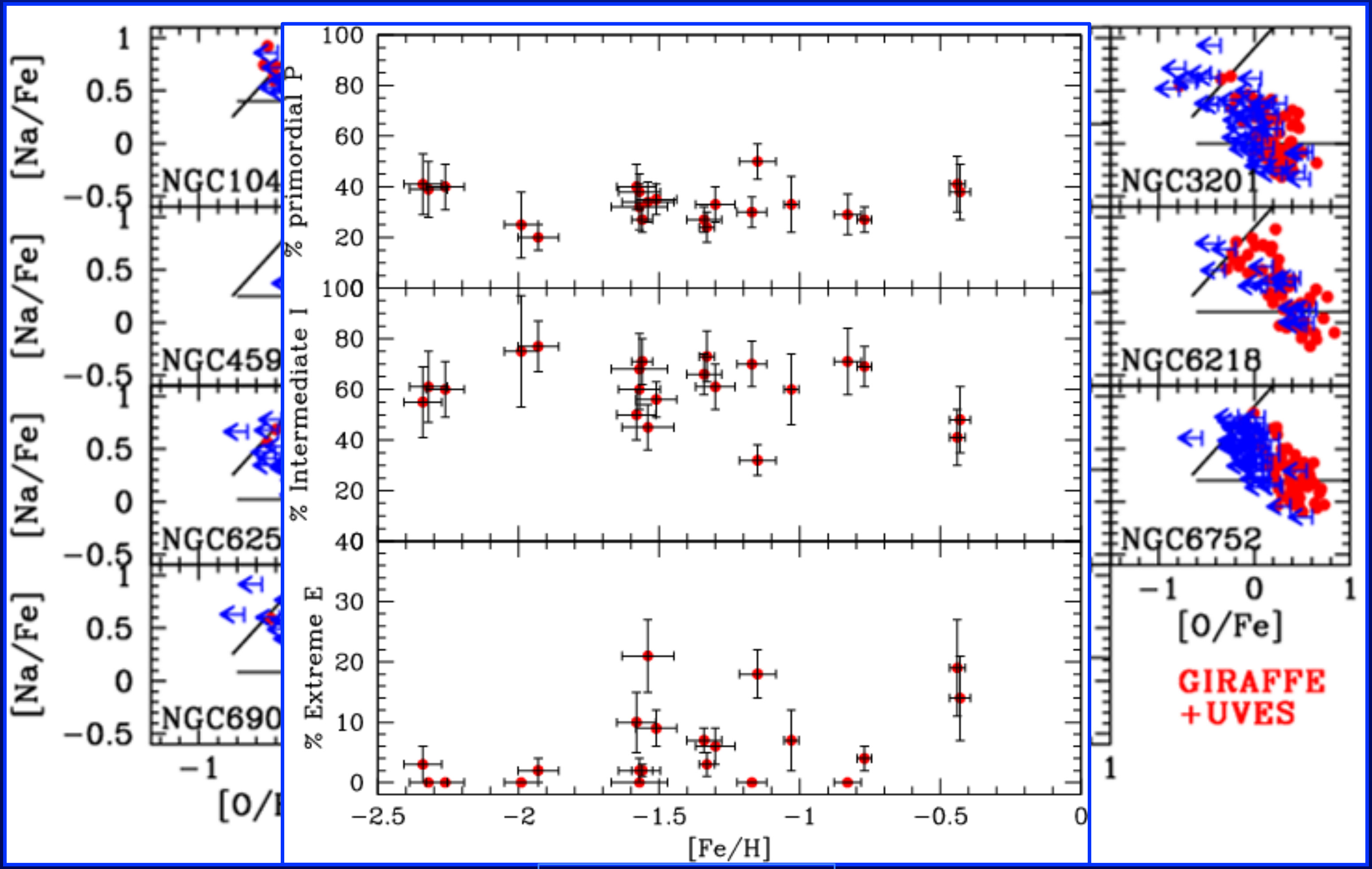
Working definitions:

P= Primeval → $[Na/Fe] < [Na/Fe]_{min} + 4\sigma$

I= Intermediate → $[Na/Fe] > [Na/Fe]_{min} + 4\sigma$ and $[O/Na] > -0.9$

E= Extremely O-poor → $[O/Na] < -0.9$

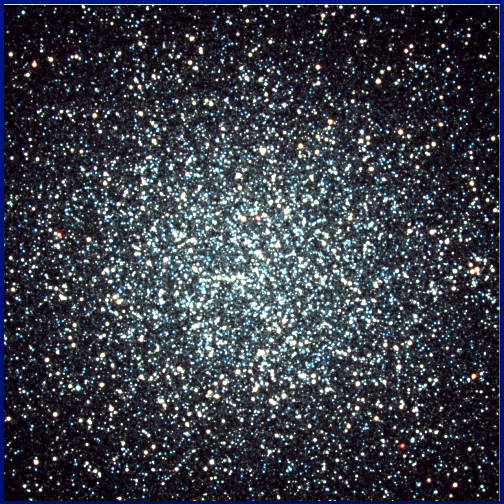
The clusters' PIE



Carretta et al. (2010)

High-Quality (& suitable!) Photometry: the damning evidence

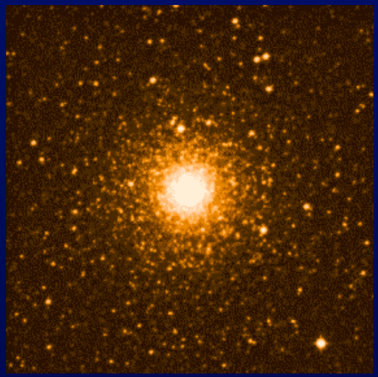
The "culprits"



The "funky": ω Centauri

The "cool": NGC2808

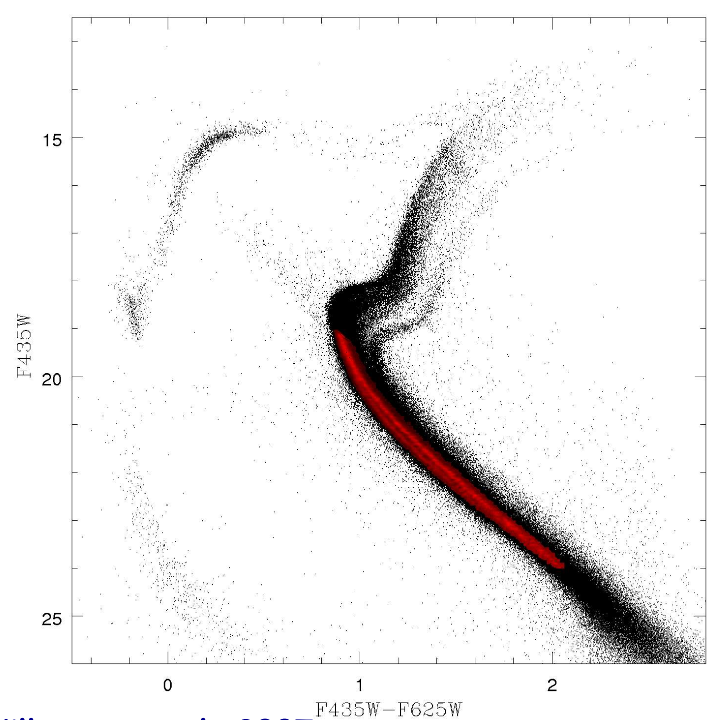
The "normal": NGC1851



The "bad twins": NGC6441 & NGC6388

"A dwarf galaxy nucleus"

ω Centauri: The "funky" GC



Villanova et al. 2007

The most massive GC in the Galaxy: $\approx 4\text{-}5 \times 10^6 M_\odot$

An unusually high ellipticity – sustained by rotation

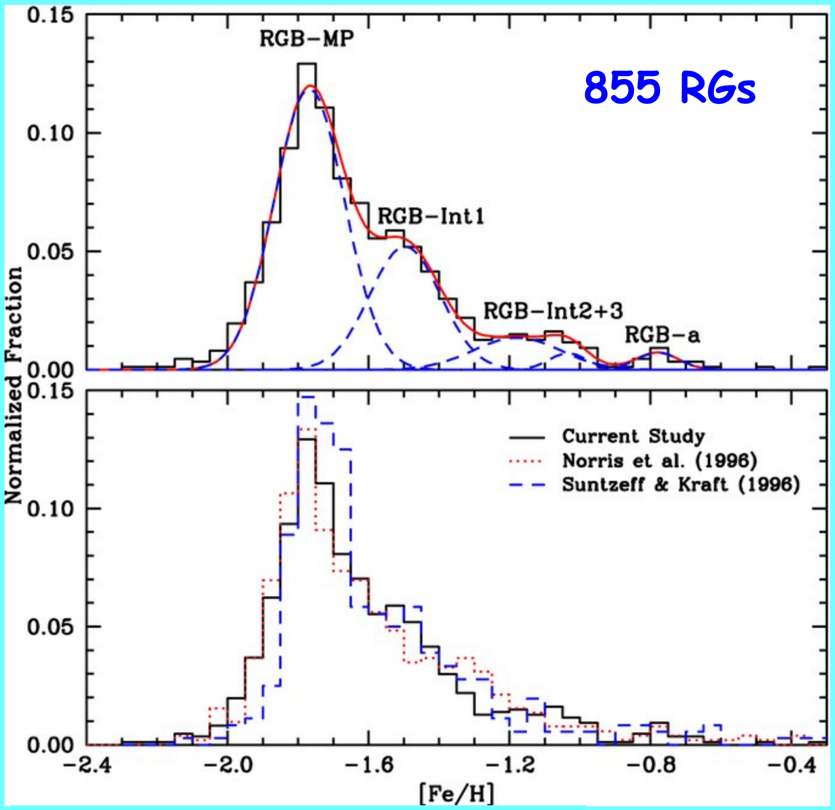
Long relaxation time ➔ not completely relaxed dynamically

a GC with a huge star-to-star abundance variations

The multipopulations' evidence:

- The discrete nature of its RGB
- The MS splitting
- The SGB multiplicity
- Spatial distribution & Kinematics

The [Fe/H] distribution from spectroscopy

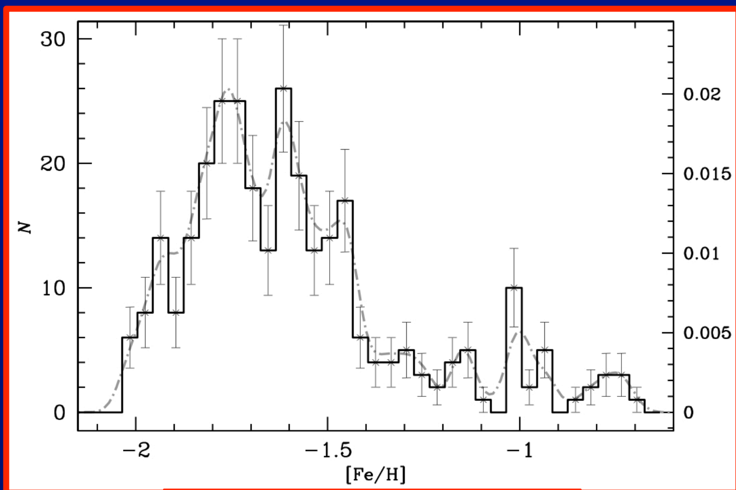


Johnson & Pilachowski (2010)

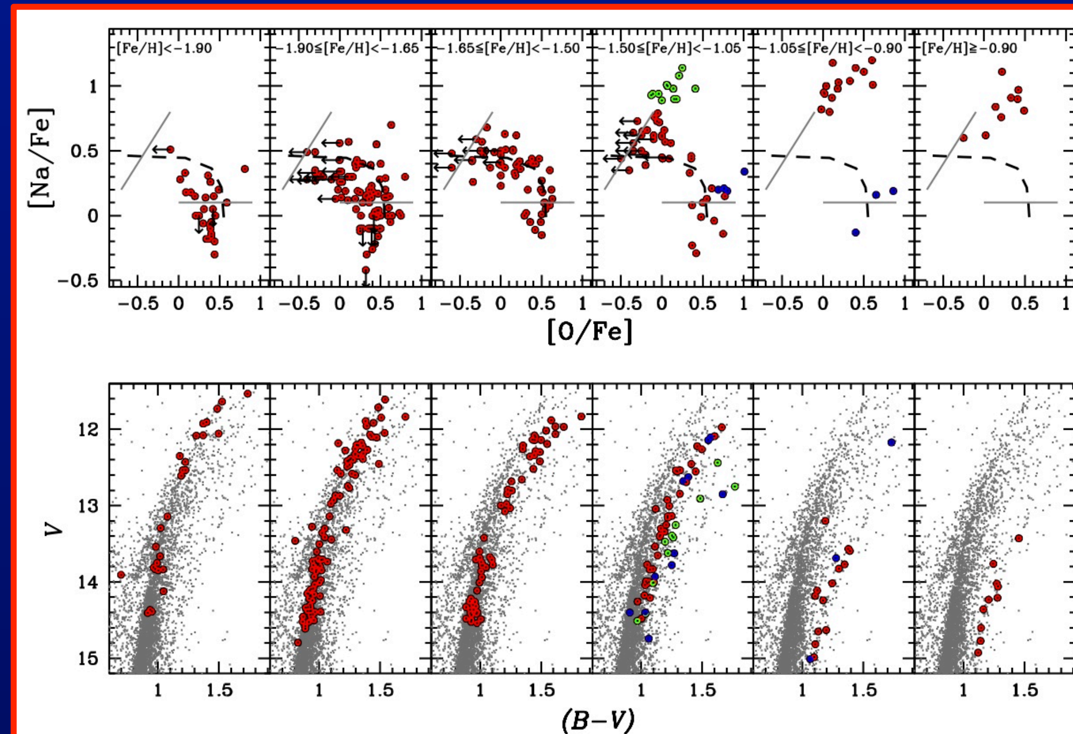
sub-population	<[Fe/H]>	%
RGB-MP	-1.8	42
RGB-Mint 1	-1.5	28
RGB-Mint 2	-1.2	17
RGB-Mint 3	-1.1	8
RGB-a	-0.7	5

See also Marino et al. (2011)

The O-Na anticorrelation for the various sub-populations



Marino et al. (2011)



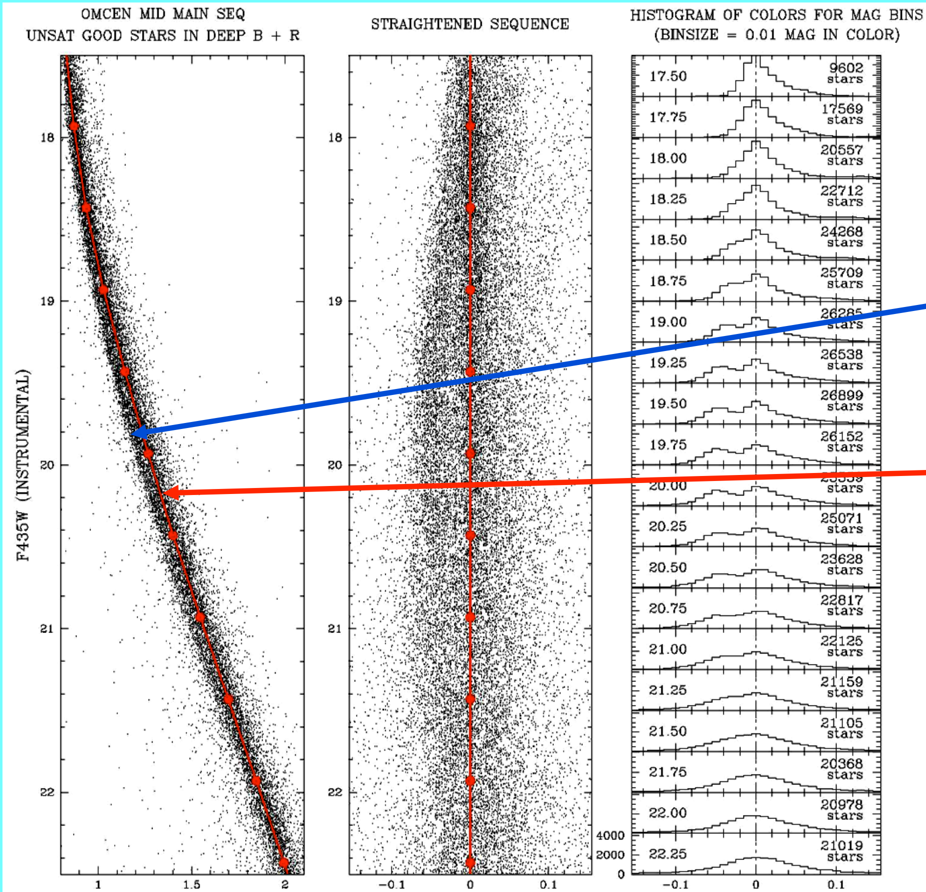
the average Na abundance increases systematically when moving from the metal-poor to the metal-rich populations;

The fraction of stars with low and intermediate O content also increases with [Fe/H];

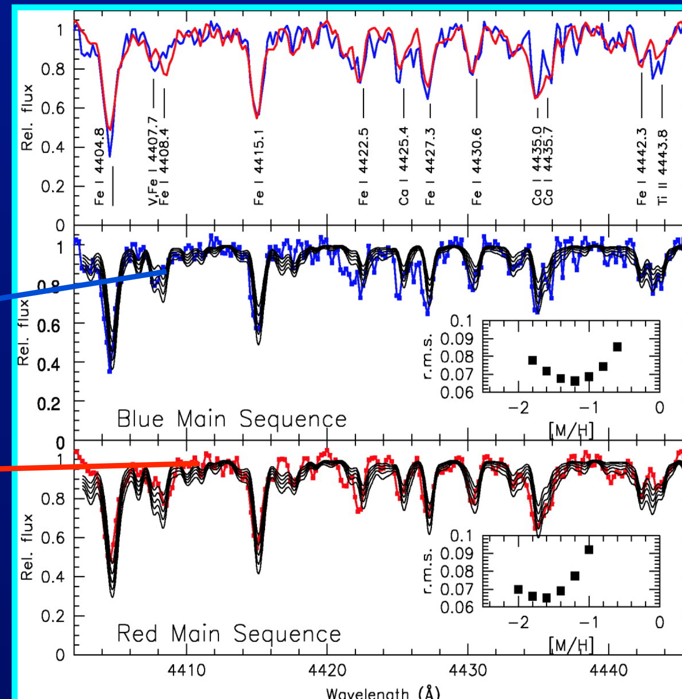
The anticorrelation disappears for stars with [Fe/H]>-1.05: most of the stars occupy a quite anomalous portion of the Na-O plane, at high Na and with large spread in O;

The most surprising result: the MS splitting

(Anderson 1997 - Bedin et al.2004)



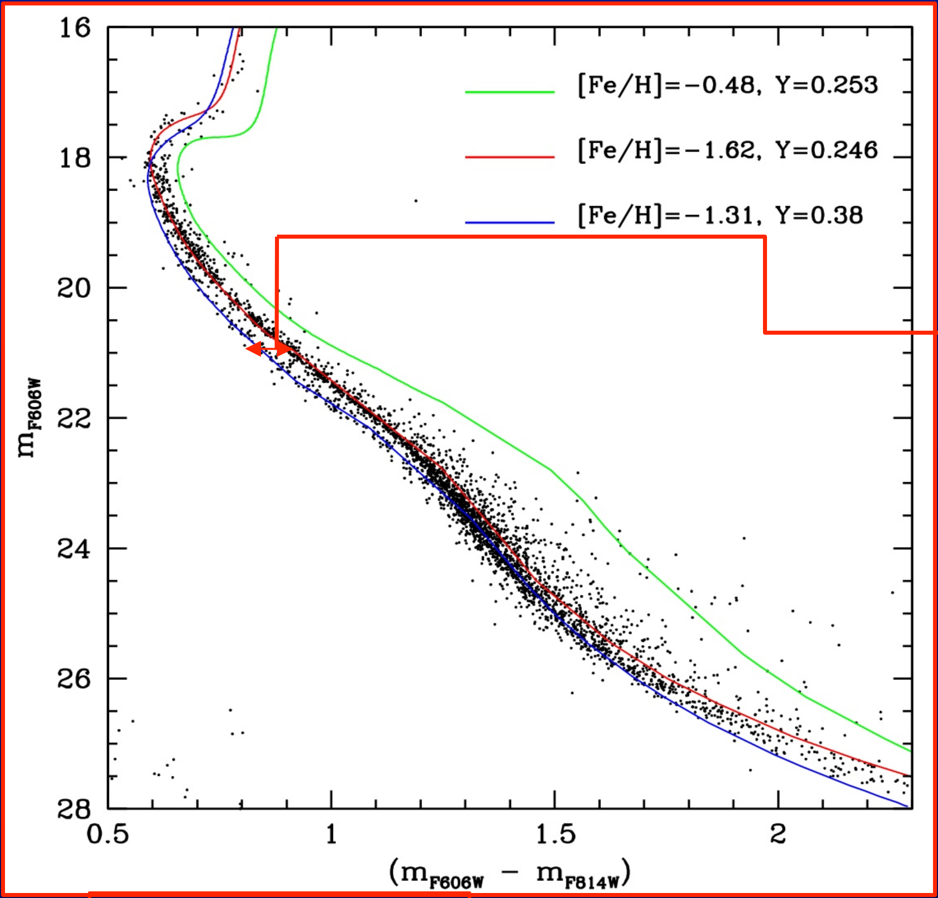
Δ[Fe/H](bMS-rMS)~0.30±0.20 dex



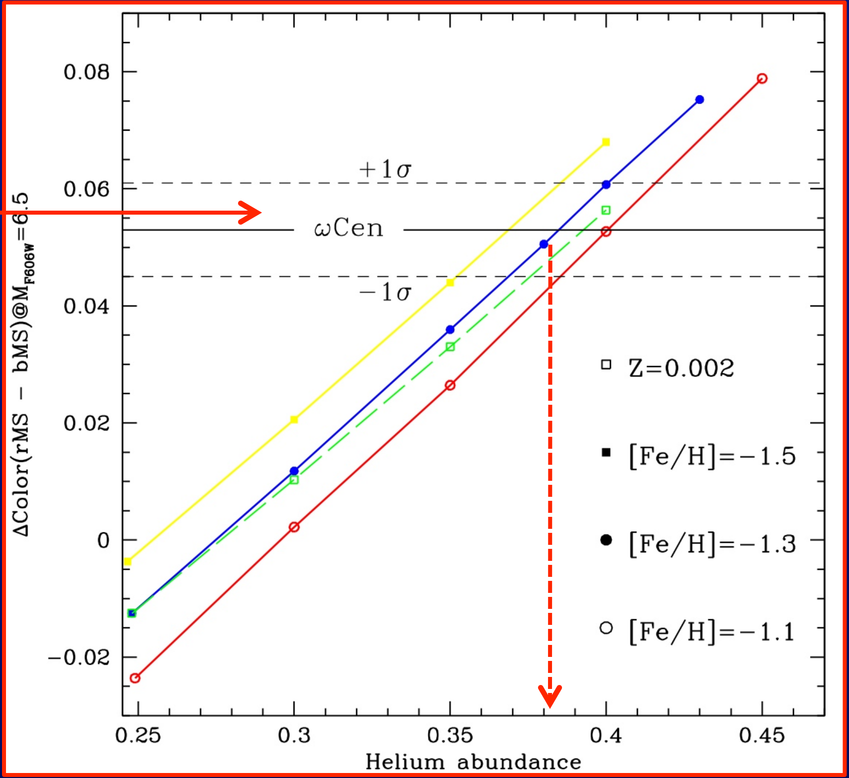
GIRAFFE@VLT spectra
(Piotto et al. 2005)

Red MS	≈75%
Blue MS	≈25%

The faintest MS loci in omega Centauri



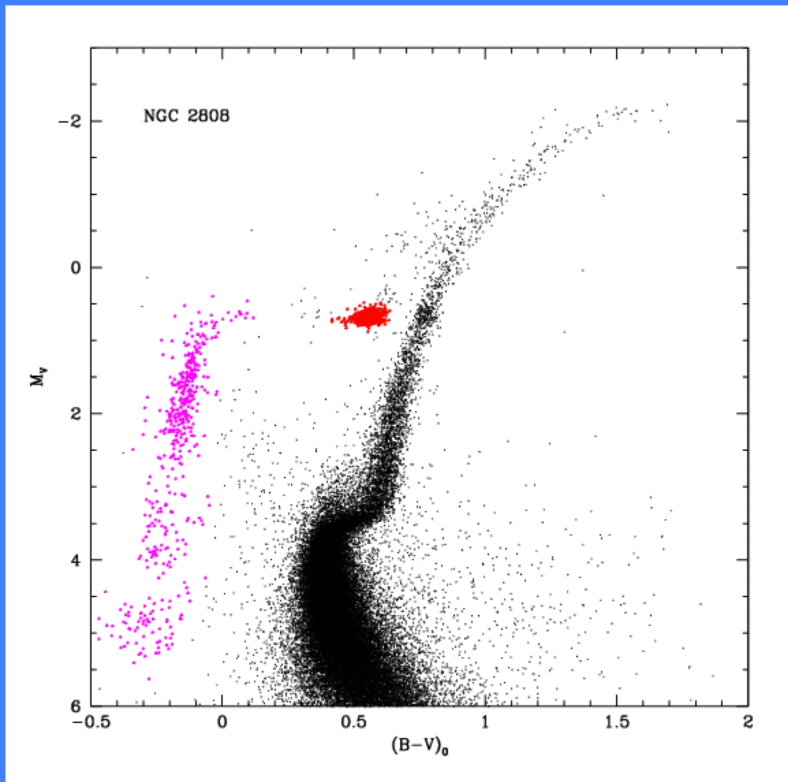
King et al. (2012)



Y=0.38

A super He-rich stellar component is present in this *GC* (see also Norris 2004)

NGC 2808: The "cool" GC



Piotto et al. (2002)

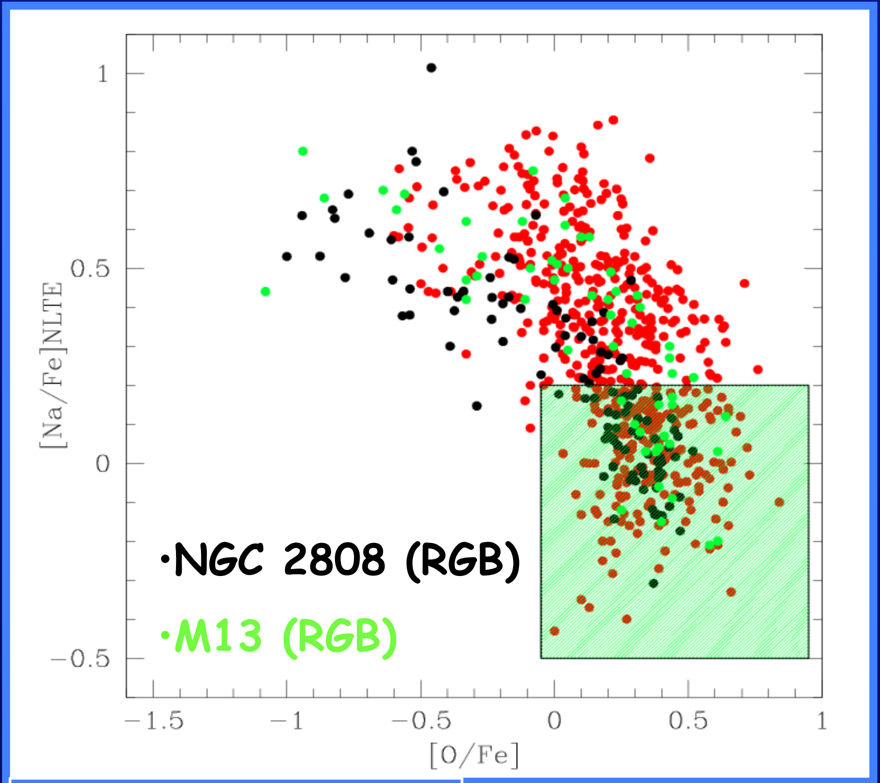
One of the most massive GCs in the Galaxy: $\approx 2\times10^6 M_\odot$

The multipopulations' evidence:

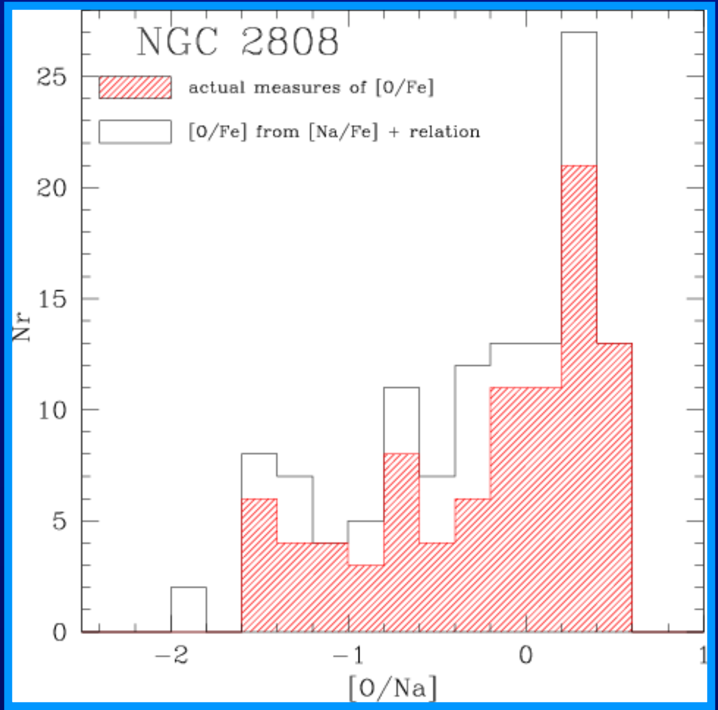
- The peculiar chemical patterns
- The MS splitting

The chemical patterns of RGB stars

The Oxygen - Sodium anticorrelation

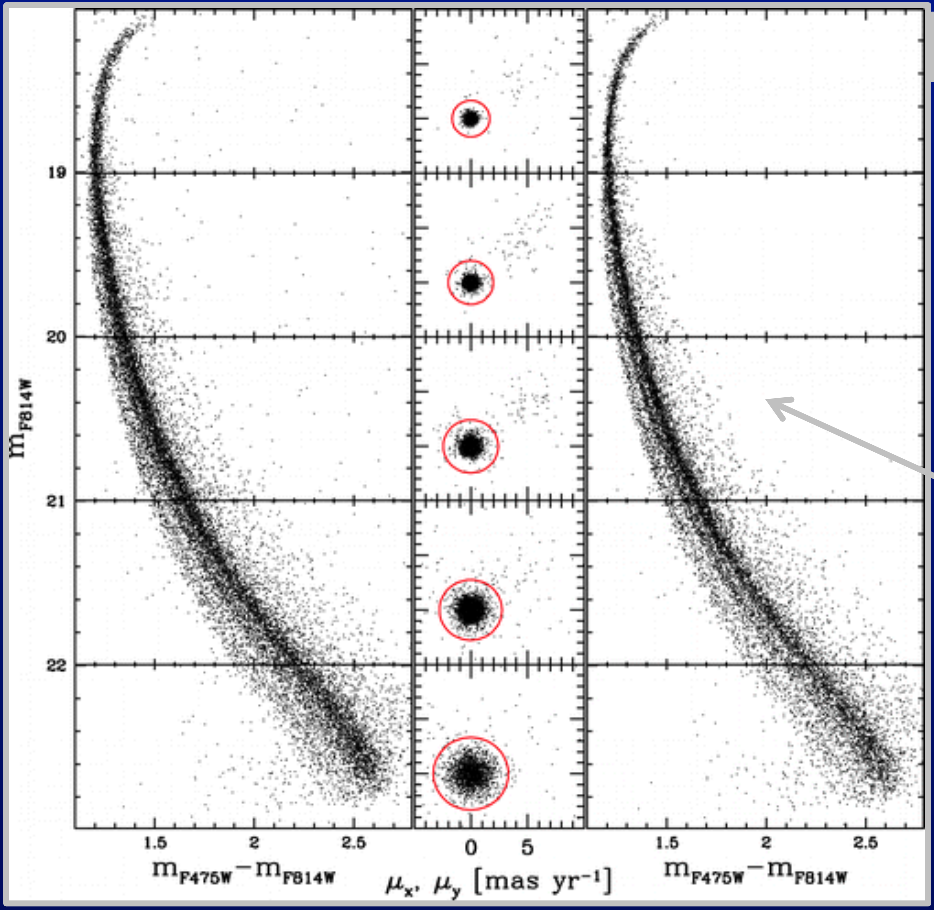


Carretta et al. (2006)



A "strong" O-Na anticorrelation: besides a bulk of O-normal stars, it seems to host two groups of O-poor and super O-poor stars

The MS splitting: the undisputable evidence

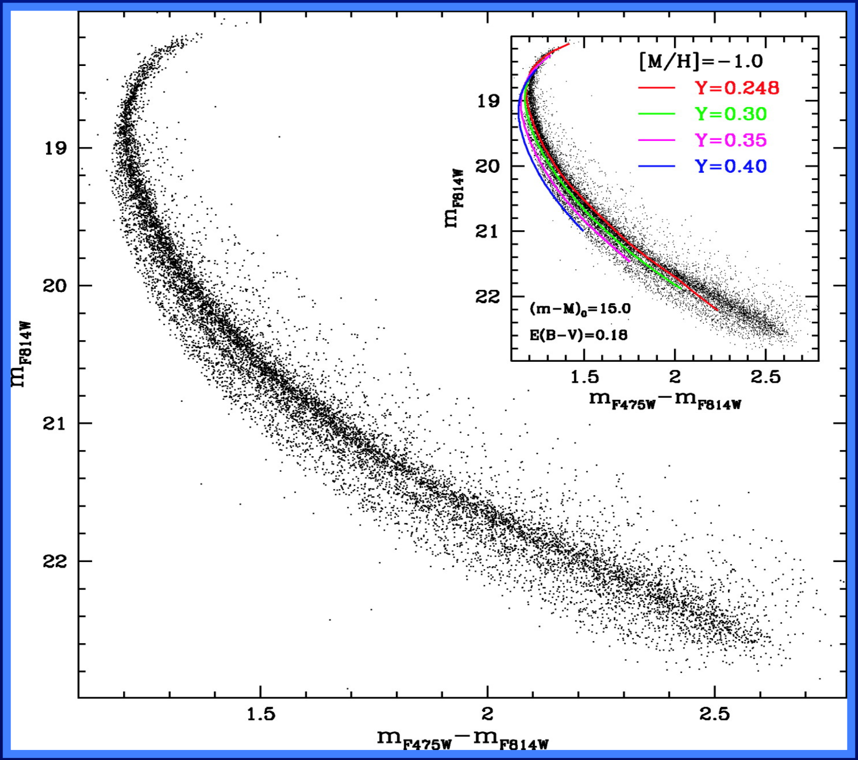


Piotto et al. (2007)

cluster members, differential reddening corrected, CMD

NGC 2808 represents the second, direct evidence of multiple stellar populations in a GC

the theoretical interpretation



is there a link with the 3 groups of RGB stars characterized by different O abundances?

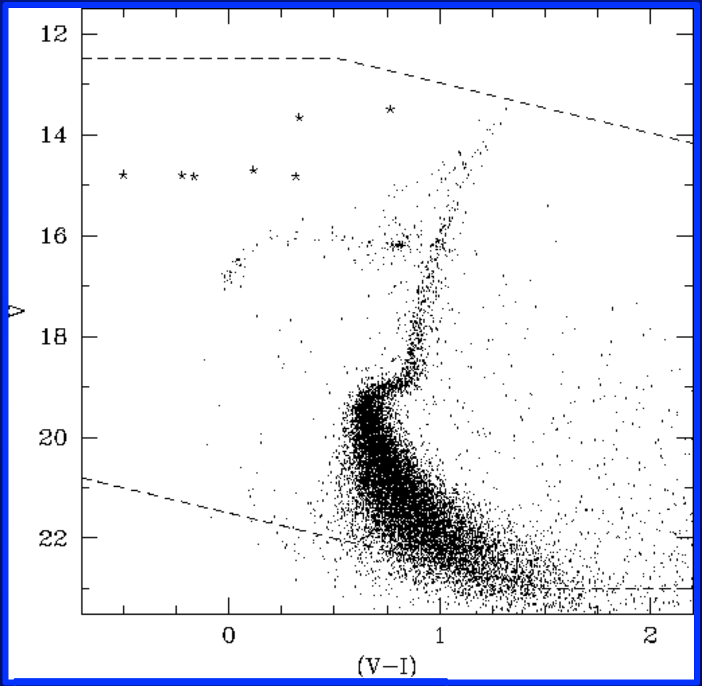
some hints:

- high-T CNO cycle → O depletion, He production
- population ratios

the evidence of 3 distinct MS loci suggests the presence of 3 subpopulations:

- a "canonical" pop. with Y~0.24;
- a first He-rich pop. with Y~0.32;
- a second He-rich pop. with Y~0.40;

The "normal" GC: NGC 1851



Saviane et al. (1998)

A not-too-much massive GC: $\approx 10^6 M_\odot$

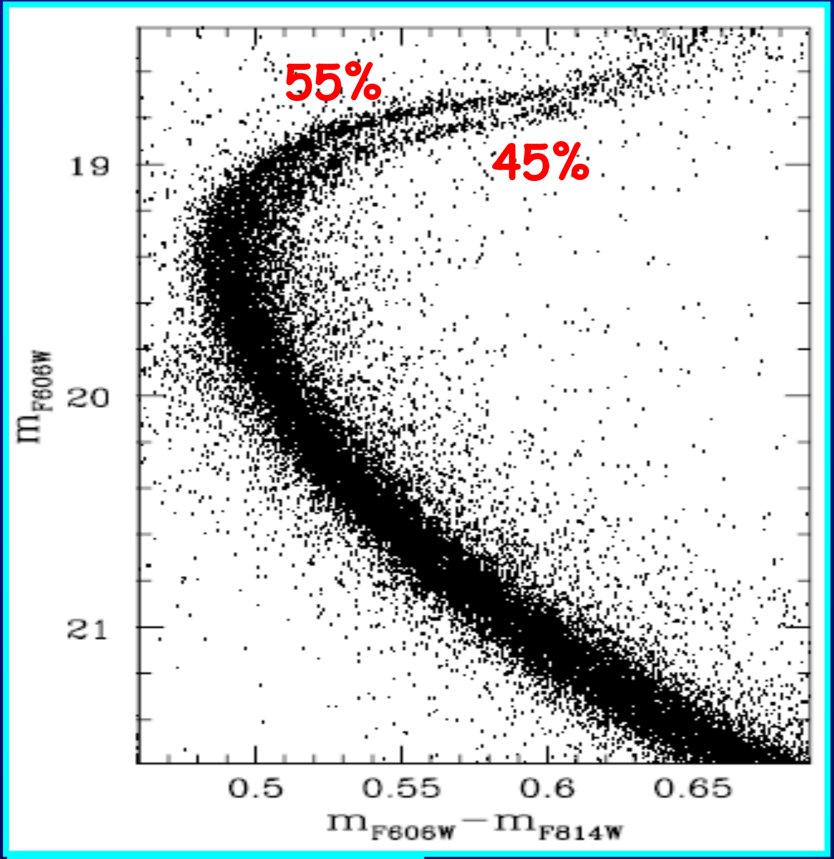
40% of the studied RGB stars show "extraordinarily strong" CN bands (Hesser et al. 83)

support to the previous results and evidence for a bimodality in the s-elements abundances from Yong & Grundahl (2007)

The multipopulations' evidence:

- The Sub Giant Branch splitting

The evidence of multipopulations

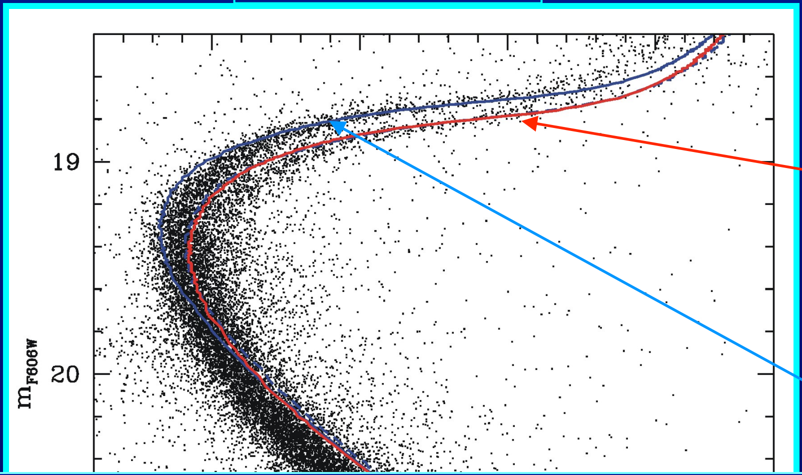


(Milone et al. 2007)

- The Sub Giant Branch splits into two well-defined branches
- If this split is due only to age effect, the two SGBs should imply two star formation episodes separated by ~1Gyr
- No splitting is present along the MS…
- the width of both the MS and RGB poses severe constraints on the maximum possible variation of He and/or metals

A different interpretation: two sub-pops with distinct abundance patterns

Cassisi et al. (2008)



Stellar models accounting for a CNONa anticorrelations

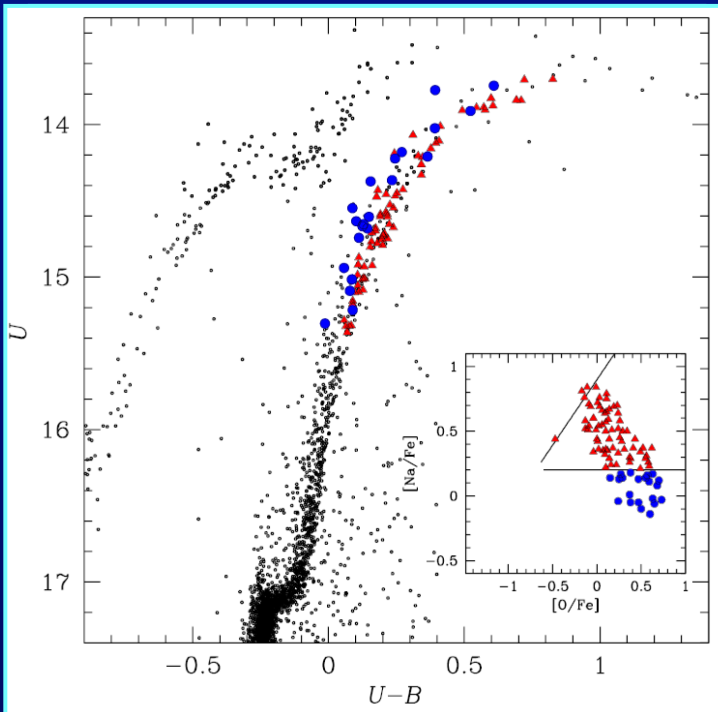
Stellar models accounting for a normal mixture

When assuming that the fainter SGB is associated with a population with a peculiar chemical pattern for CNO and Na, NO age difference has to be invoked…

The spectroscopical analysis of Yong et al. (2009) now fully support this scenario: a spread of ≈ 0.6 dex is present for the ratio [CNO/Fe]!!! (but see also Villanova et al. (2010)

The case of NGC6752 & NGC6656 & NGC6121…

Two not massive GCs showing clear evidence of multiple populations

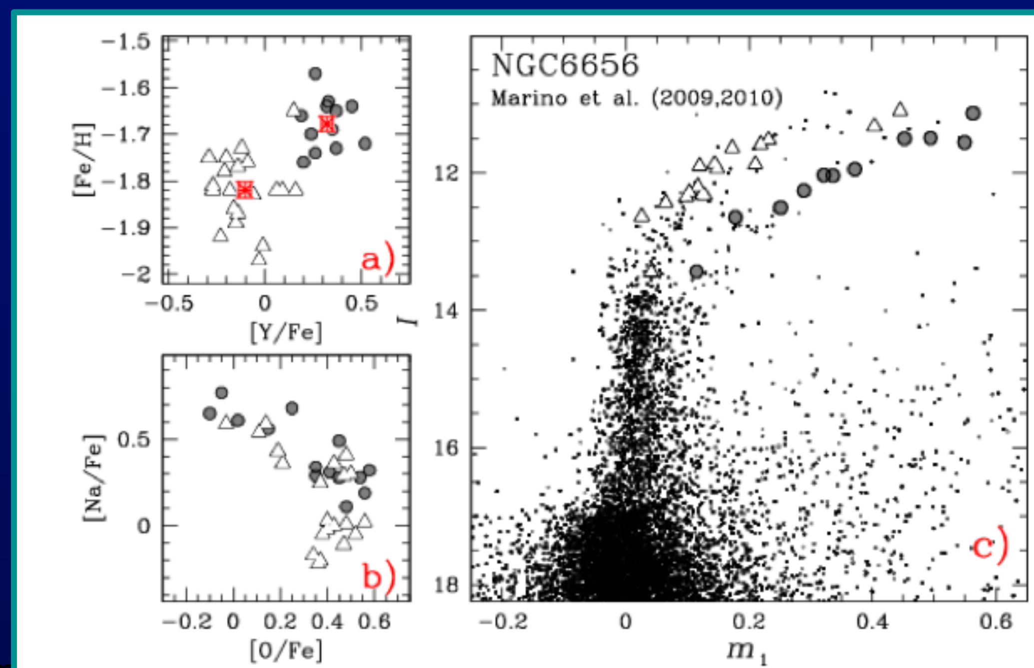


In the U, (U-B) CMD:

Na-poor/O-rich/CN-weak – I° generation
➔ blue RGB

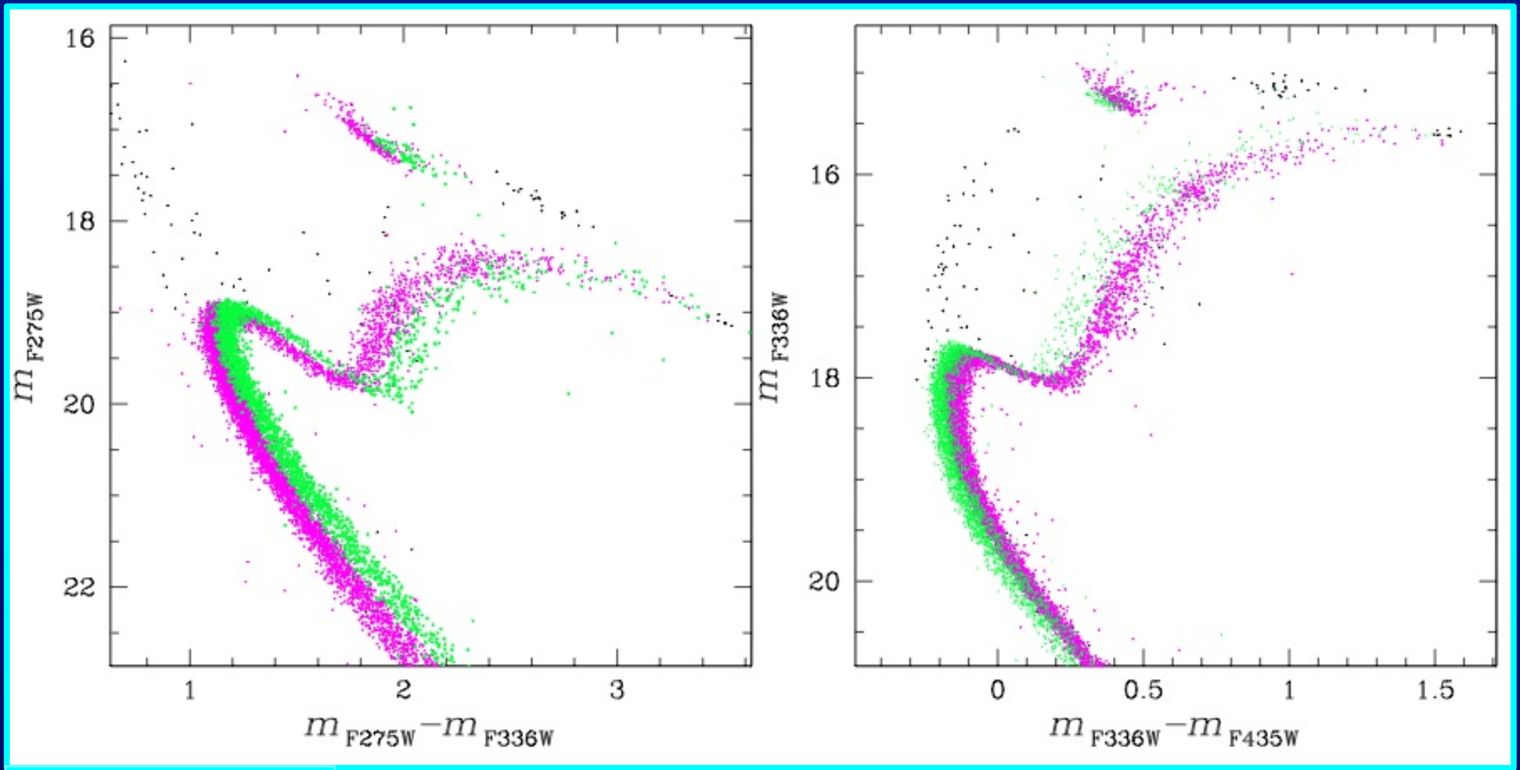
Na-rich/O-poor/CN-strong – II° generation
➔ red RGB

…also in the Stroemgren filters…



Milon

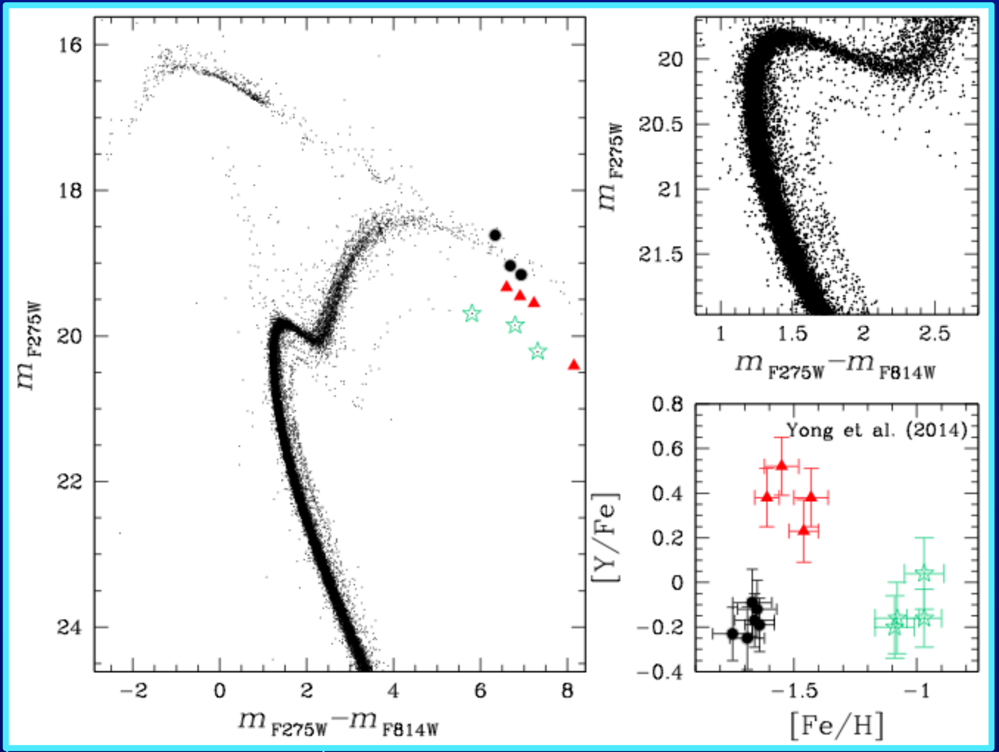
The multiple populations in 47Tuc



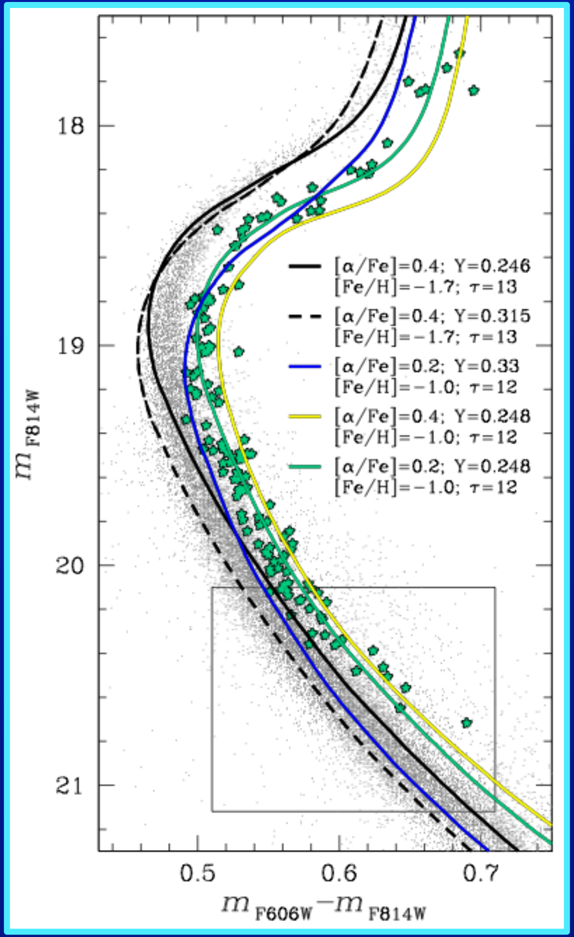
Milone et al. (2012)

Group	color code	sequences	chemical composition	fraction (R<~2 arcmin)	(R>~15arcmin)
G_a	green	MSa+SGBa+RGBa+HBa	CN-weak, O-rich, Na-poor, Y~0.25	~20%	~40%
G_b	magenta	MSb+SGBb+RGBb+HBb	CN-strong, O-poor, Na-rich, Y~0.265	~80%	~60%

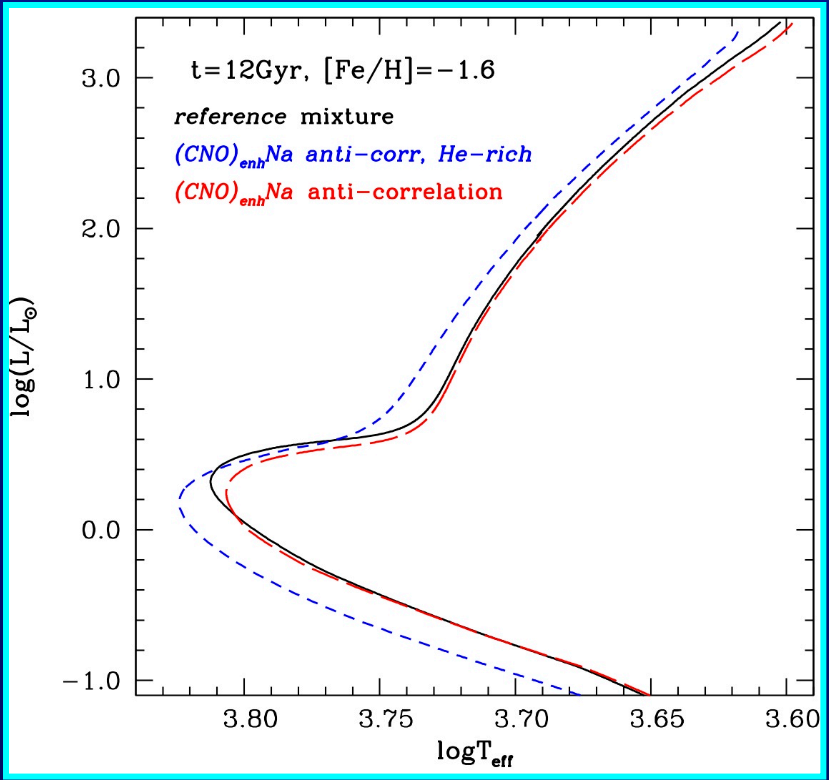
An other spectacular case: M2



Milone et al. (2014)



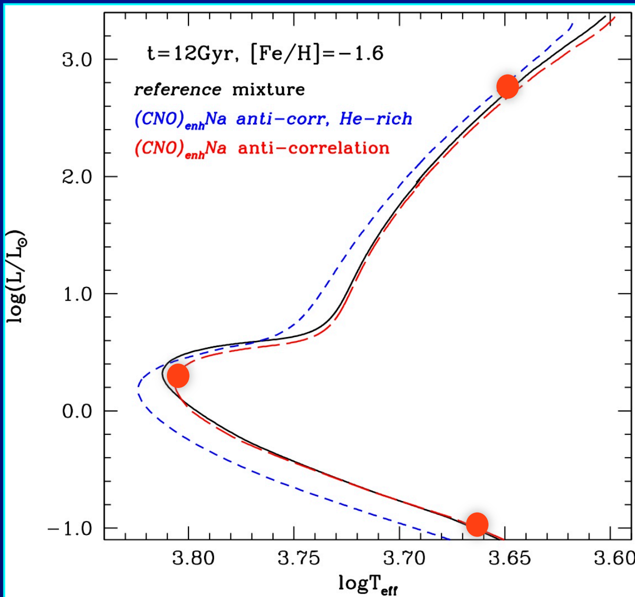
The theoretical evolutionary scenario: appropriate stellar models & the fundamental rôle of model atmospheres

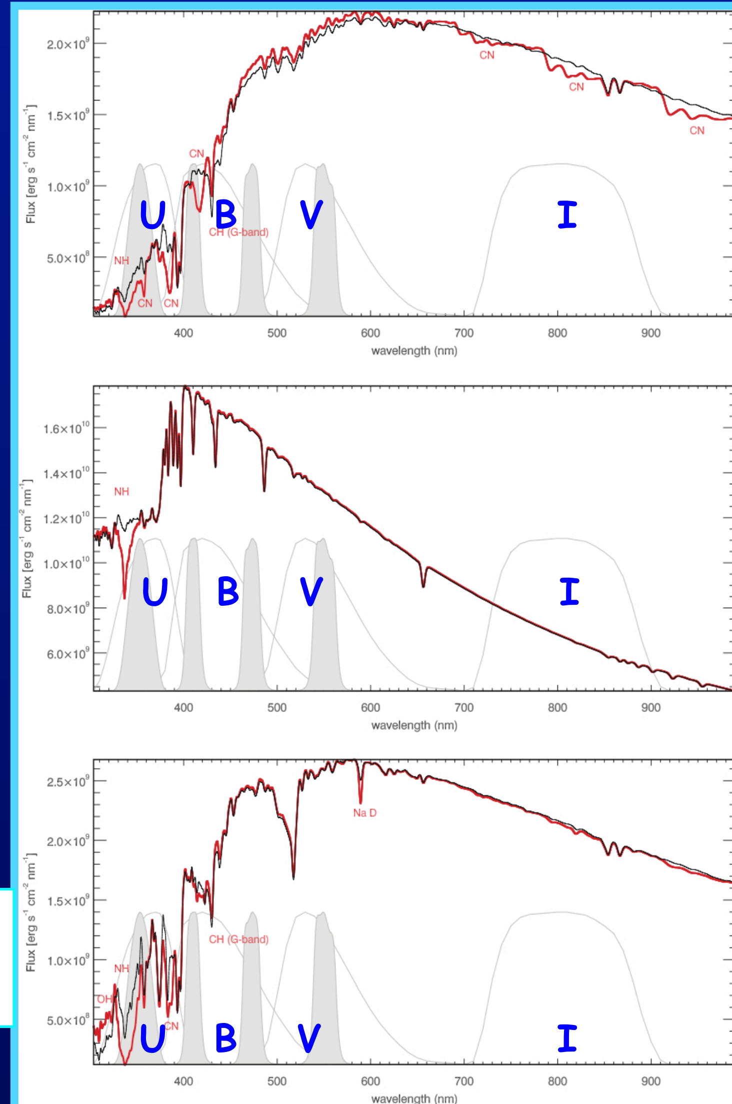


In the H-R diagram, at fixed [Fe/H], a clear separation (split) of an evolutionary sequence can be obtained:

- for the MS, only as a consequence of a huge He-enhancement;
- for the SGB, only as a consequence of an increase of the (C+N+O) sum;
- in the case of the RGB, only as a consequence of an He increase;

...but multi-band observations suggest that the changes in the stellar Spectral Energy Distribution induced by the peculiar chemical patterns are important...;





RGB
T_{eff}=4476K, logg=1.2

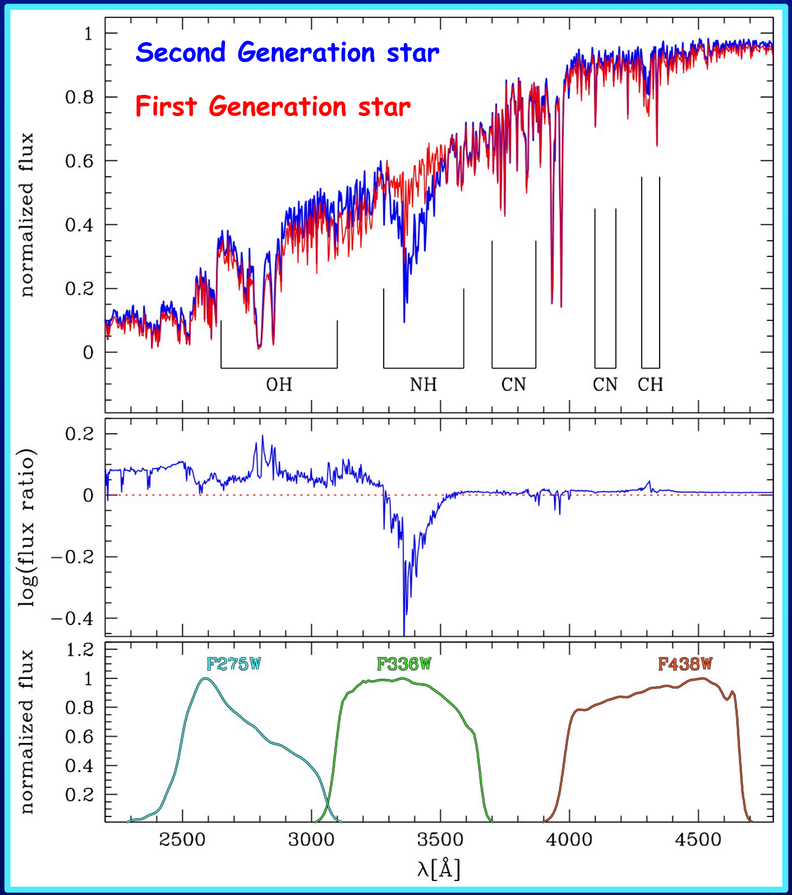
TO MS
T_{eff}=6490K, logg=4.22

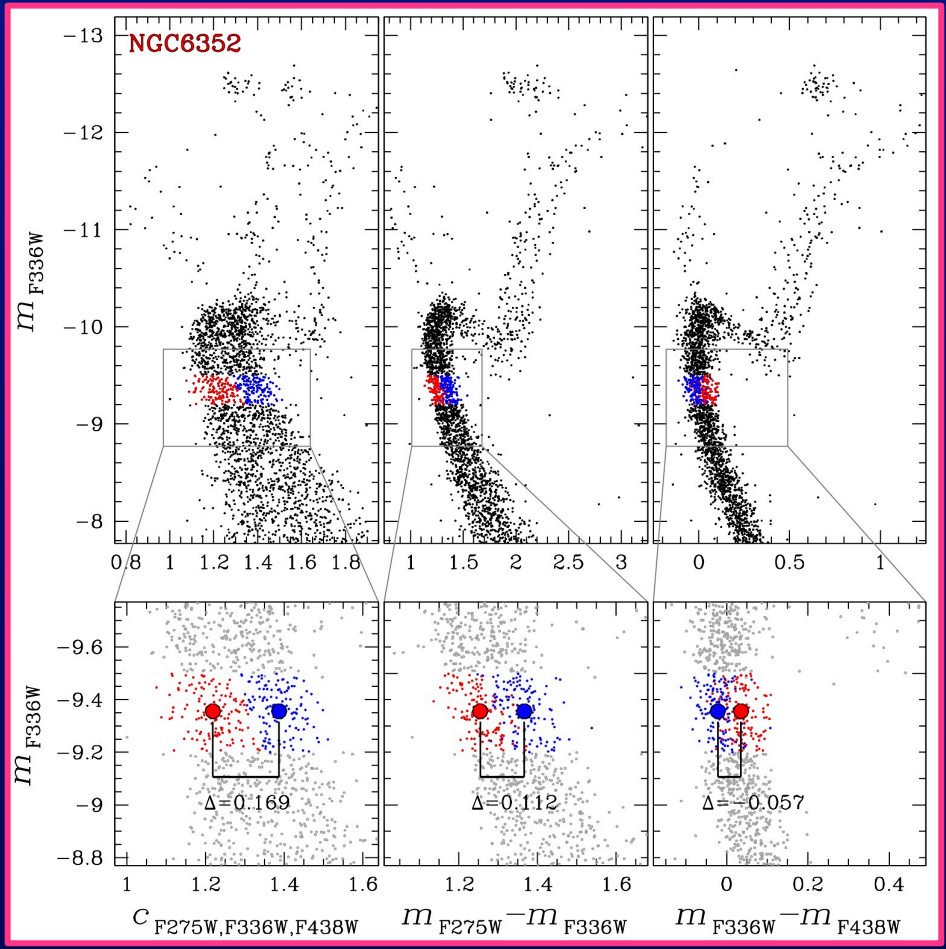
low MS
T_{eff}=4621K, logg=4.47

- black: reference mixture
- red: $(CNO)_{ext}$Na anti-correlation

light-element changes affect mainly the portion of the spectra short of about 400 nm owing to the changes in molecular bands (...,NH, CN, and OH in the fainter MS stars...)... this has a huge impact in the UV WFC3 filters...

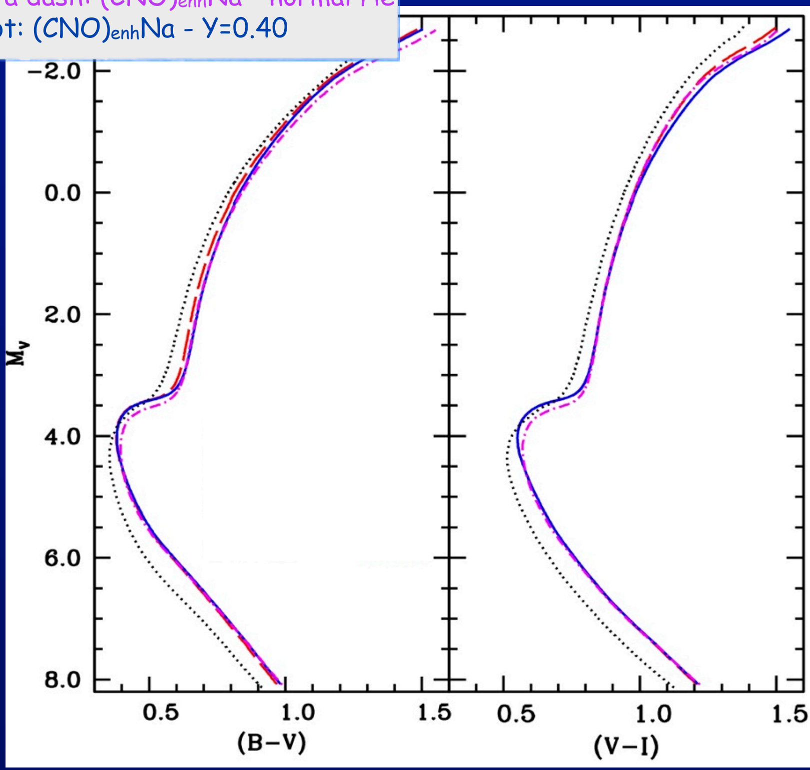
SG chemical peculiarities & UV WFC3 filters

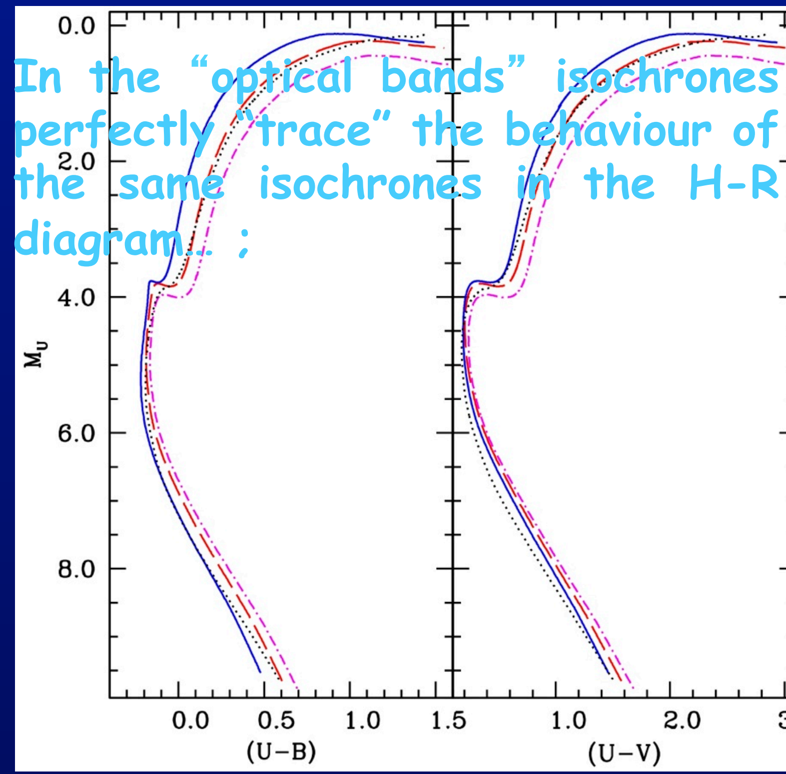




“self-consistent” isochrones for multiple population GCs

- blue solid: reference mixture
- red dash: CNONa
- magenta dash: $(CNO)_{enh}Na$ - normal He
- blue dot: $(CNO)_{enh}Na$ - Y=0.40



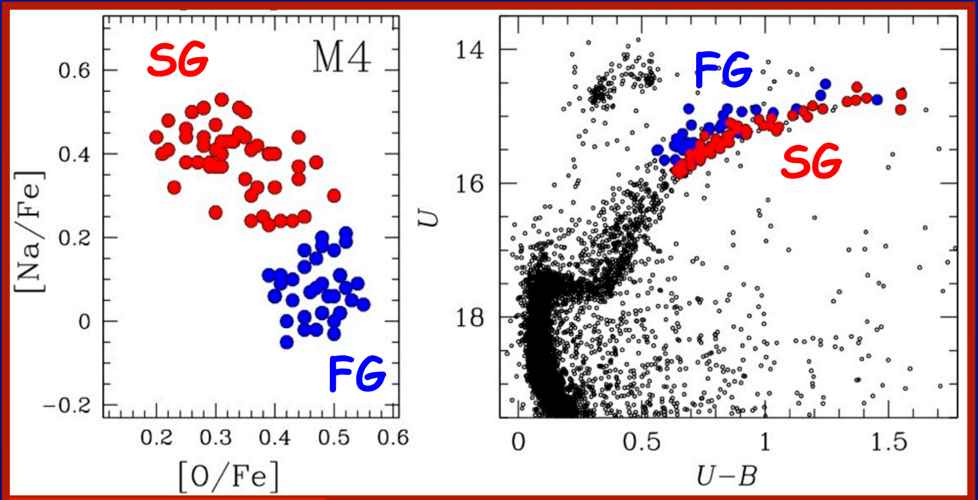


In the “optical bands” isochrones perfectly “trace” the behaviour of the same isochrones in the H-R diagram… ;

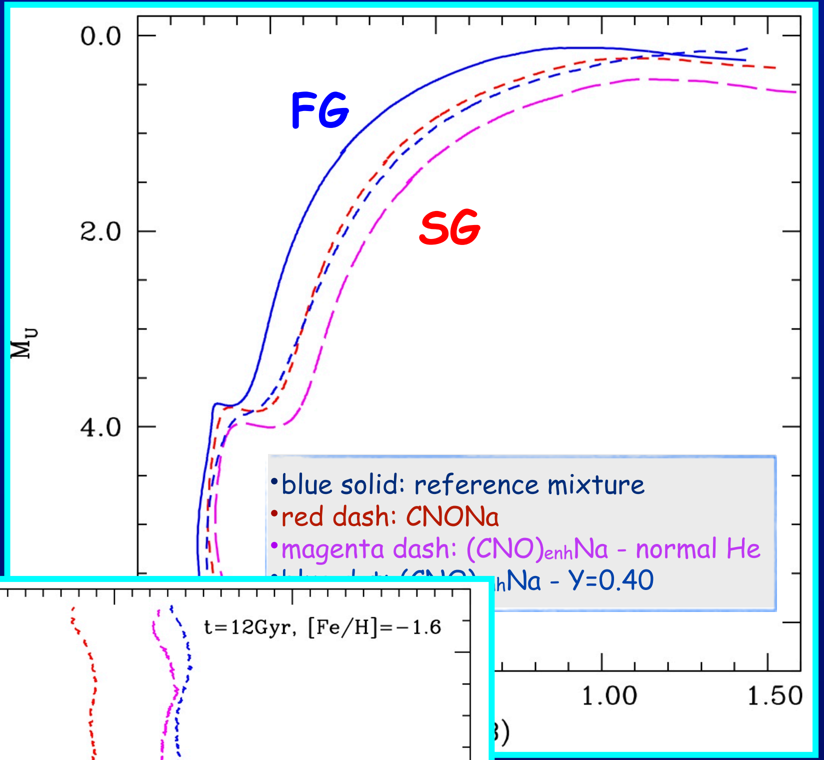
When “bluer” filters are used, CNONa anti-correlations and He differences can produce multiple sequences from the MS up to the RGB:

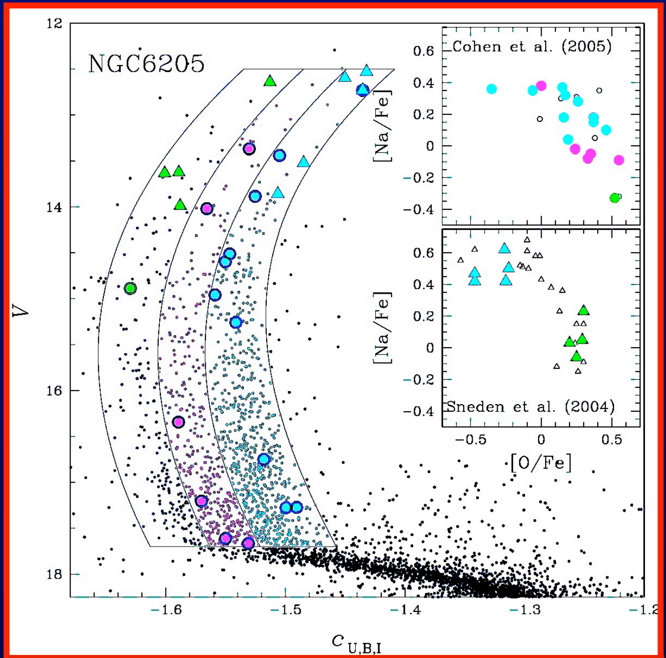
- This does not depend on the CNO sum;
- He-enhancements work in the opposite direction of light-element anti-correlations;

"self-consistent" isochrones for MPs: interpretative analysis

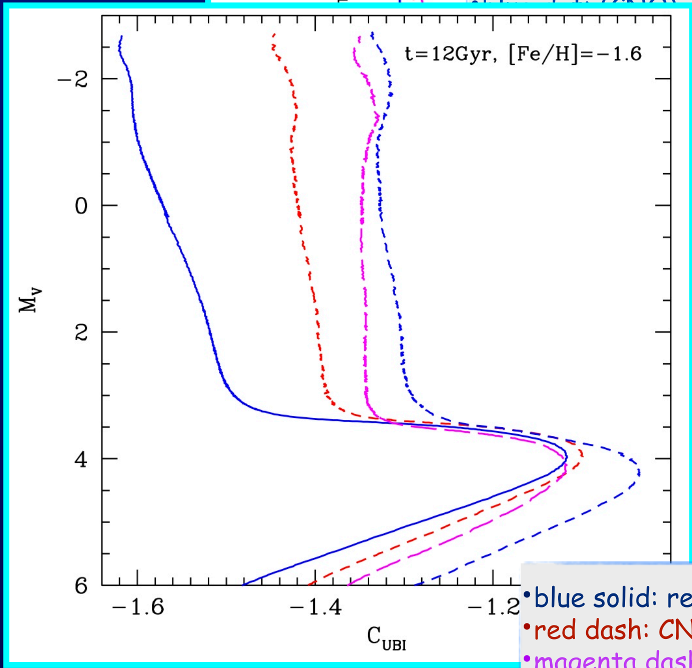


Marino et al. (2008)





SUMO Project: Monelli et al. (2013)



•blue solid: reference mixture
•red dash: CNONa
•magenta dash: $(CNO)_{enh}$Na - normal He
•blue dot: $(CNO)_{enh}$Na - Y=0.40

Open issues in the MP phenomenon

- Polluters;
- Stellar Ejecta Dilution;
- Mass Budget;
- Formation Scenario(s);

is there a link between the MP phenomenon and the Galaxy formation process?

A (possible) GC formation scenario

(Carretta et al. 2010)

- ✓ Formation of a precursor population, with a raise in [Fe/H], sometimes fast;
- ✓ **Triggering formation of a large primordial population (first generation);**
- ✓ Winds from massive stars and core collapse SNe **stop** further star formation and clean the region from primordial ISM;
- ✓ Low velocity wind from massive AGB stars (!) **generates a cooling flow** (D'Ercole et al.) + dilution with pristine gas(!);
- ✓ **Second generation stars form in this cooling flow;**
- ✓ Core collapse SNe for this second generation stops further star formation;
- ✓ At some time, decoupling between Dark Matter and gas;

The "Mass Budget" problem

Only ≈5% of the mass of FG stars comes out as matter with the "appropriate" chemical patterns suitable for making SG stars

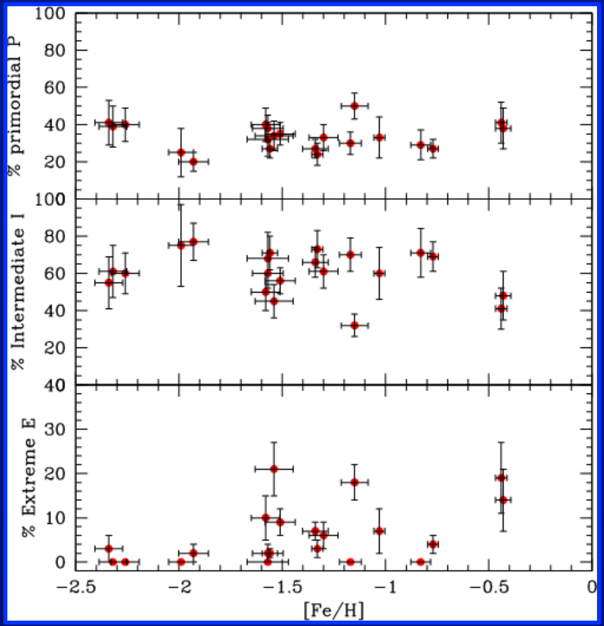
$$M_{progenitor} \approx M_{SG(today)} \times 20 \times \varepsilon^{-2}$$

ε is the star formation efficiency

by assuming a *canonical value* of 10% for the star formation efficiency, the multiplying factor to $M_{SG(today)}$ becomes ≈ 2000

for a typical value $M_{SG(today)} \approx 10^5 M_\odot$ ➔ $M_{progenitor} \approx 2\times10^8 M_\odot$
(and $4\times10^9 M_\odot$ in the case of the GC ω Cen)

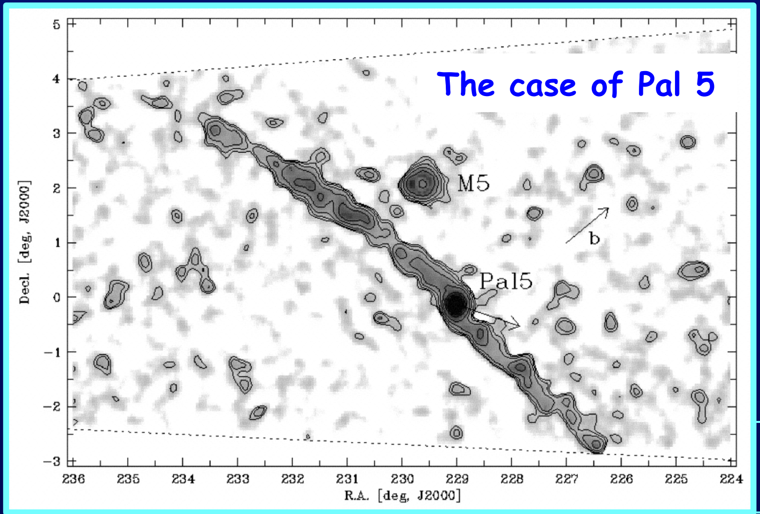
This implies that GCs were quite more massive (from 10 up to 50/100) than at present time



GCs can actually lose stars due to:

- ✓ Violent relaxation following gas expulsion/mass loss from massive stars and energy injection via SNe events (Baumgardt et al. 08);
- ✓ Evaporation on a longer timescale due to 2-body encounters and other mechanisms (such as disk shocking…) (Aguilar et al. 88);

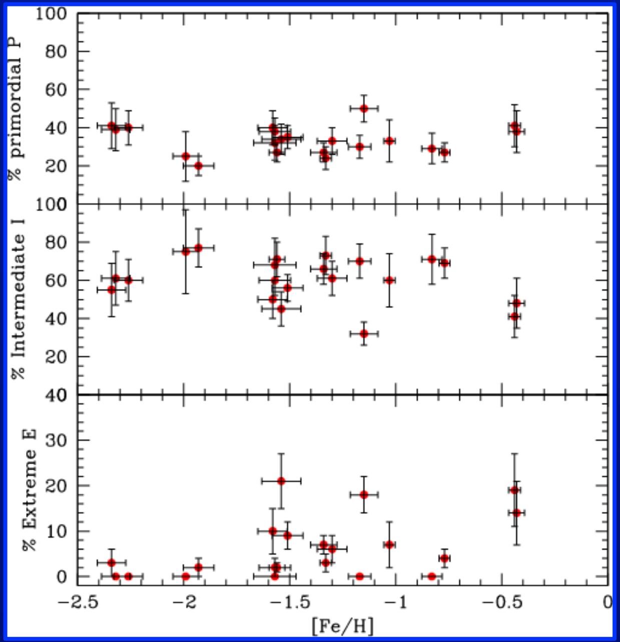
due to this second effect, some % of the stars should be removed within a relaxation time



23.2kpc from the Sun
Overall extension of more than 22° (10kpc)
More than 100% of the mass of the cluster in the tails

Odenkirchen et al. (2003)
Carlberg et al. (2012)

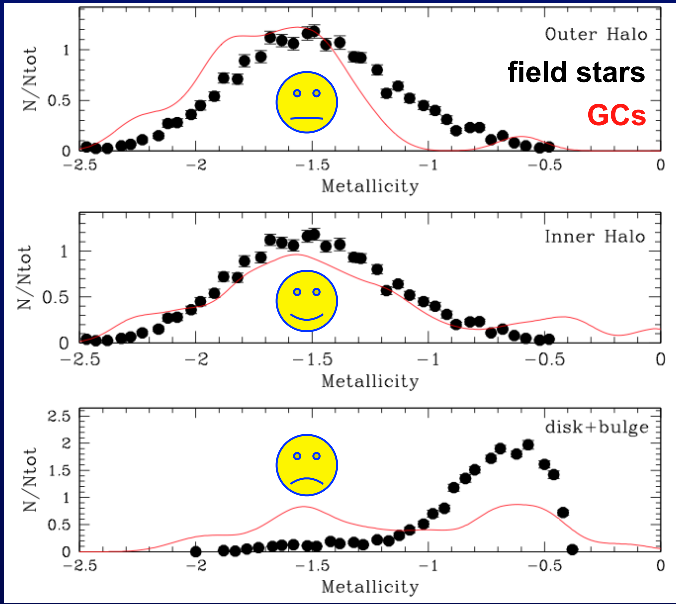
GGCs could lose a substantial fraction of their original mass



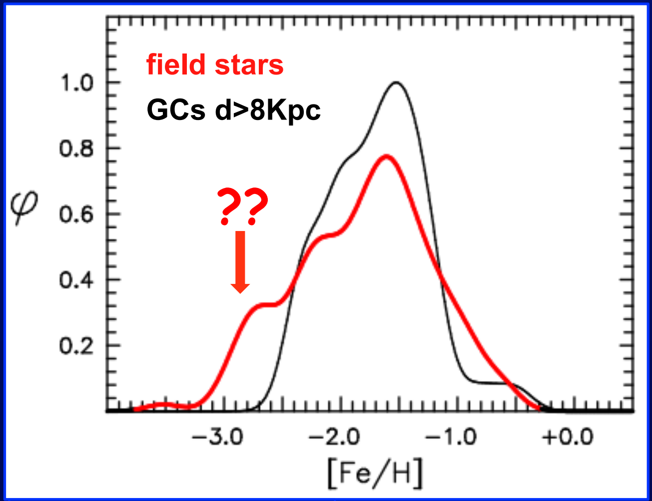
Present-day SG/FG star ratio provides a strong argument suggesting that GGCs have to lose a major fraction (≈75%) of their First Stellar Generation...

The Galactic halo might (largely) be made by FG stars!!!

A proof: metallicity distribution of GGCs versus field stars

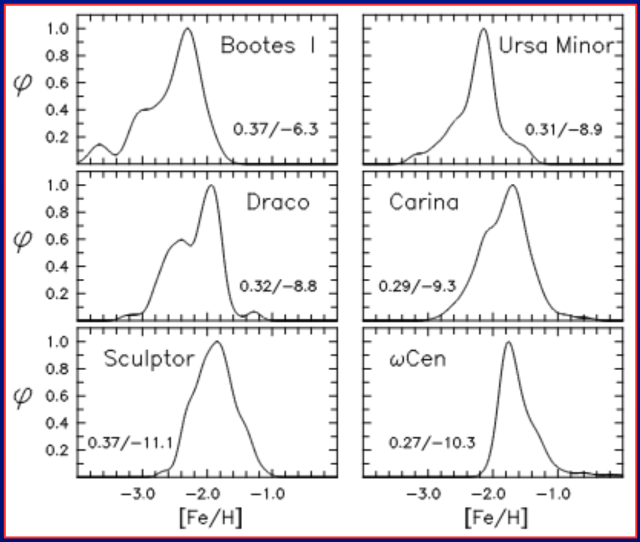


Gratton et al. (2012)



Frebel & Norris (2013)

The metallicity distribution of MW dwarf galaxies

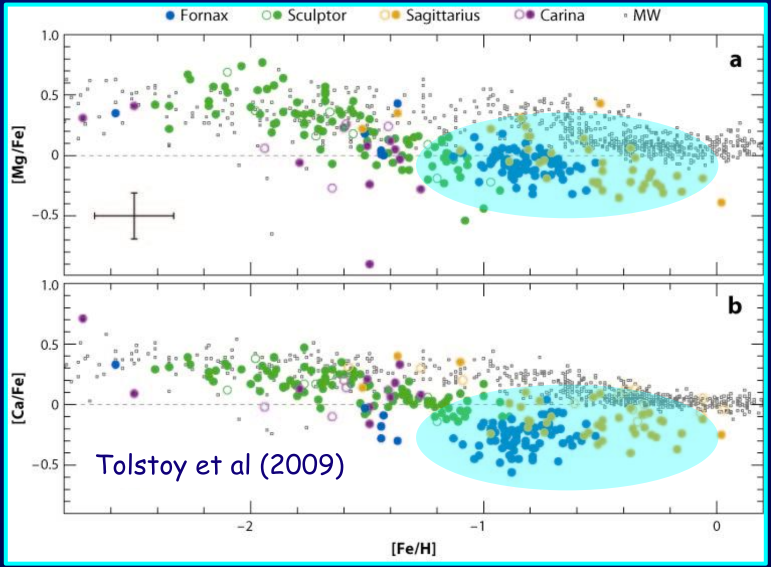


at odds with (the majority of) GGCs all dwarfs show large [Fe/H] spread…

in the faintest dwarfs (M_V>-7) there is a significant fraction of very metal-poor stars ([Fe/H]<-3) …

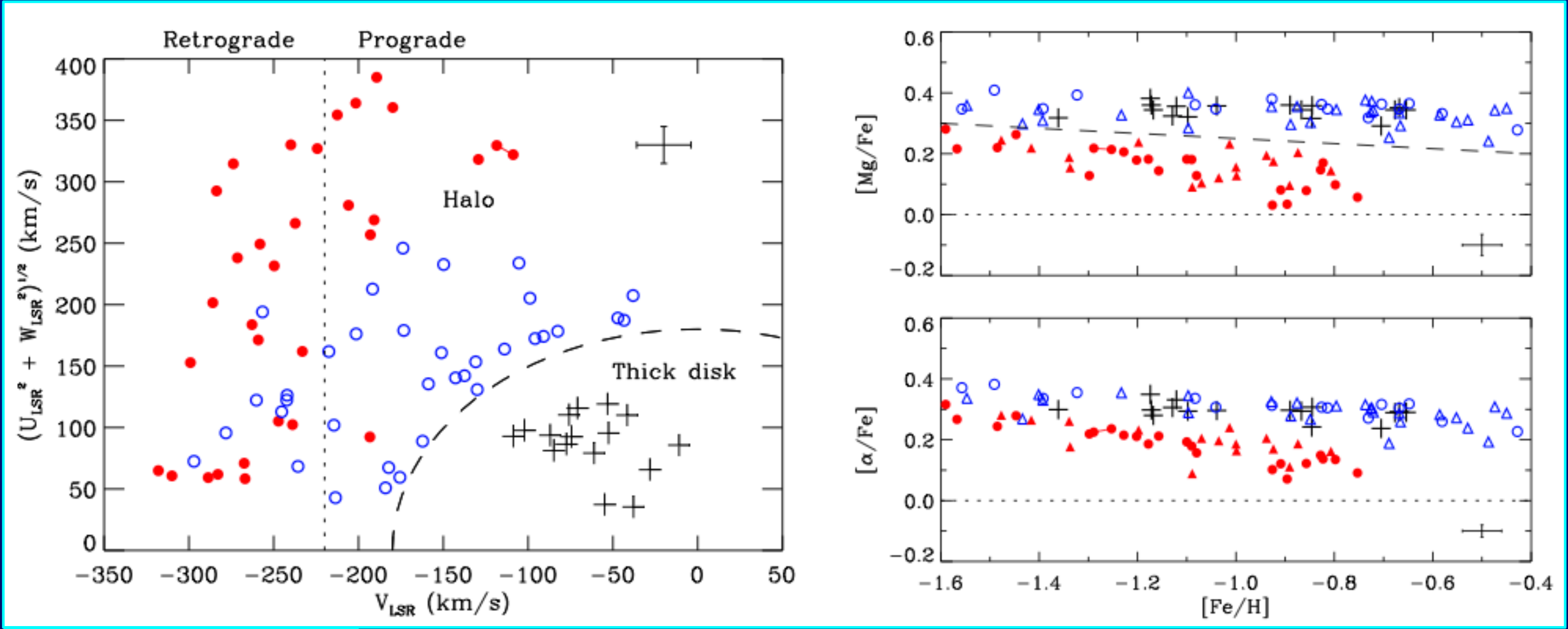
a relationship between ultra-faint dwarfs and the extremely metal-poor MW stars?

a signature of a dwarf accretion process?



When comparing the α-element enhancement in LG dwarfs and the (bulk of the) MW field, it appears that a low [α/Fe] is a key signature of the Milky Way's dwarf galaxies…

an hint of "accretion" from the α-element enhancement

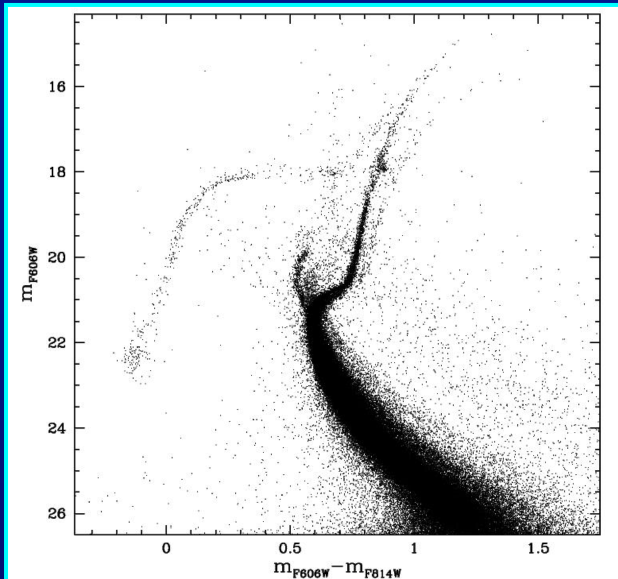


Nissen & Schuster (2010)

- a significant fraction of Halo stars have a low [α/Fe] value;
- most of them are on retrograde orbits…

This results is consistent with the view that dwarf galaxies have played an important role in the formation of the Milky Way halo

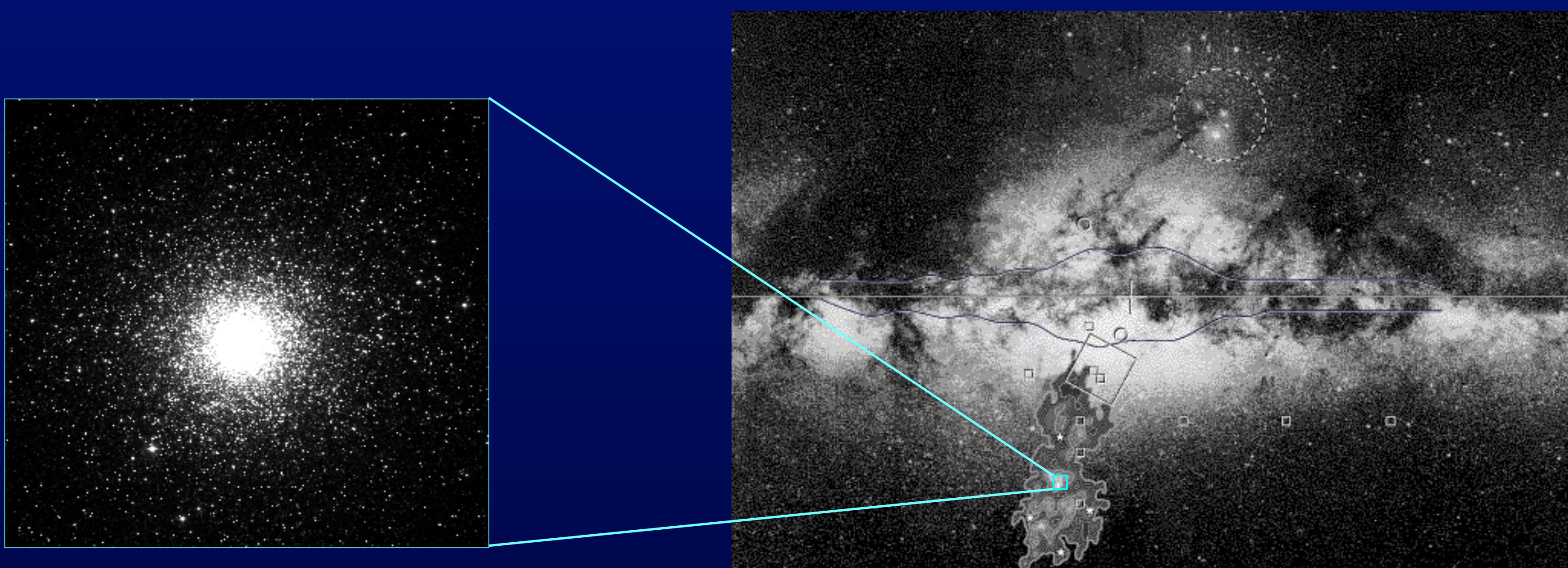
M54: an undisputable evidence



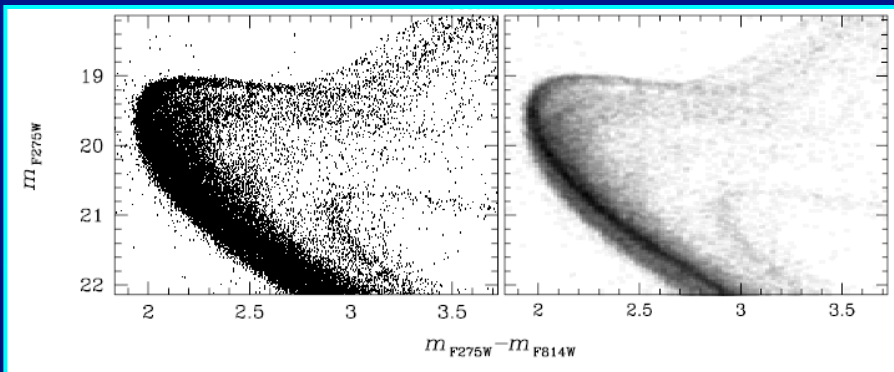
It coincides with the nucleus of the Sagittarius dwarf galaxy

It might be born in the nucleus or, more likely, it might be ended into the nucleus via dynamical friction (Bellazzini et al. 2008)

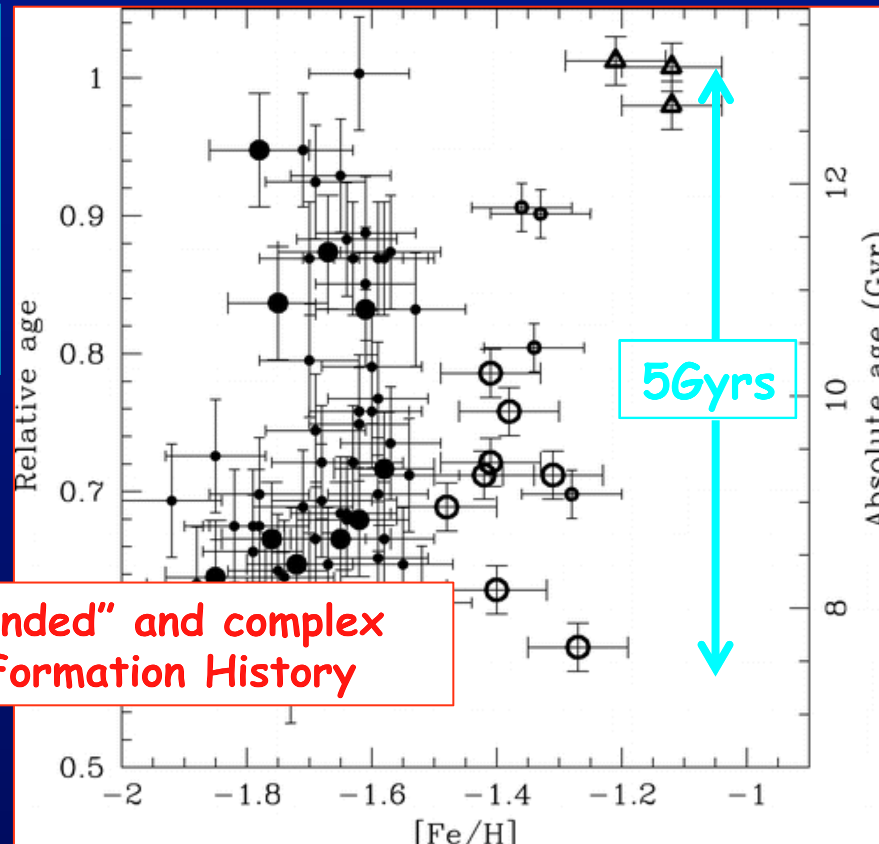
…but the important fact is that, today "The massive GC M54 is part of the nucleus of a disaggregating dwarf galaxy"



The case of ω Cen



Bellini et al. 2010

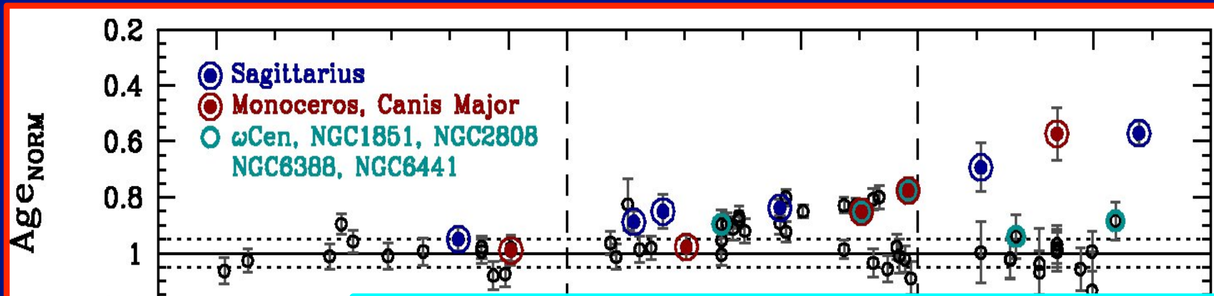


an "extended" and complex
Star Formation History

Is this evidence suggesting that the different sub-populations had multiple birth location, eventually related also with a merging process?

The "*merger within a fragment*" scenario early envisaged by Norris et al. (97)?

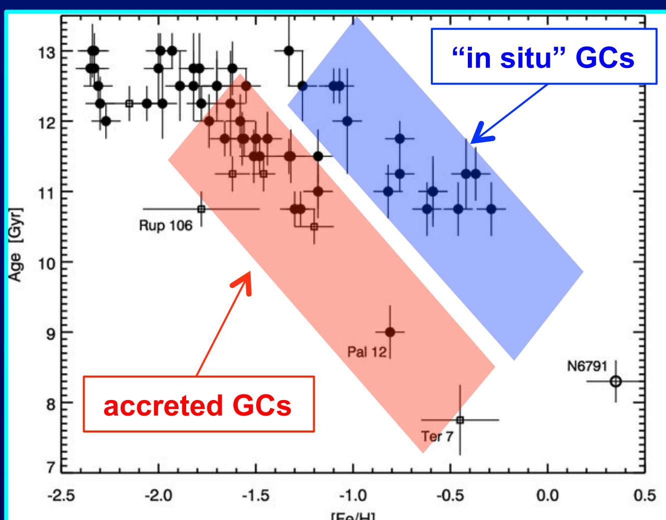
Can we use GGCs properties to investigate the accretion process?

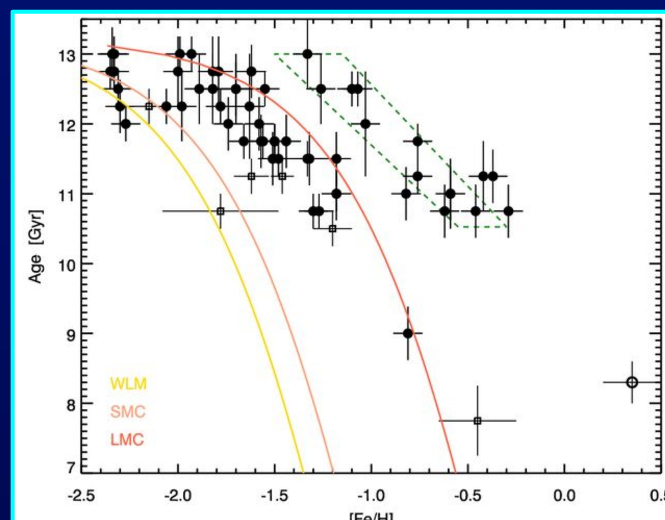


Marin-Franch et al. (20

Assumption:
The AMR of GCs is representative of the AMR of the dSph from which they originate

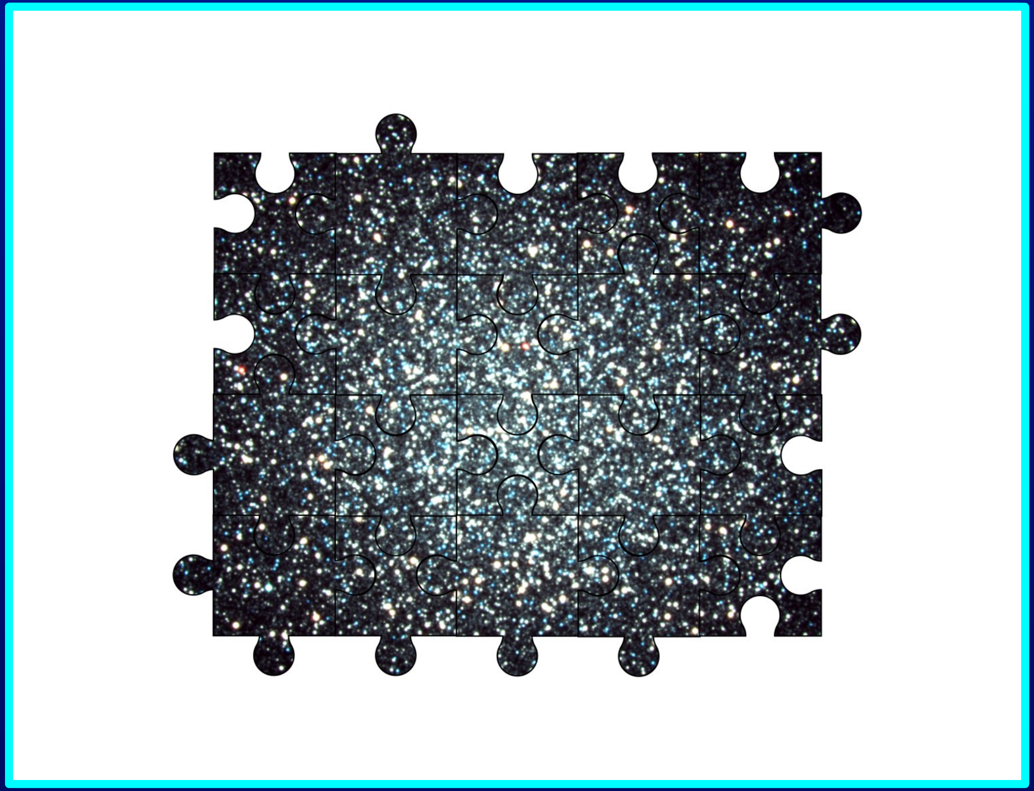
From the mass-metallicity relation of galaxies:
A decrement of 0.6 dex in metallicity implies a decrement of mass of the galaxy by $\Delta\log(M)$=2dex, or galaxies of M~10^7- few times10^8 Msun (typical of Sgr-LMC)





Leaman et al. (2013)

Conclusions



… the path to piece the jigsaw puzzle together is still long…