The oldest stellar populations in the Milky Way:

the Multiple Stellar Population Phenomenon in Galactic GCs and its implication for Galaxy formation

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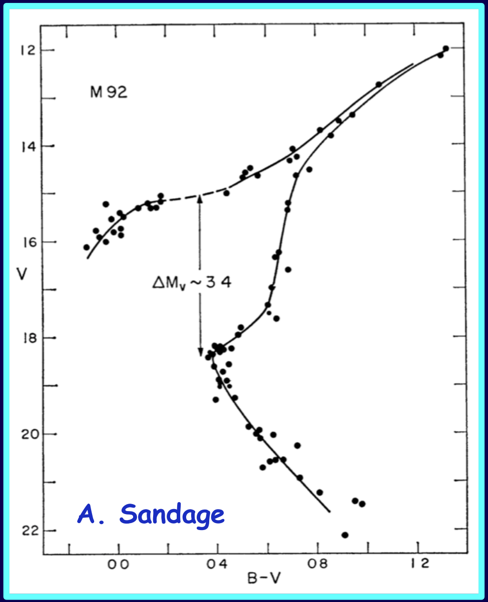
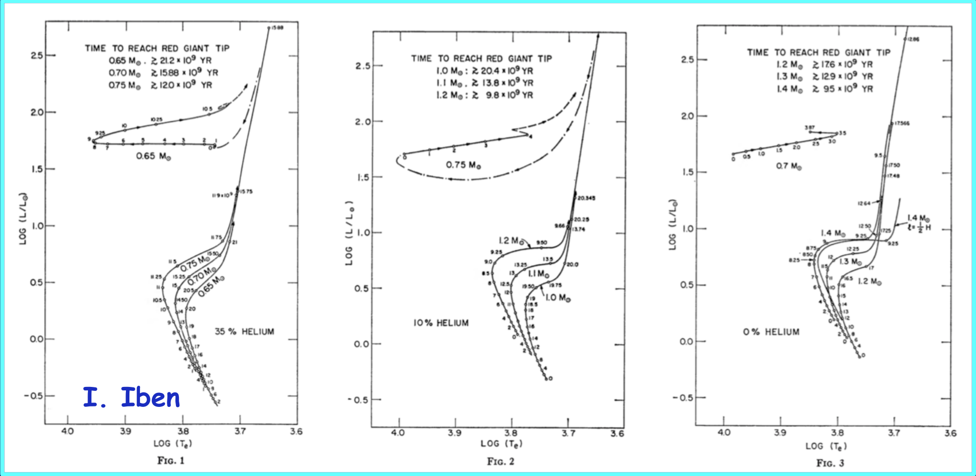
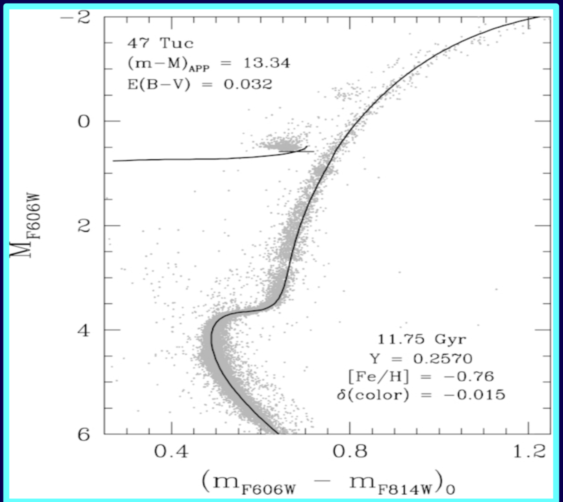
Galactic Globular Clusters: fundamental "particles"

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







- GCs absolute ages a lower limit for the age of the Universe…
- GCs relative ages a fundamental constraint for the Galaxy formation scenario(s)…

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

The GCs paradigma:
they host single-simple stellar populations

What is a "Simple Stellar Population"?

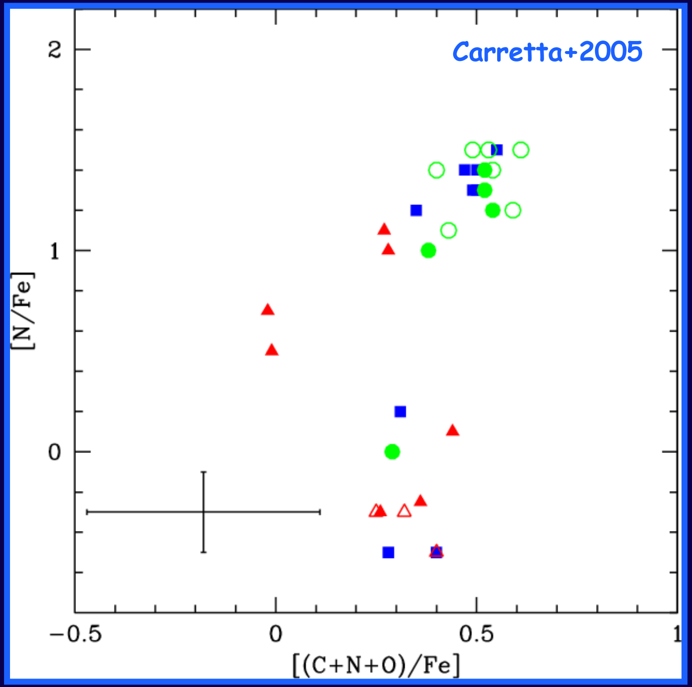
- "A Simple Stellar Population (SSP) is defined as an assembly of coeval, initially chemically homogeneous, single stars.
- Four main parameters are required to describe a SSP, namely its age, composition (helium, metals…) and initial mass function.
- In nature, the best examples of SSP's ~~are~~ were star clusters…."

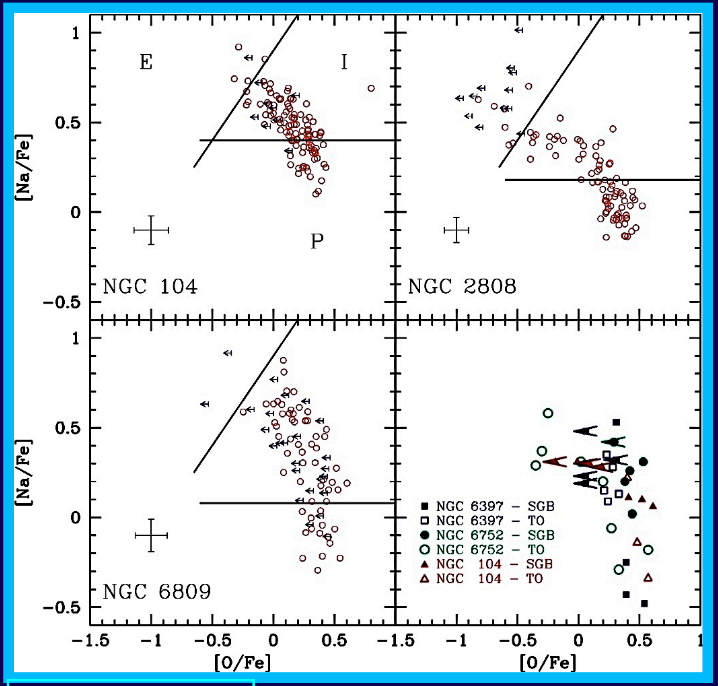
The peculiar chemical patterns of multiple stellar populations

✓ **light elements anti-correlations**

- **Na-O anti-correlation**
- **Mg-Al anti-correlation**
- **C-N and N-O anti-correlations**

✓ **C+N+O enhancement**





Carretta (2012)

In general, the CNO sum seems to be constant

The peculiar chemical patterns of multiple stellar populations

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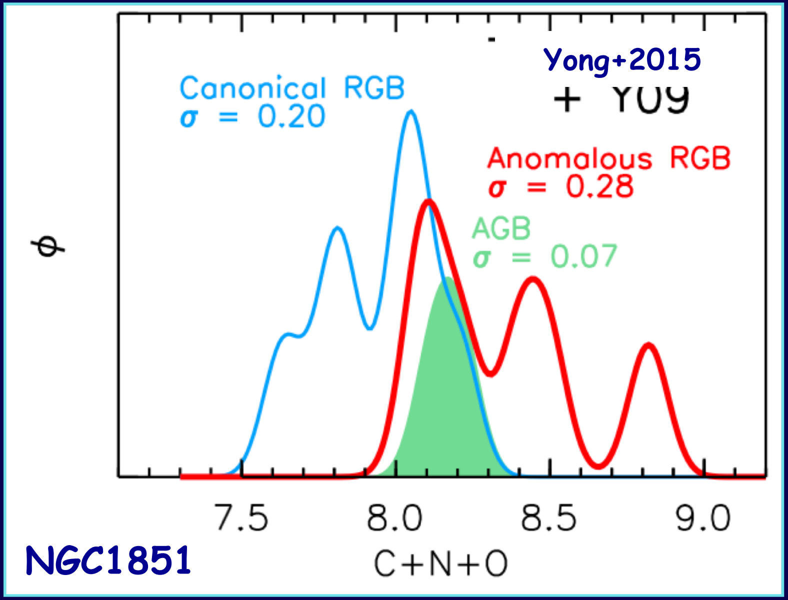
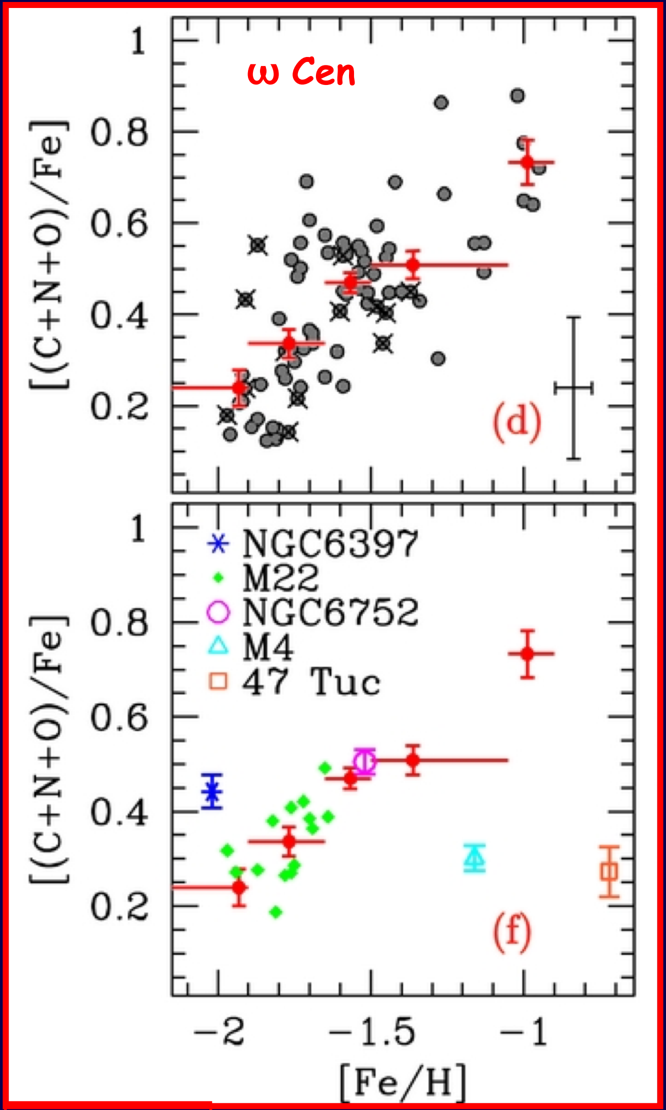


+

- NGC1851
- ω Centauri
- ....



Marino+2012

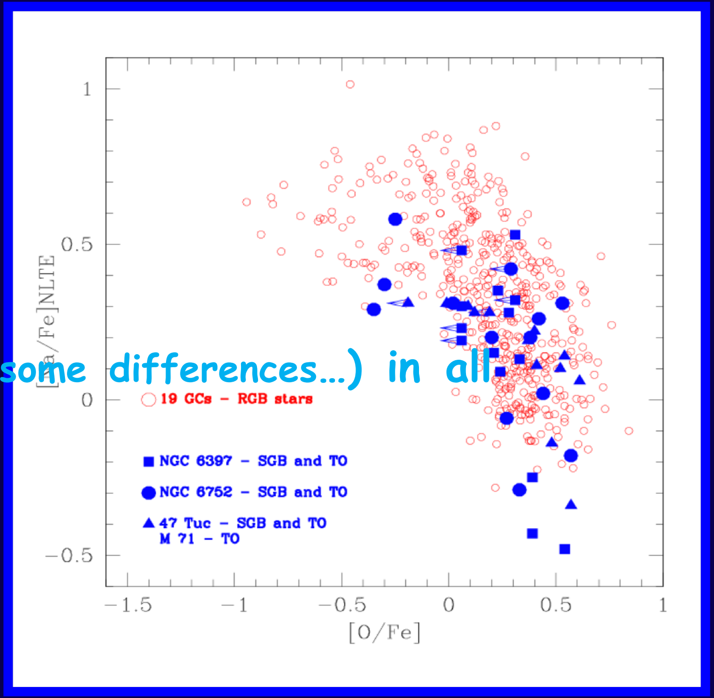
✓ The C & N abundances in GCs are very different than in field giants

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

✓ These anticorrelations also in unevolved stars

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

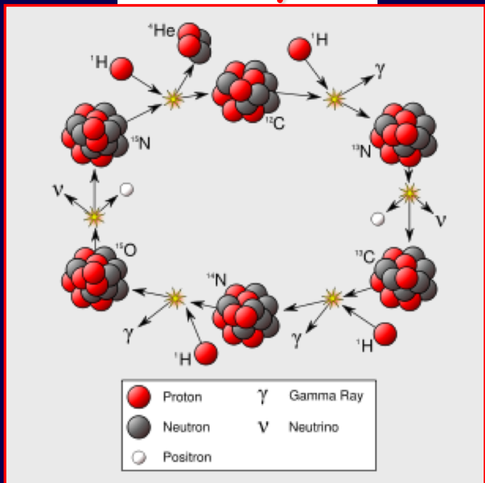
No "simply" surface pollution…



✓ These abundance patterns are present (with some differences…) in all GCs and not only in the most massive ones

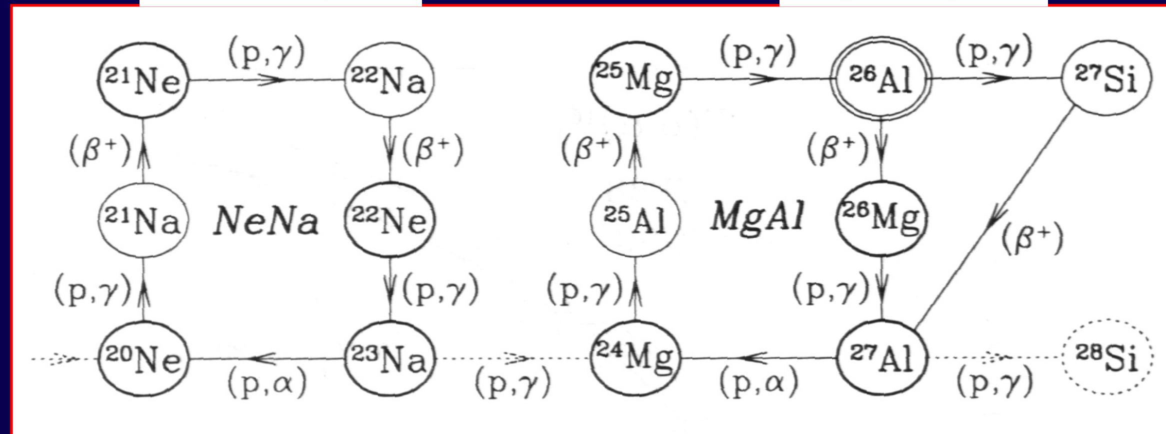
Light element(anti-)correlation ⇒ high-T proton captures

CNO cycle



T~20MK

NeNa cycle **MgAl cycle**



T~35MK **T~50MK**

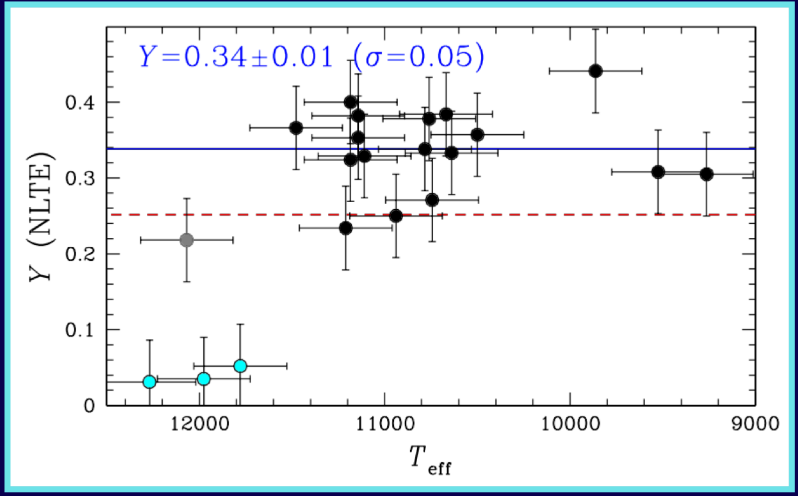
In the same zones where these "burning" cycles are expected to operate, a significant amount of Helium is present…

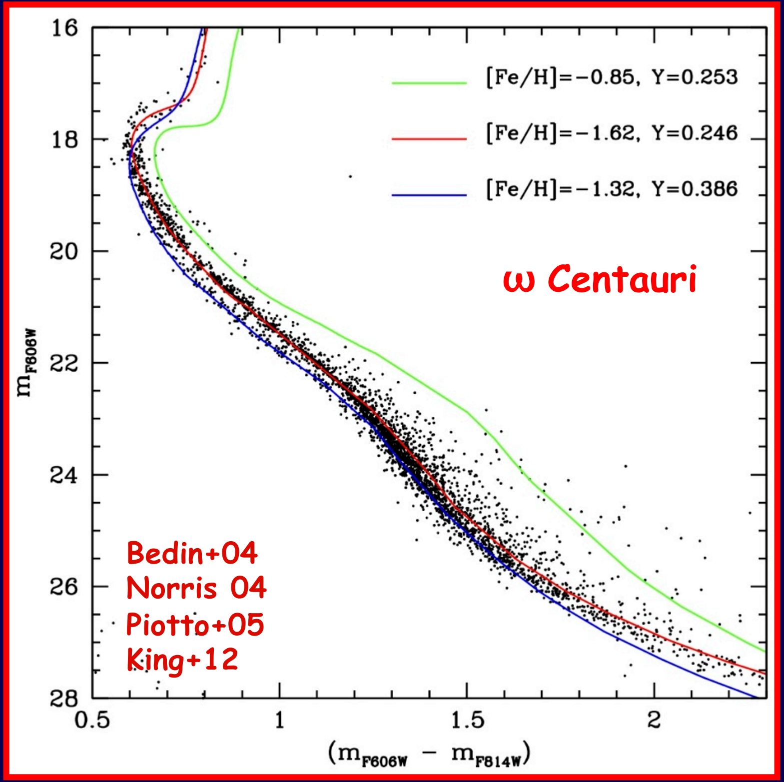
✓ **Helium enhancement**

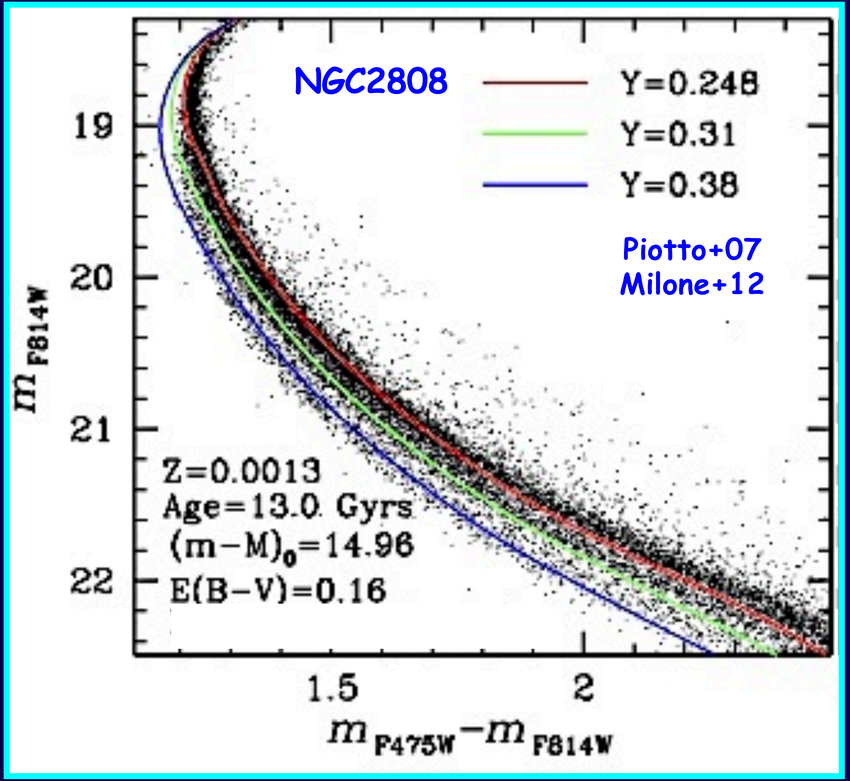
Direct spectroscopic measurements (e.g. Marino+14)

Indirect estimates (Bragaglia+10);

MS "splitting" in optical photometric bands;



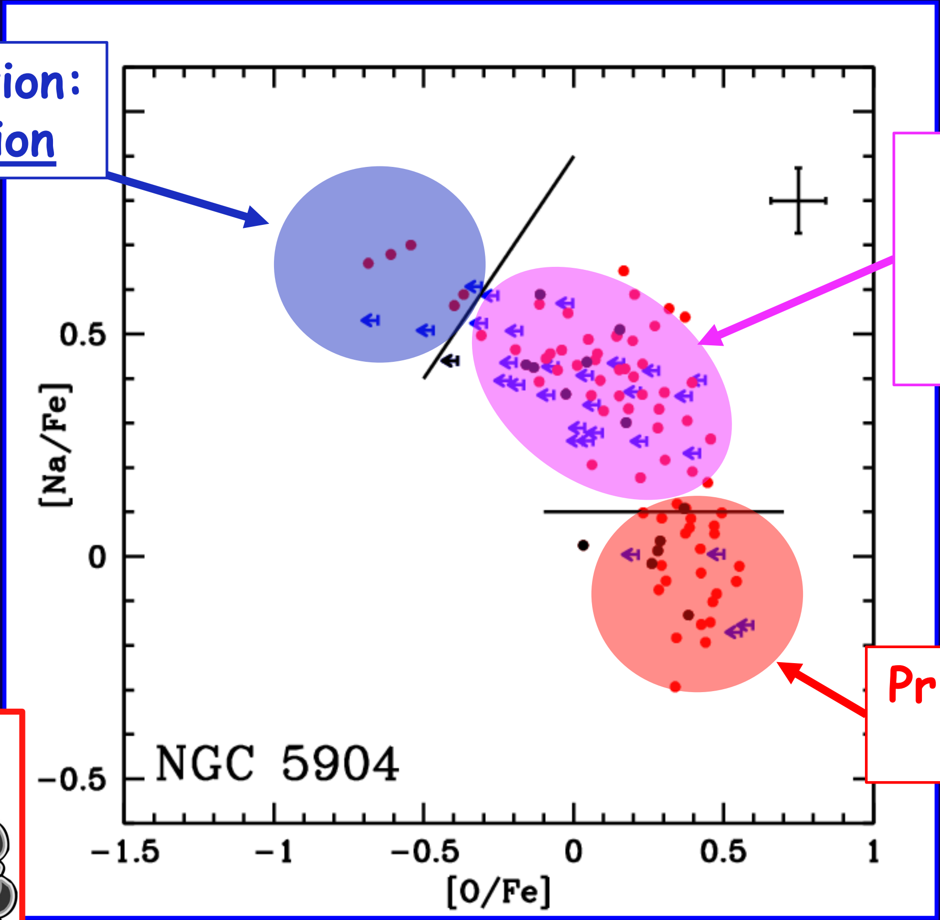




Distinct sub-populations in the same cluster:

Star clusters as "small" complex galaxies…

Extreme population:
Second generation

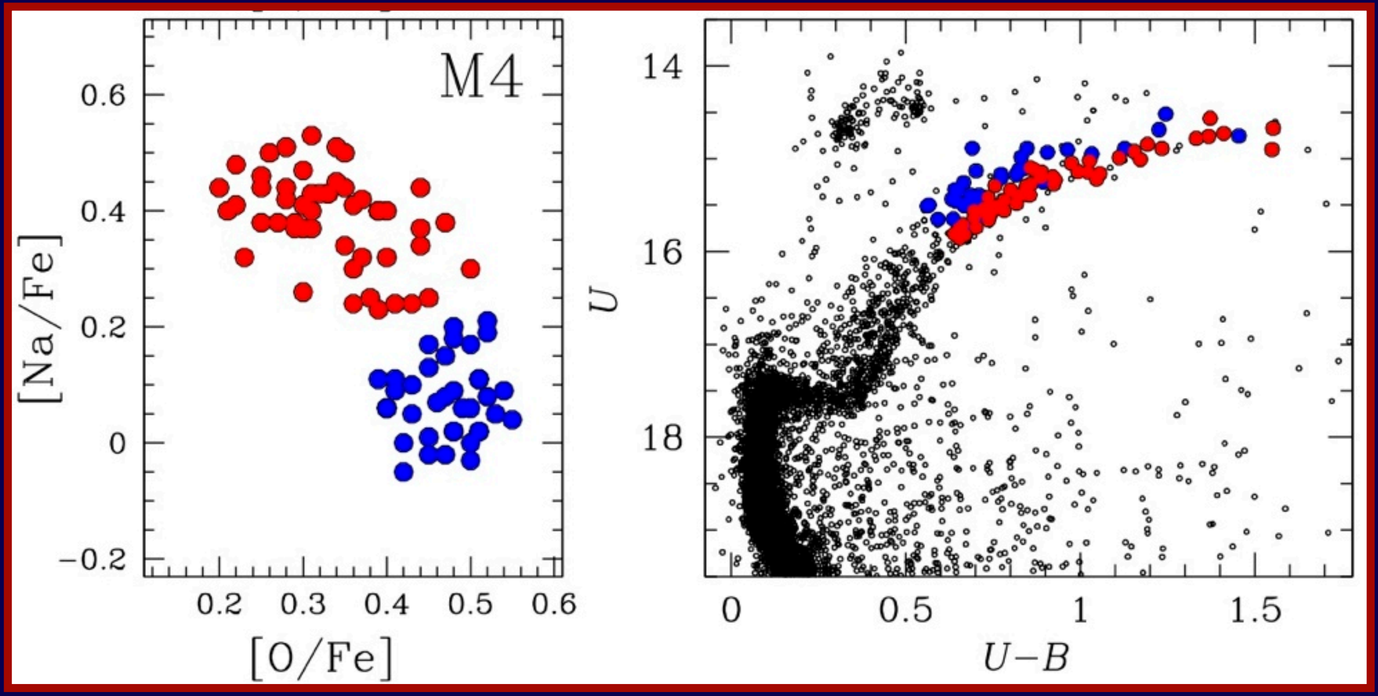


Intermediate population:
Second/Third generation

Primordial population:
First generation

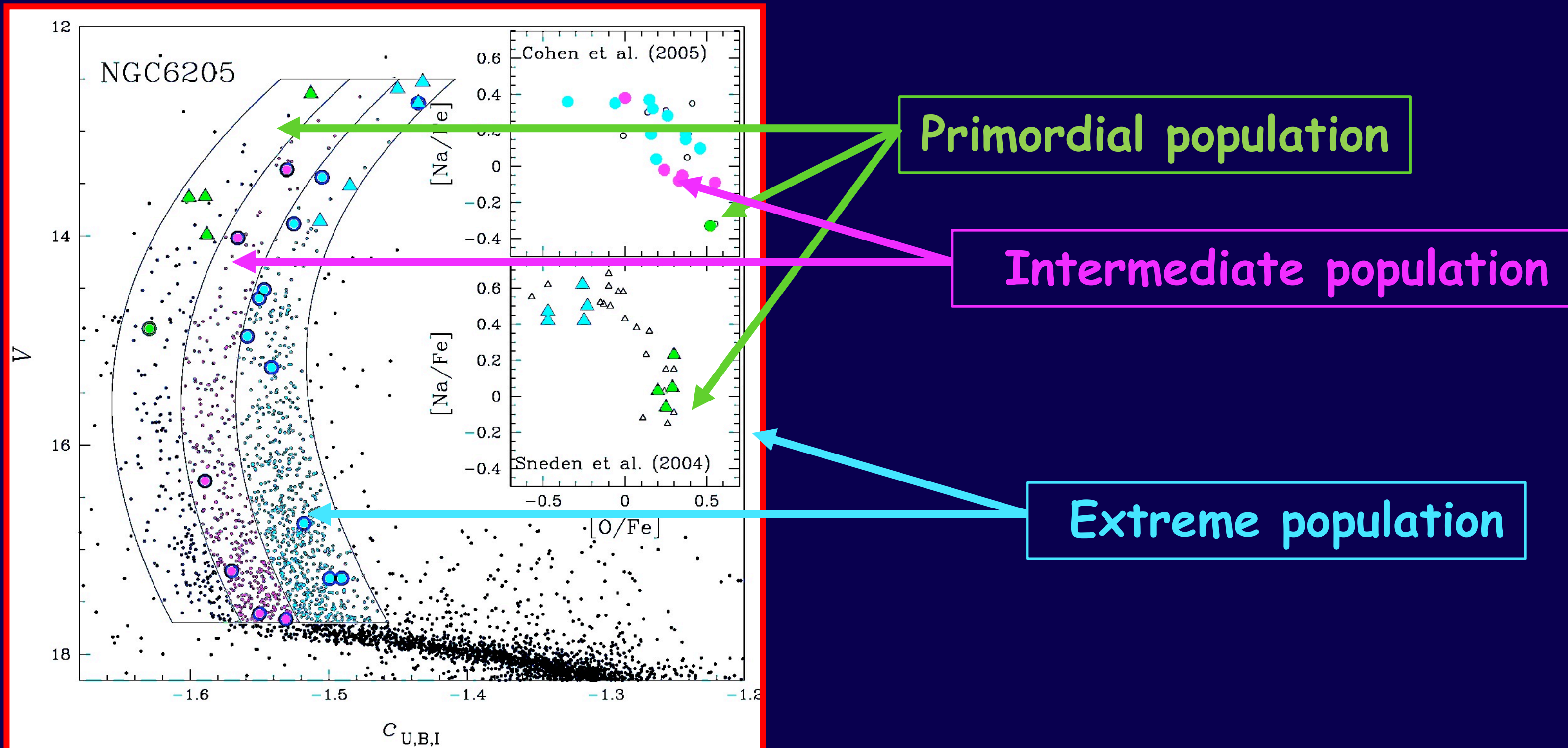
But… we still lack of … a master chef…

UV photometric surveys:
the Pandora's box or the Rosetta stone?



- ✓ Na-poor/O-rich/CN-weak – I° generation ➔ blue RGB
- ✓ Na-rich/O-poor/CN-strong – II° generation ➔ red RGB

UV photometric surveys: playing with photometric bands

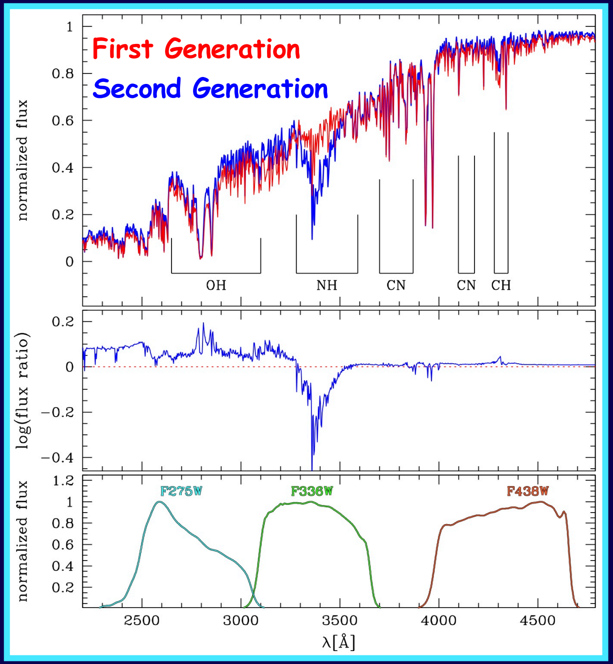


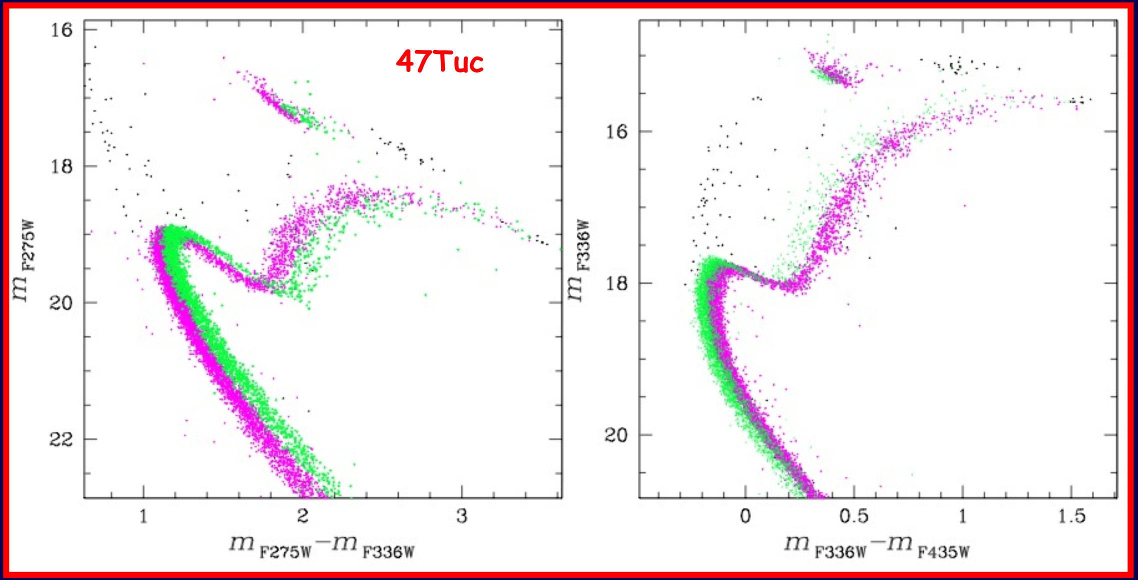
Monelli et al. (2013)

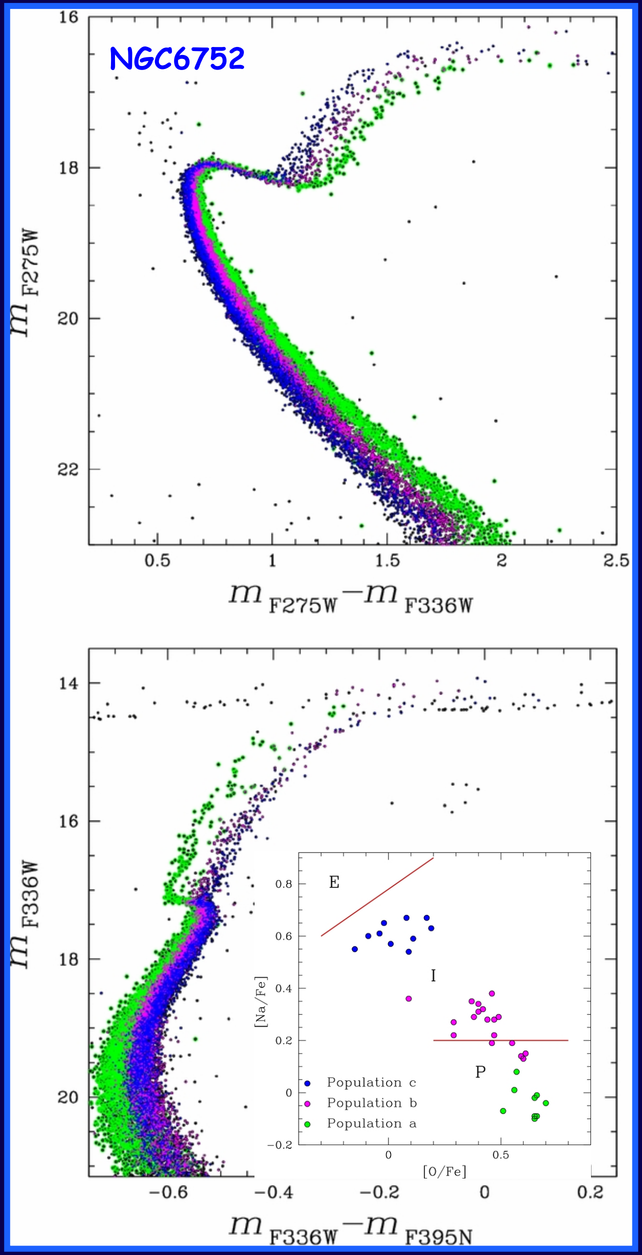
$$c_{UBI} = (U-B) - (B-I)$$

The HST UV Legacy Survey of Galactic Globular Clusters

- •170 orbits
- •About 60 GCs (UV + Optical data)







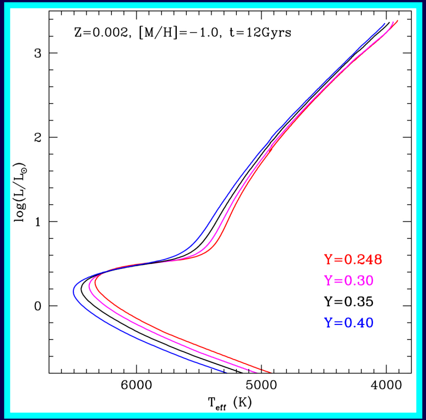
- distinct sequences from the MS up to the AGB stage…
- …also in clusters with no "huge" He enhancement…
- "swapping" sequences…
- …clear correlations with the abundance patterns…

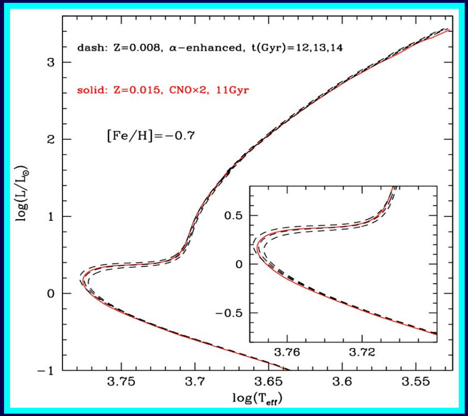
In order to understand the "whole (crime) scenario" it is mandatory to investigate the Multi-Population Evolutionary Framework

➢ How these chemical patterns affect the evolution of Stars?

A chemical abundance variation can affect the structural/evolutionary properties via a change in "basic" ingredients needed for stellar model computations:

- ✓ Thermodynamical properties
- ✓ Radiative opacity
- ✓ Nuclear burning efficiency





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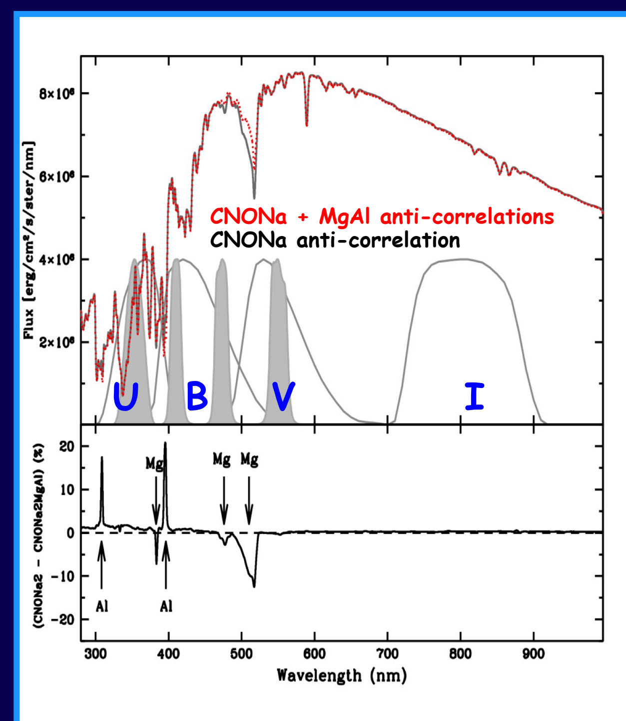
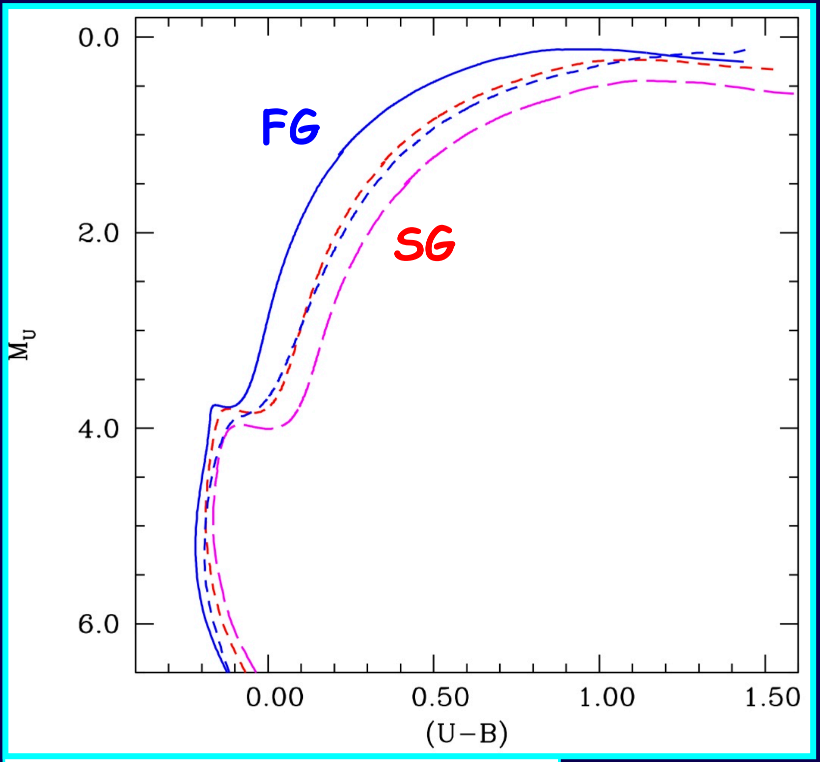
➢ What about the Stellar Spectral Energy (SED) distribution…?



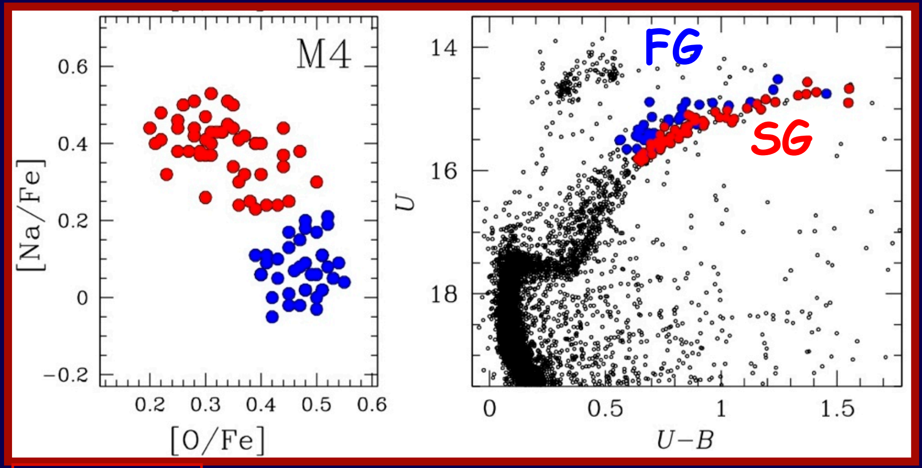
isochrones for multiple populations: a self-consistent approach



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

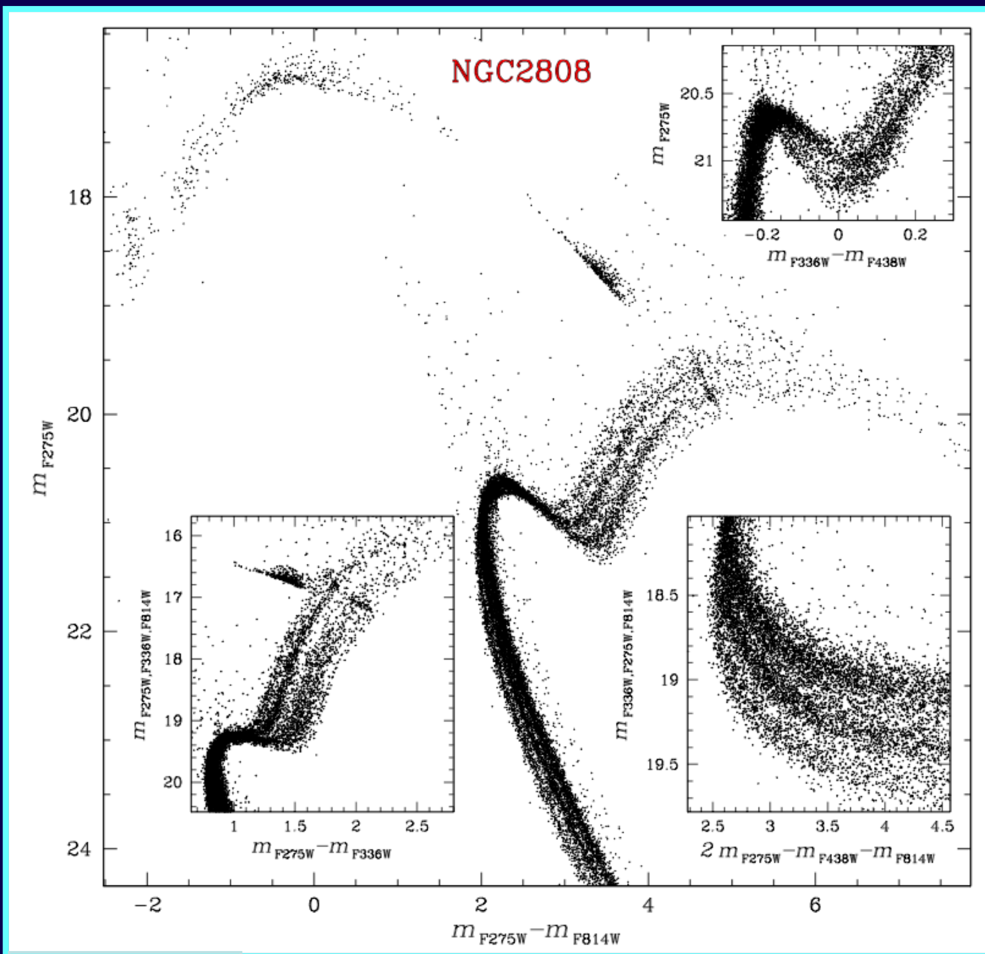
At odds with "optical bands" CMDs, UV CMDs are hugely affected by the presence of light element anti-correlations and He differences among the distinct sub-populations:

- a C+N+O enhancement makes the effect larger;
- He-enhancements "work" in the opposite direction of light-element anti-correlations;

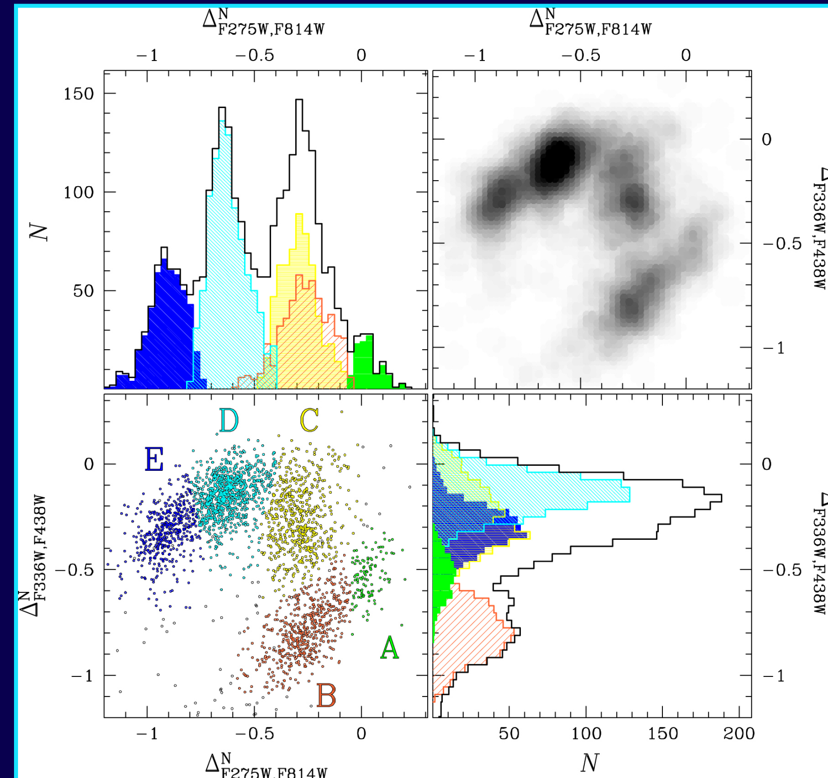


Marino+08

NGC2808: a "cool" cluster



Milone+15



C15[1]	M15[2]	[O/Fe][3]	[Mg/Fe][3]	[Al/Fe][3]	[Na/Fe][3]	[Fe/H][3]
P1	B	0.30	0.38	0.05	0.03	−1.13
		Δ[O/Fe][4]	Δ[Mg/Fe]	Δ[Al/Fe]	Δ[Na/Fe]	Δ[Fe/H]
P2,I1	C	−0.1	0.0	0.2	0.2	0.0
I2	D	−0.7	−0.3[5]	1.0[5]	0.4	0.0
E	E	−0.9	−0.4[5]	1.2[5]	0.8	0.0

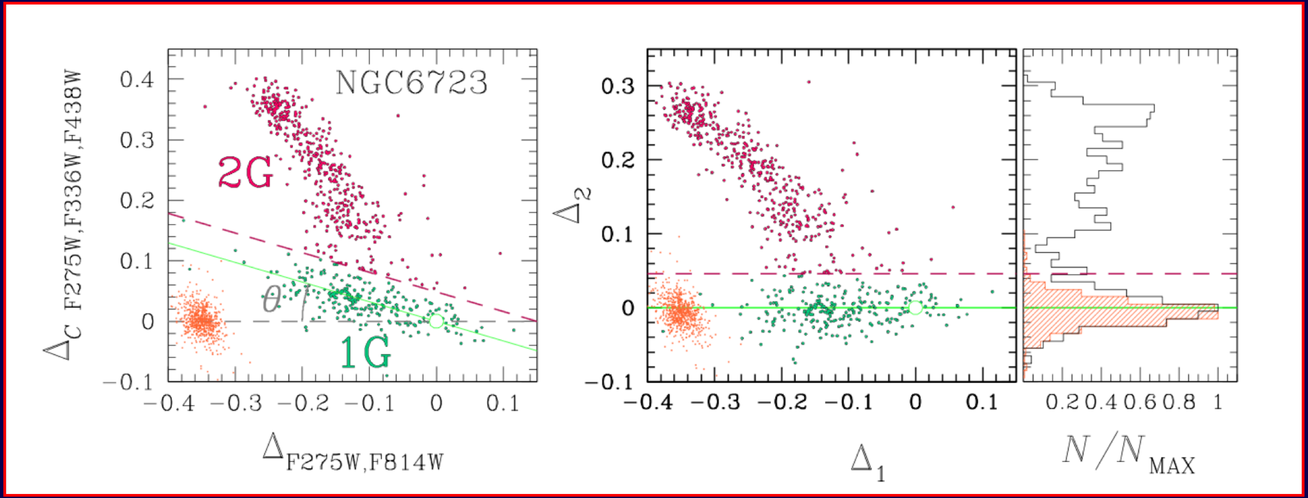
Pop.	ΔY	Δ[C/Fe]	Δ[N/Fe]	Δ[O/Fe]
C	0.00	−0.3	0.6	−0.1
D	0.05	−0.7	0.9	−0.5
E	0.10	−1.0	1.2	−0.8

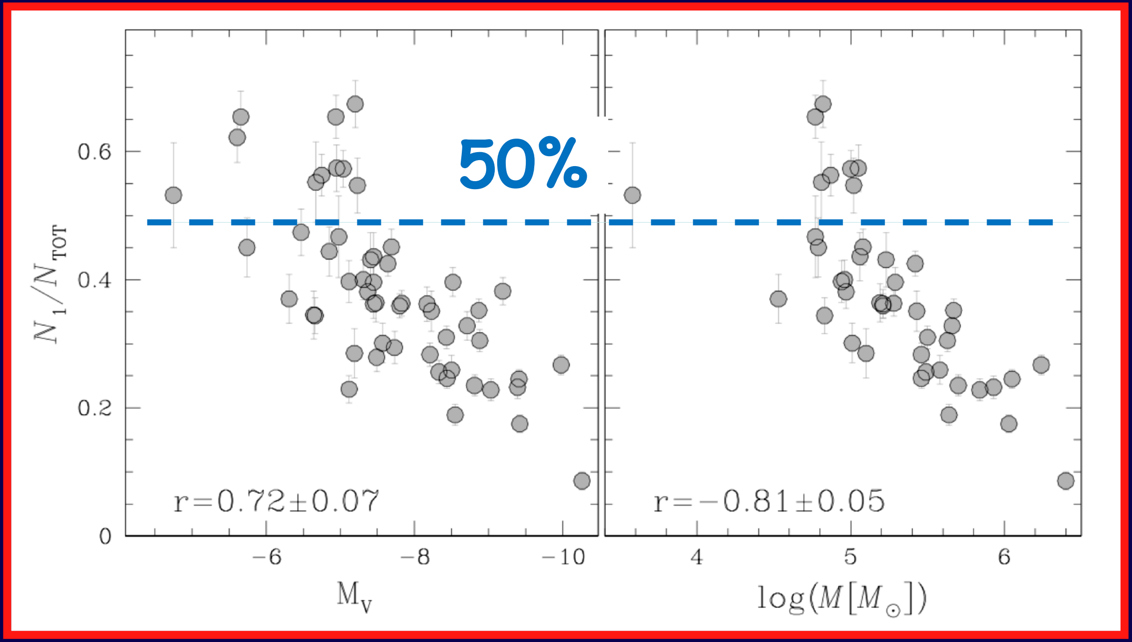
RGB	Pop A	Pop B	Pop C	Pop D	Pop E
percentage	5.8±0.5	17.4±0.9	26.4±1.2	31.3±1.3	19.1±1.0

Open issues

- Who are the Polluters?
- Stellar Ejecta Dilution…;
- Actual frequency of 2G stars & Mass Budget;
- How to form Stars in a very crowded environment?
- Formation Scenario(s);
- Is there a link between the MP phenomenon and the Galaxy formation process?

Actual 1G/2G population ratio





What does it mean in the context of the cluster formation?

Strong correlation between 1G frequency and actual cluster mass!

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

⬇

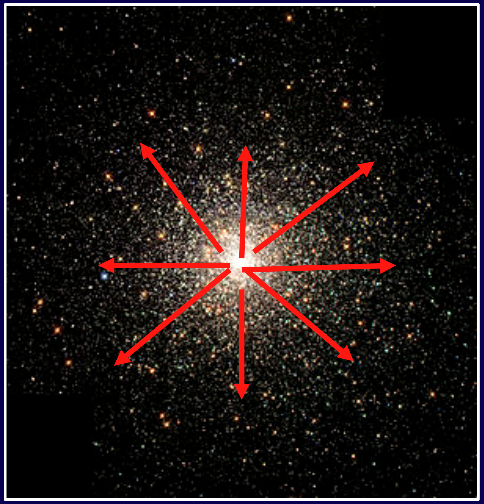
for a typical value $M_{SG(today)} \approx 10^5 M_\odot$ ➔ $M_{progenitor} \approx 2 \times 10^8 M_\odot$ (and $4 \times 10^9 M_\odot$ in the case of the GC ω Cen)

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

Possible '*ad hoc*' solutions to the "Mass Budget" problem

- ✓ Top-heavy first generation mass function;
- ✓ A second generation mass function truncated above about $0.8M_{\odot}$;
- ✓ Infall of pristine gas;
- ✓ A first generation with an initial mass 10 to 20 larger than its present mass;

→ A significant fraction of cluster FG stars has to be lost

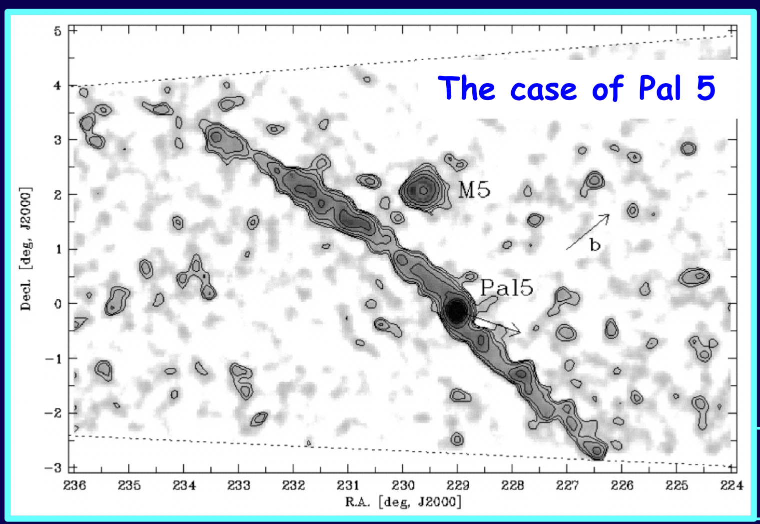


How can GCs actually lose FG stars?

- ✓ **Evaporation** on a longer timescale due to 2-body encounters and other mechanisms (such as disk shocking…) (Aguilar et al. 88);

Since the 2-body relaxation time increases with both the total mass and the size of the system, mass loss induced by this process in an Hubble time is negligible… (for a $10^7 M_\odot$ system on a circular orbit of 4Kpc around the Galactic centre it is of the order of 500Gyr)

- ✓ **Tidal stripping** due to gravitational interactions in the Galactic gravitational field



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)

The efficiency of this process should depend on the cluster orbit parameters…

✓ **Violent relaxation induced by stellar evolution following gas expulsion/mass loss from massive stars and energy injection via SNe events** (D'ercole et al. 08);

The process is mainly driven by FG SNII

It is possible but its efficiency strongly depends on the assumed initial conditions!

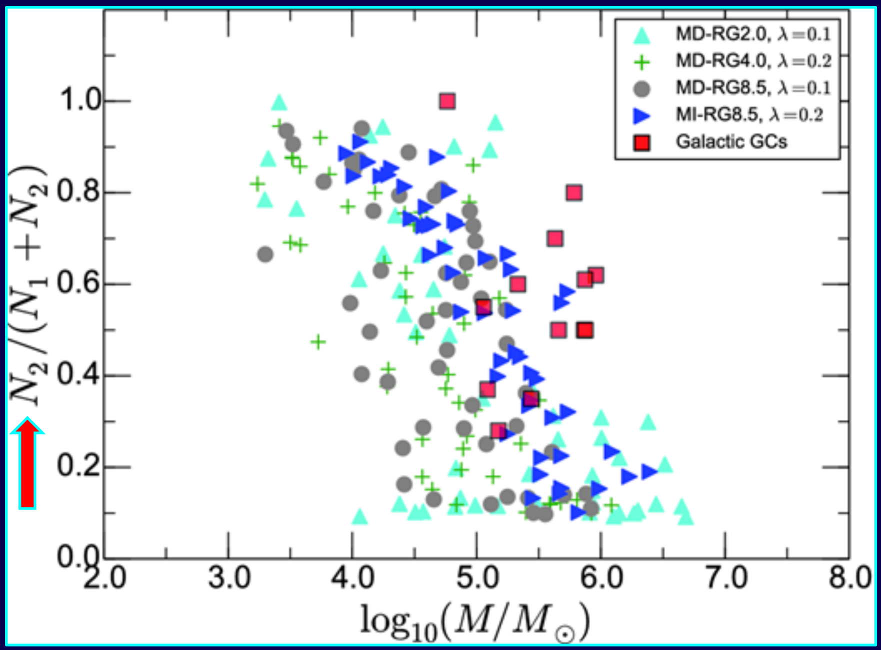
✓ **Primordial gas loss: If enough gas is left after FG and SG formation, and this gas is expelled, it is accompanied by loss of stars** (Khalaj & Baumgardt 2015)

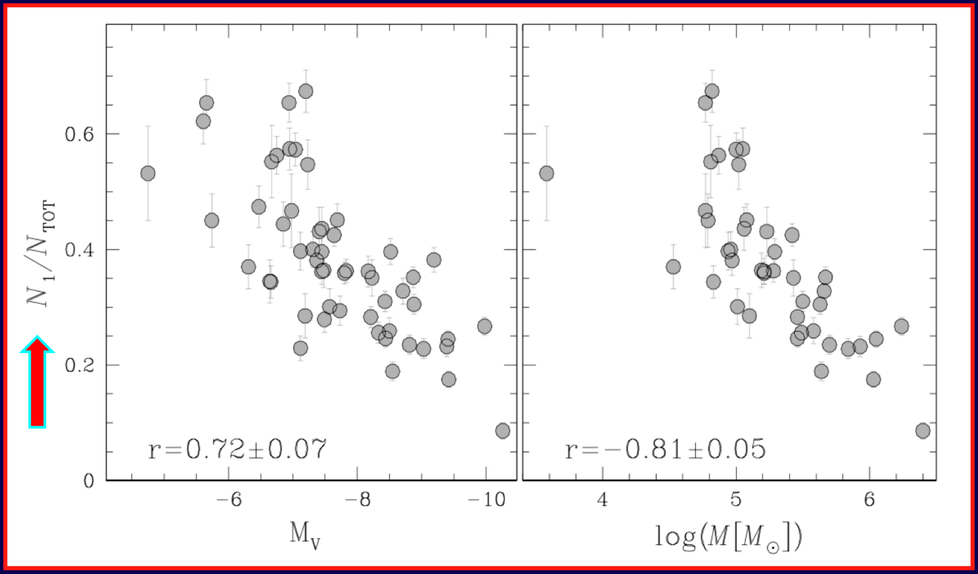
- Initial $N_{SG}/N_{FG}=0.1$
- SG stars and gas more centrally concentrated than FG stars

Upper limit of 10^5 yr for the gas expulsion time-scale.
(SNe numbers are not enough to inject the energy needed over such a short timescale)

Required typical initial stellar masses, half-mass radii and the initial mass of the primordial gas left need to be around $10^6\ M_\odot$, 1.0 pc and $10^6\ M_\odot$, respectively.
The total initial mass of each cluster is $\sim 2 \times 10^6\ M_\odot$.

Khalaj & Baumgardt (2015) simulations predict that the fraction of SG stars has to decrease with the cluster mass





observations show the opposite trend!!!

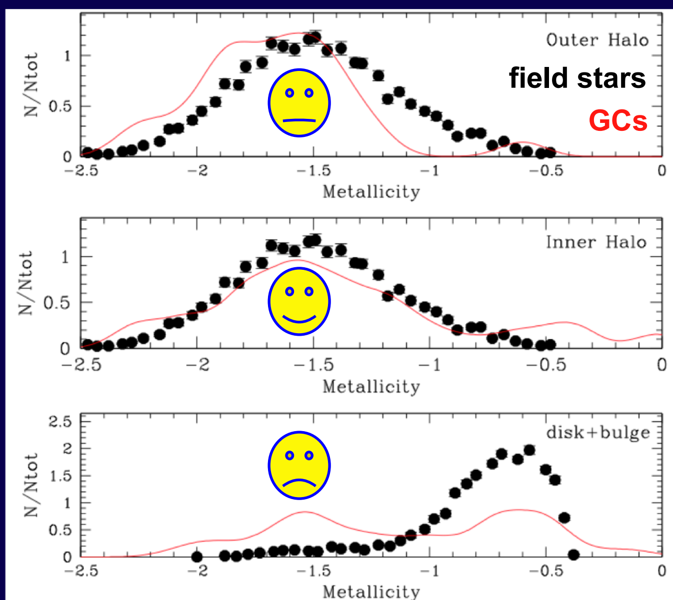
Models predict also that stronger tidal fields increase the mass loss…
but observations do not show any dependence with R_{GC}

MPs phenomenon & Galaxy formation

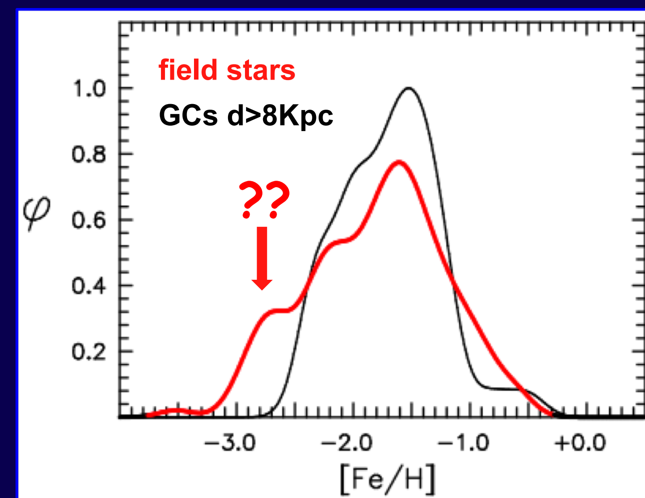
Present-day SG/FG star ratio provides a strong argument suggesting that GGCs have lost a major fraction (≈75%) of their FG…

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

A proof: metallicity distribution of GGCs versus field stars

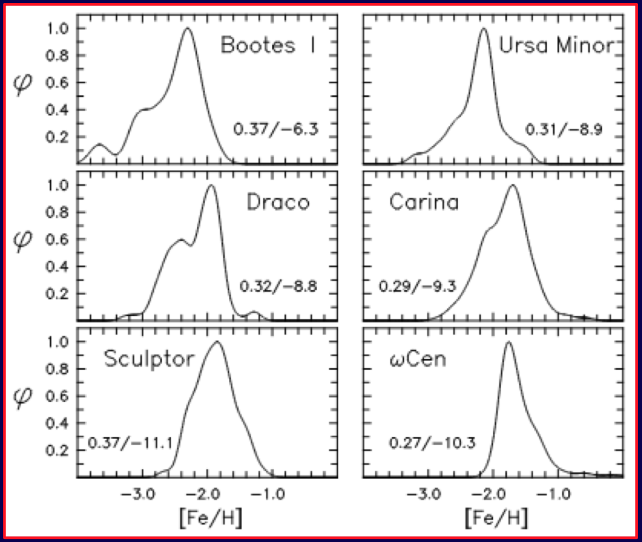


Gratton et al. (2012)



Frebel & Norris (2013)

The metallicity distribution of MW dwarfs

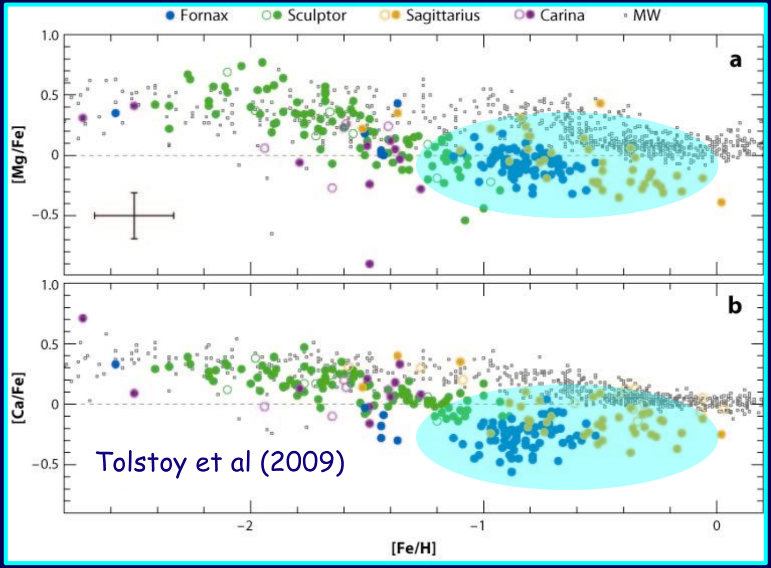


at odds with (the majority of) GGCs all dwarfs show large [Fe/H] spread…

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

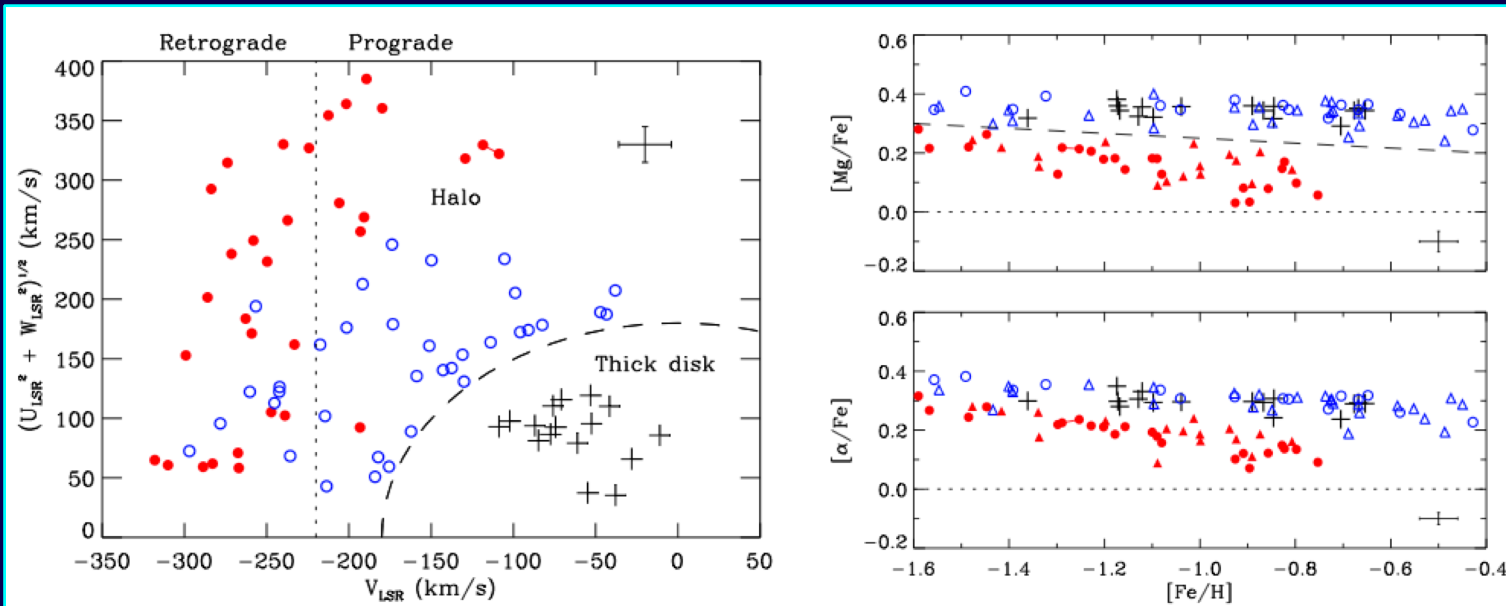
a relationship between ultra-faint dwarfs and the extremely metal-poor MW stars?

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 α–element enhancement in field stars?



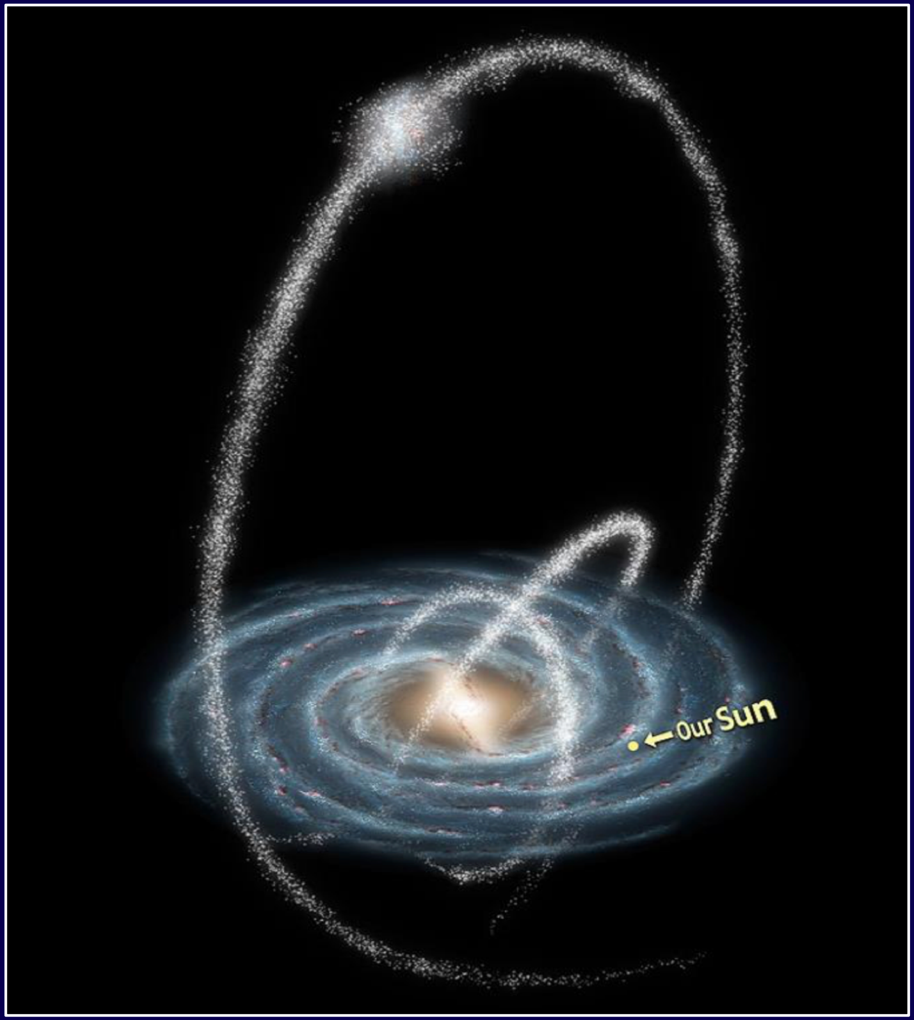
Nissen & Schuster (2010)

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

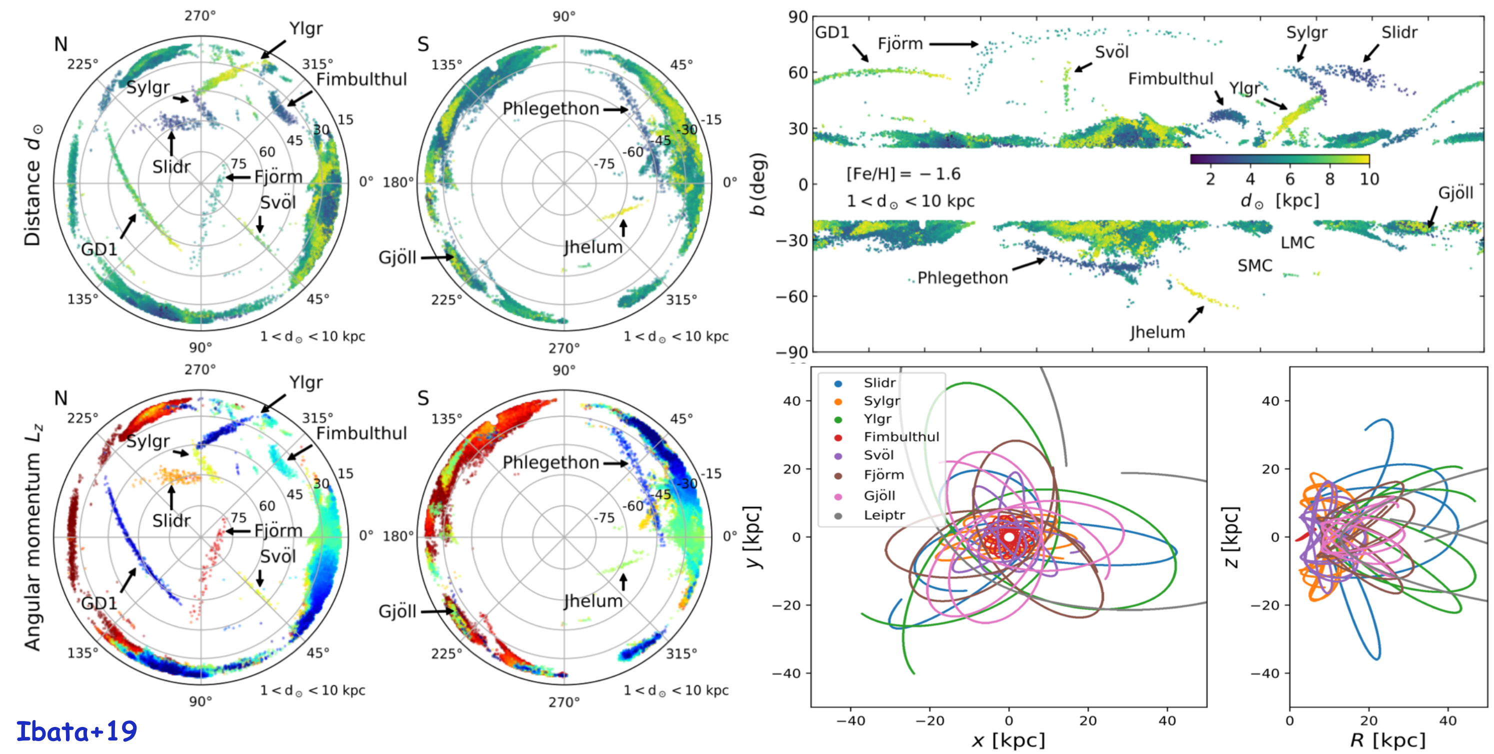
This results is consistent with the view that dwarf galaxies have played an important role in the formation of the Milky Way halo

MW dwarf accretion & Multiple Stellar Population phenomenon: any link?

Stellar Streams around the MW

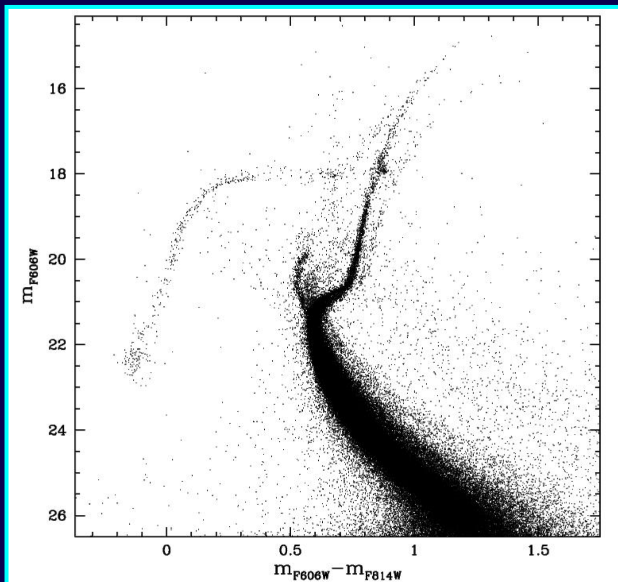


Stellar Streams around the MW



Ibata+19

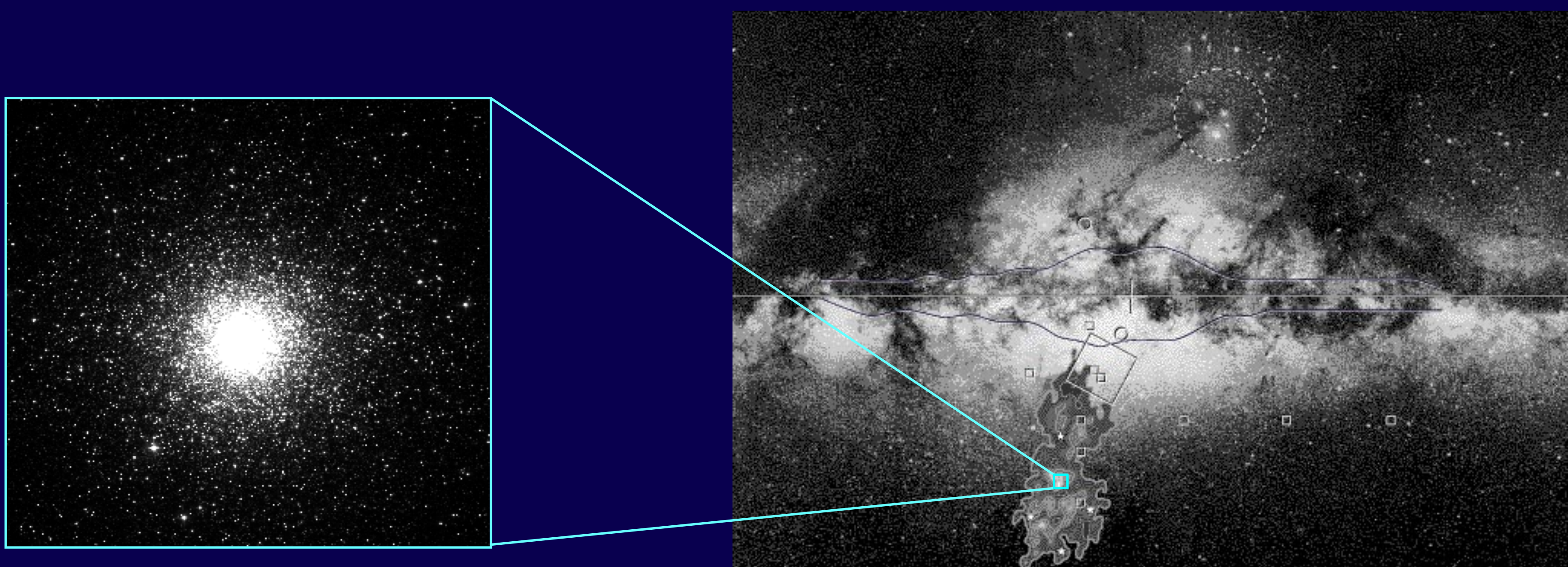
M54: an undisputable evidence



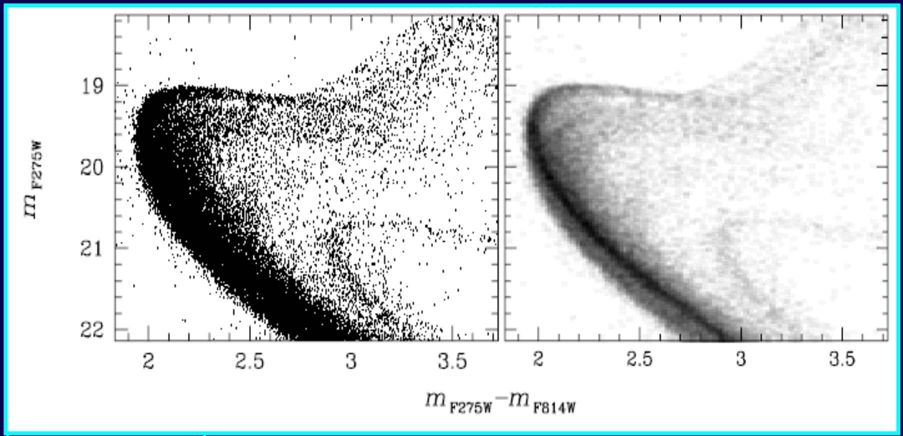
It coincides with the nucleus of the Sagittarius dwarf galaxy

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

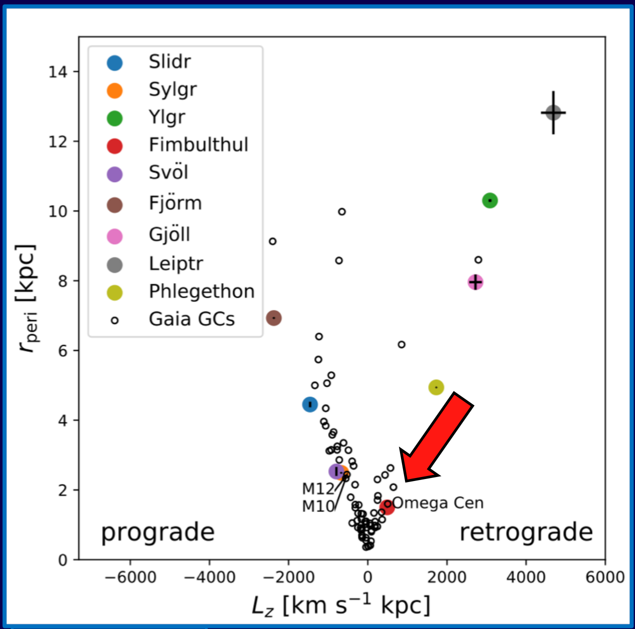
…but the important fact is that, today "The massive GC M54 is part of the nucleus of a disaggregating dwarf galaxy"



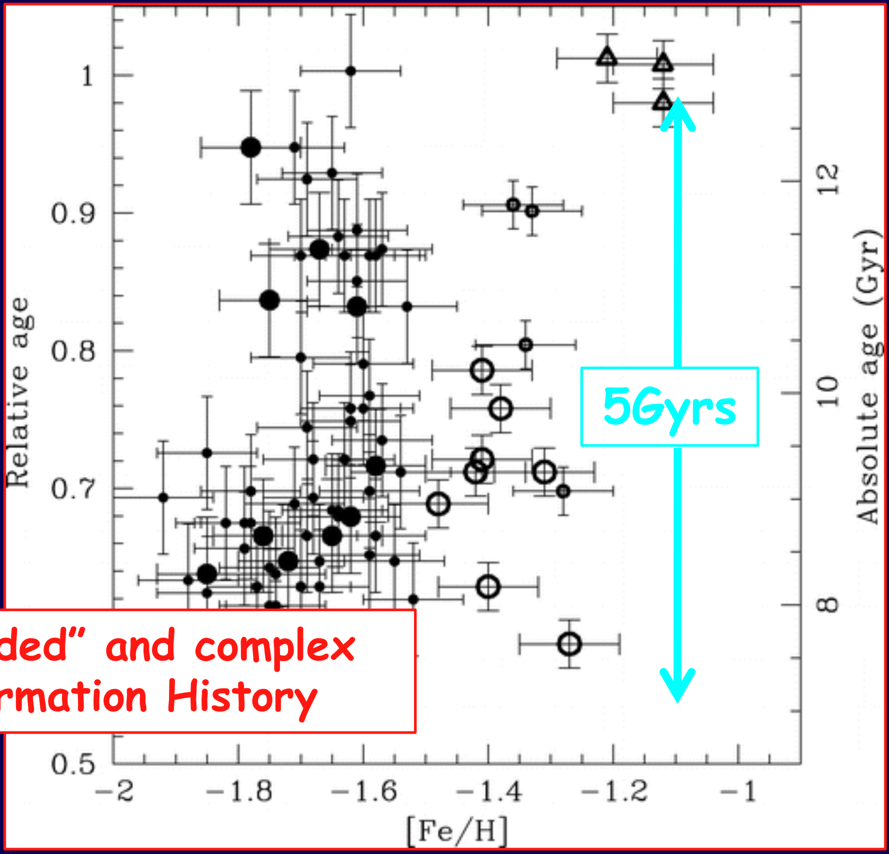
The case of ω Cen



Bellini+2010



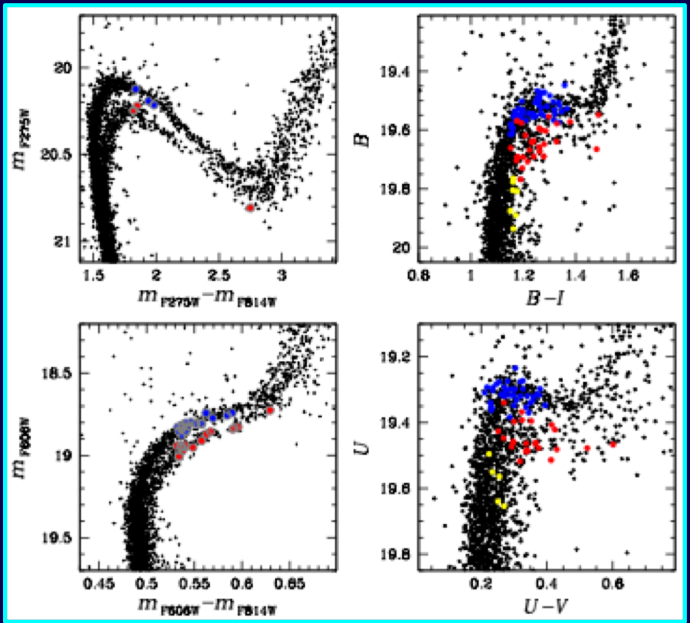
Ibata+2019

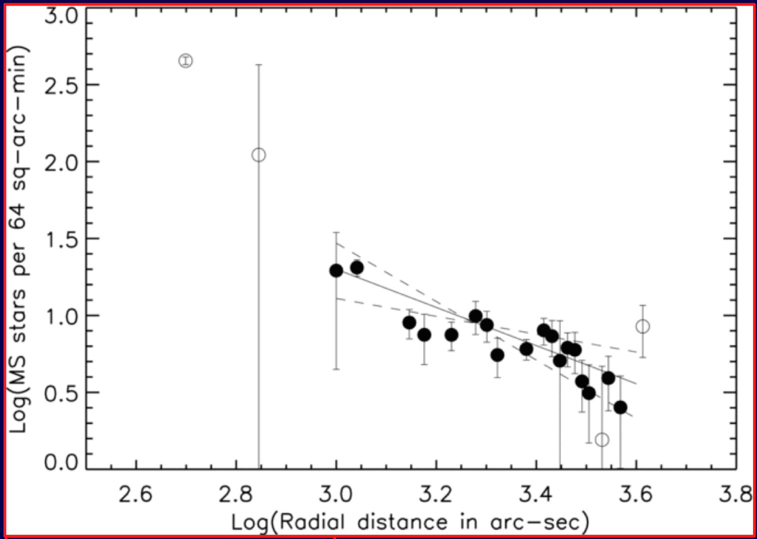


an "extended" and complex Star Formation History

Are these findings suggesting that this cluster is the final outcome of a merging process?

Stellar Halo around GCs: the case of NGC1851



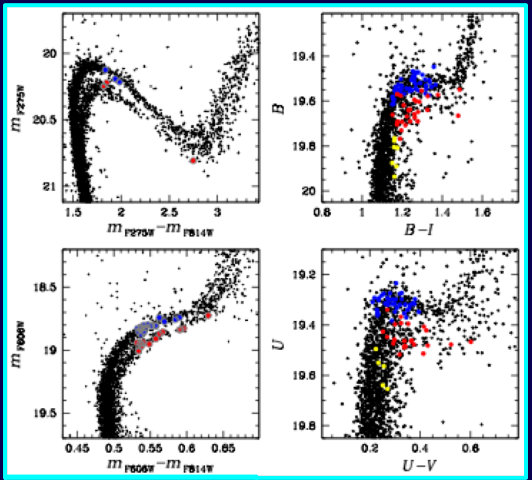


Olszewski et al. (2009)

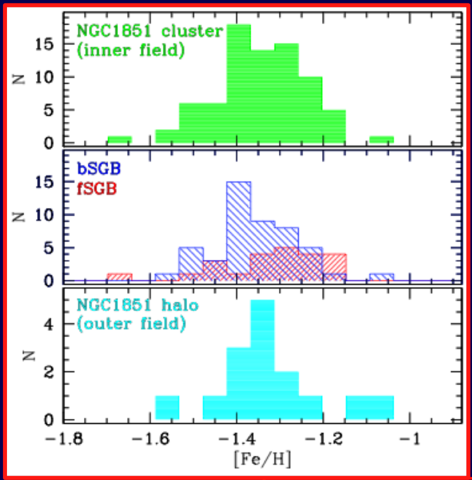
NGC1851 has an halo

- ✓ current models of GC formation do not predict it;
- ✓ the effect of tidal influences on the parent dwarf galaxy?
- ✓ the results of the merging of 2GCs in a dwarf + the dwarf's field (Bekki & Young 2012, 3 populations expected)?

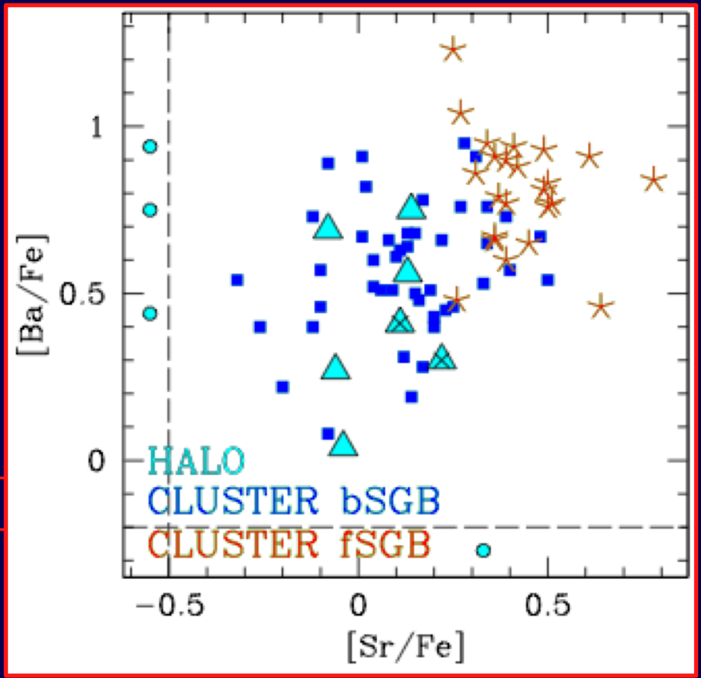
Stellar Halo around GCs: the case of NGC1851



Piotto et al. (2012)



Marino et al. (2014)

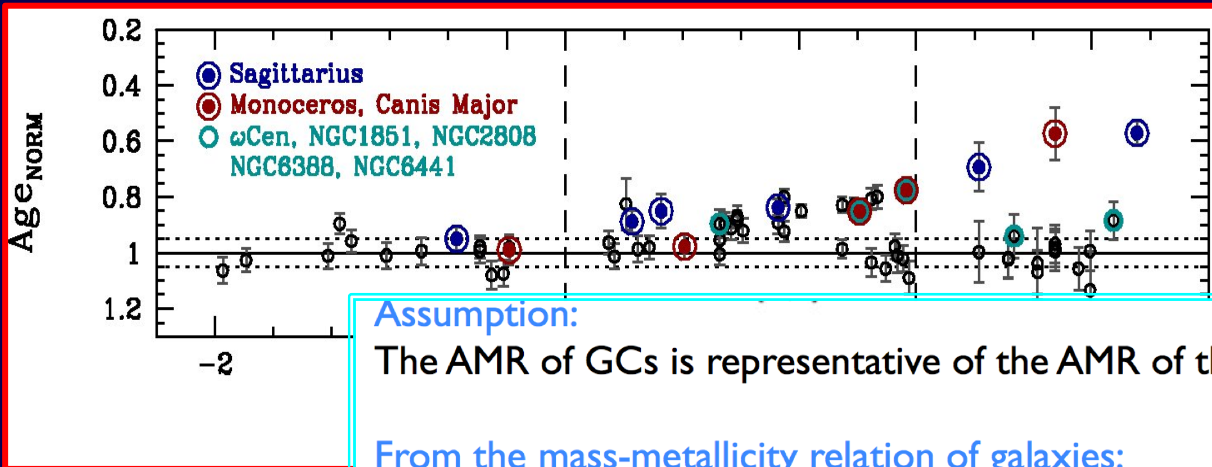


the spectroscopical characterization suggestes that:

- ✓ the halo has the same metallicity distribution as the cluster;
- ✓ the halo stars show s-element abundances consistent with those of the bright-SGB (the FG!);

Are we looking at a particular phase of the cluster evolution: **a very extended envelope of stars that is in the process of escaping from the GC but still bound to it** (that will be lost during the MW disk crossing & presumably recreated as the GC moves through the MW halo…)

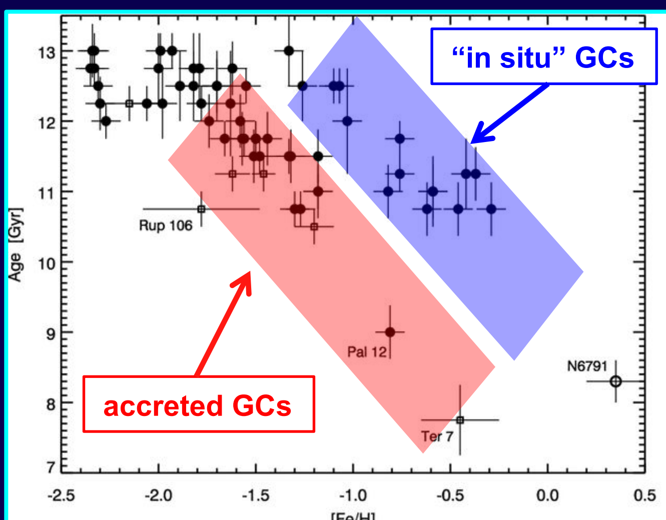
Can we use GGCs age-dating to investigate the accretion process?

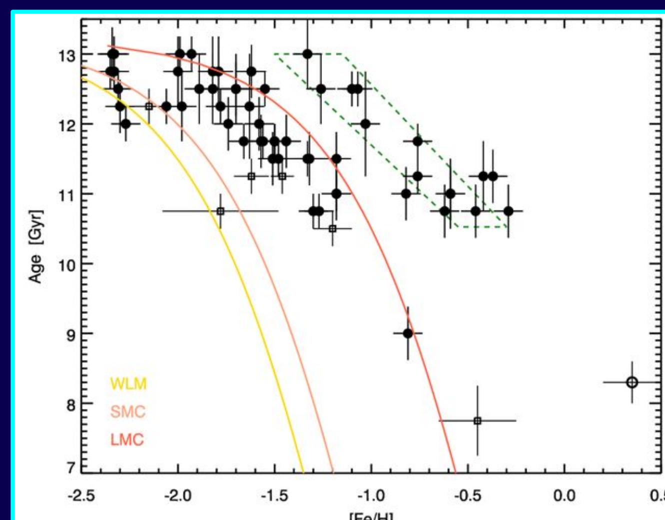


Marin-Franch et al. (20

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)

How did the Milky Way form and evolve?

Gaia + spectroscopic surveys
→wealth of information to study:

-Kinematic and chemodynamic structures

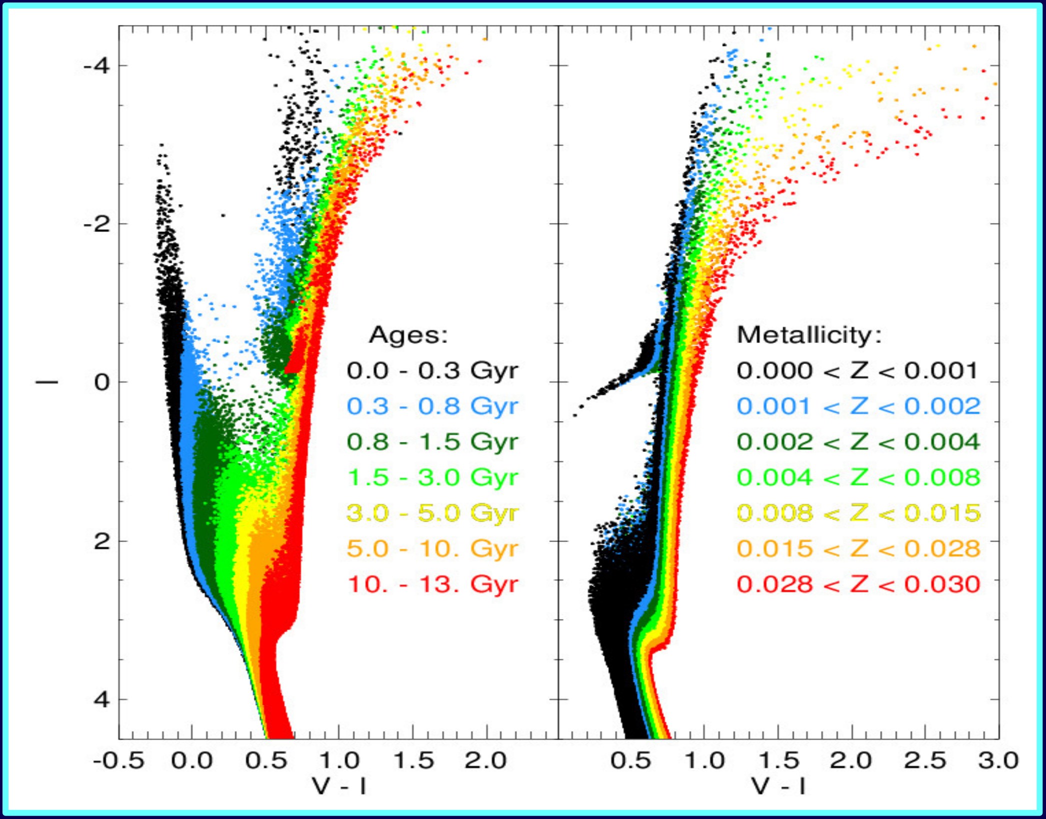
-Star Formation History (ages) within them

A reliable Star Formation History (SFH) for the MW structures, allows to study:

- How old are the oldest stars in the disk(s)? (epoch of disk formation)
- What is the stellar age distribution across the disk(s) (mode of formation and evolution)
- Are there actually differentiated thin and thick disks or there is a continuum of properties?
- What are the ages of the stars in the halo? Are there age gradients within the halo?
- What is the age / SFH of accreted structures?
- Did accreted structures induce star formation in the disk?

How to obtain an accurate age dating?:

COLOUR-MAGNITUDE DIAGRAM (CMD) REACHING THE OLDEST MAIN SEQUENCE TURNOFF

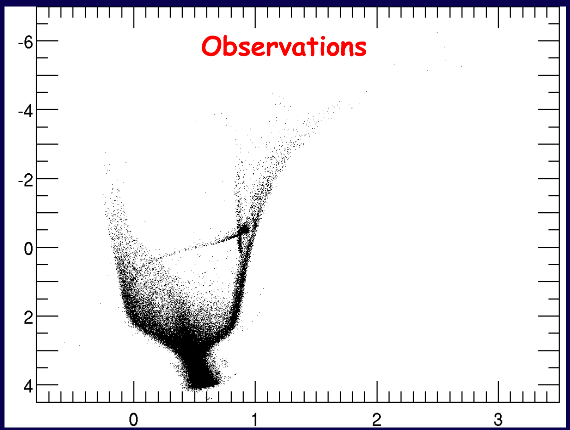


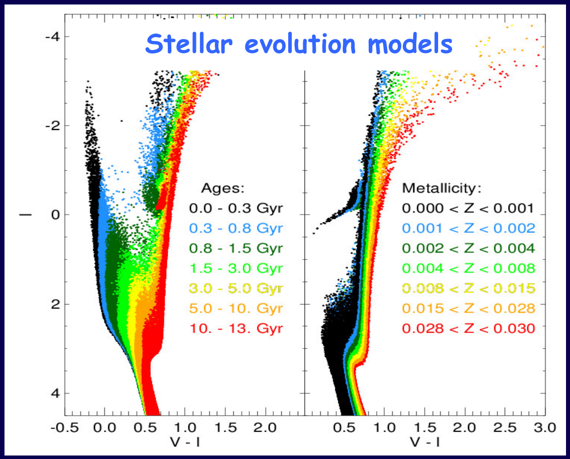
The age-metallicity degeneracy in the CMD affects mainly RGB stars, and it is very successfully broken when stars in the main sequence, down to the old turnoff, are observed.

Deriving Star Formation Histories by CMD fitting is a widely recognized, standard technique in Local Group galactic astronomy, over the last 20+ years (e.g. Bertelli et al. 1992)

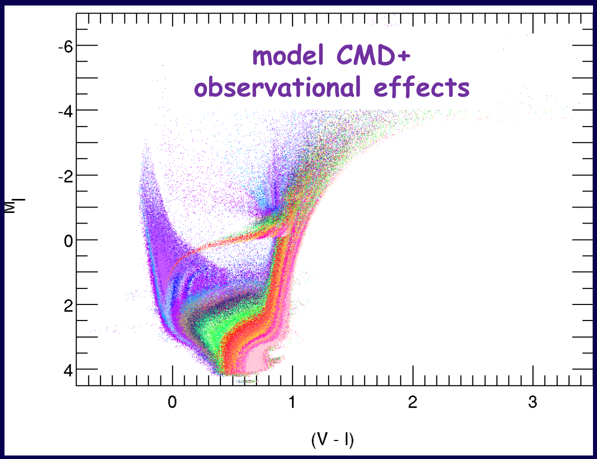
Quantifying the Star Formation History of Resolved Galaxies

The distribution of stars in the observed CMD is compared with that of a number of *simple populations* in a model CMD where observational errors are simulated.

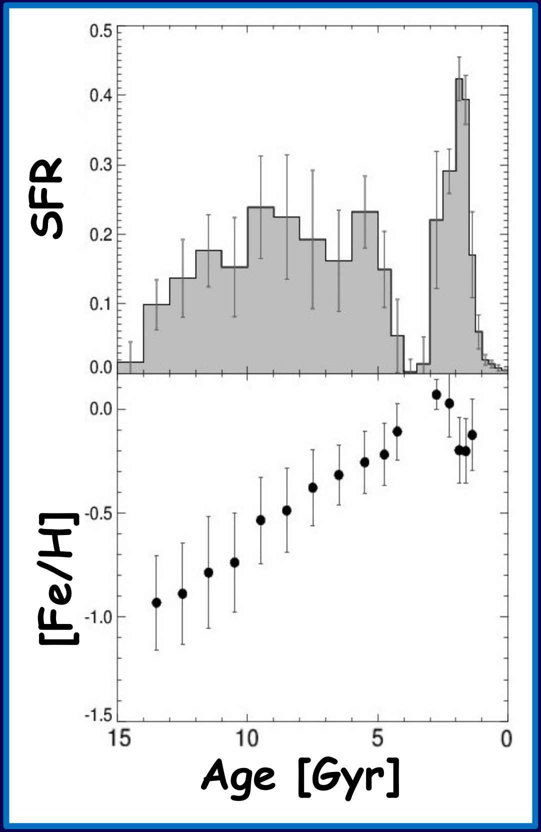




By using a merit function, we obtain the combination of simple stellar populations that best reproduces the observed CMD, i.e., **SFR(t) and Z(t)**



Star Formation History



Estimate the age and metallicity with a precision of 10-20%

Master Sample queried from the Gaia archive:

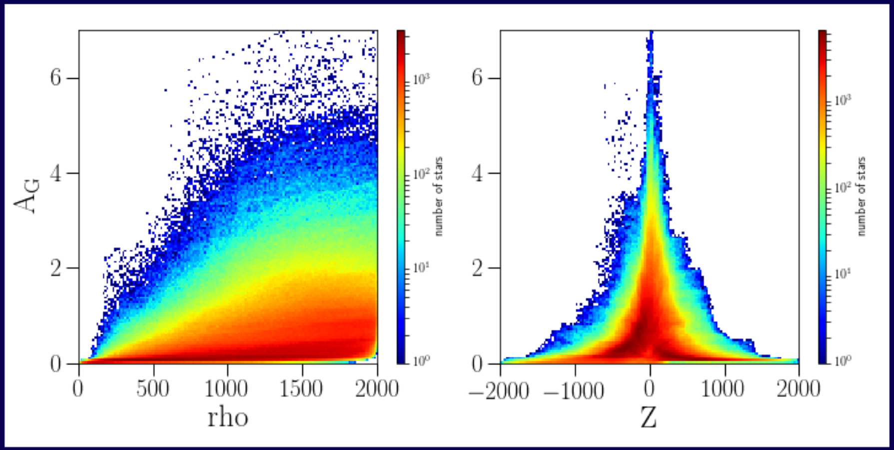
→ Sphere of 2 Kpc radius around the Sun

→ Maximum distance modulus: (m-M)=11.5

→ Faintest $G \approx 16.5$ (M_G=5)

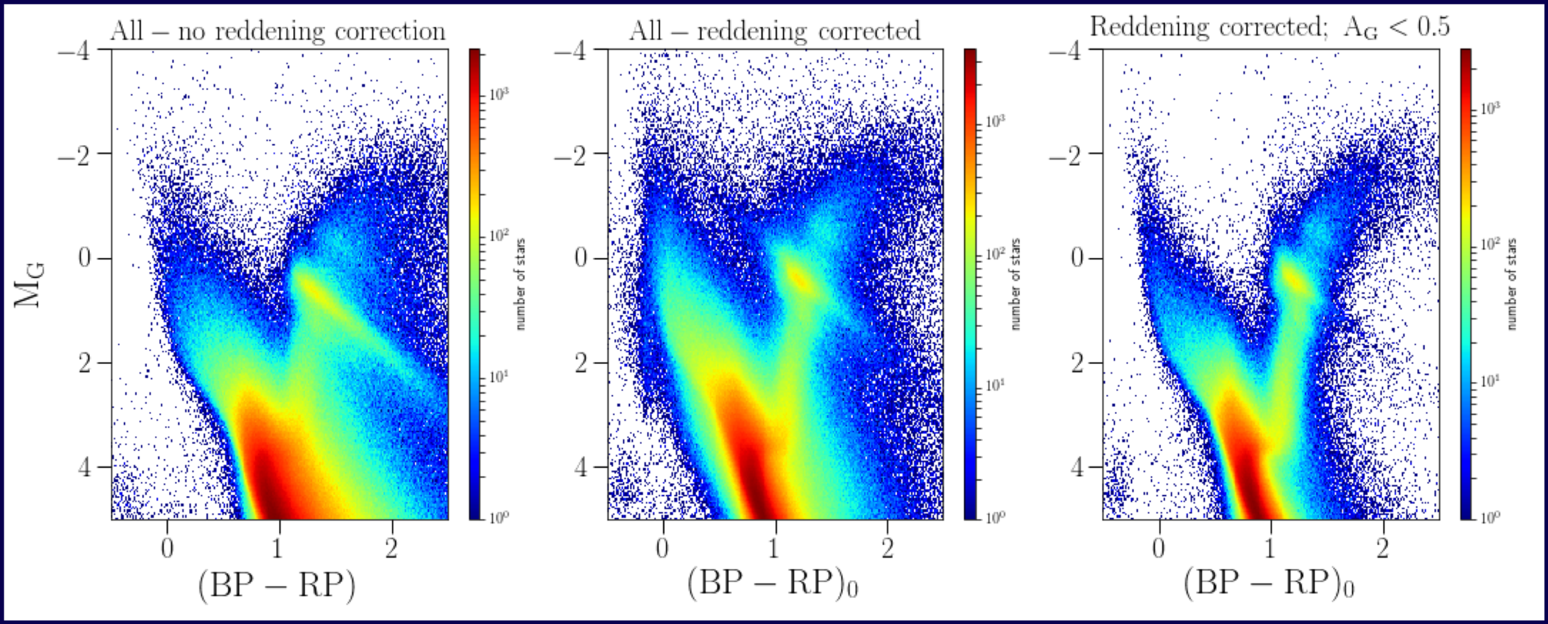
≈40 Million stars down to $M_G \approx 5$

Extinction is an issue for samples close to the plane and extending beyond the immediate solar neighborhood.

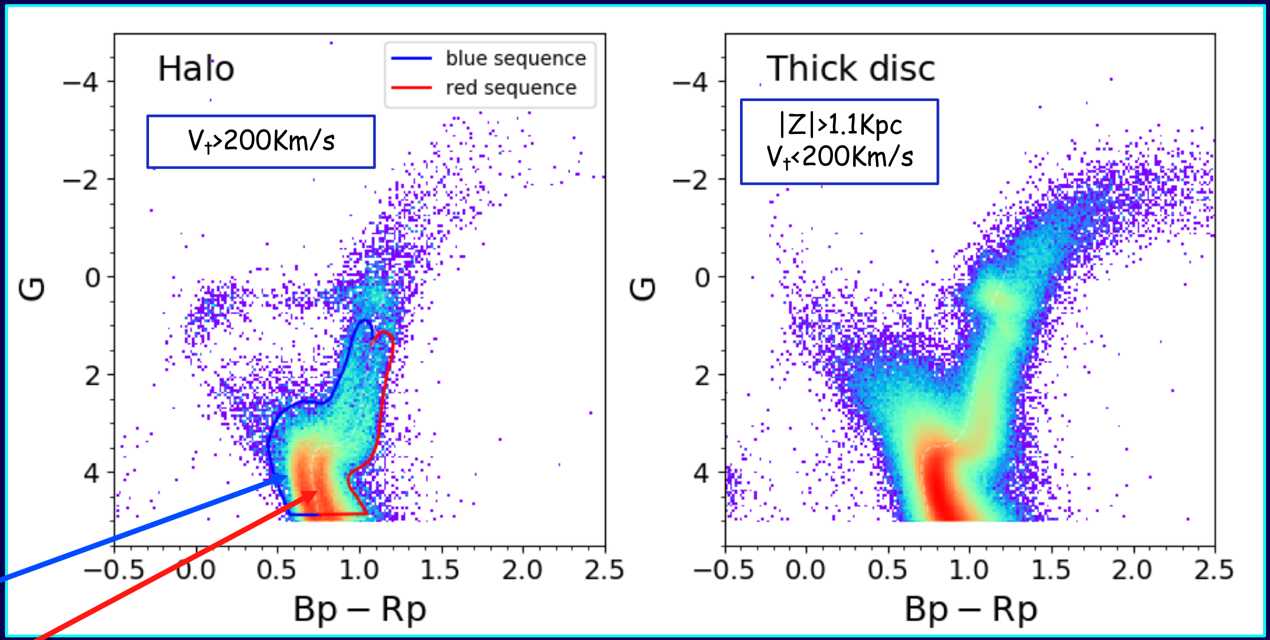


- Adopted the Lallement et al. (2018) 3D dust map; absorption in Gaia bands calculated following Casagrande & VandenBerg (2018);

- Limited to $A_G < 0.5$ for samples with $|Z|<400$ pc;



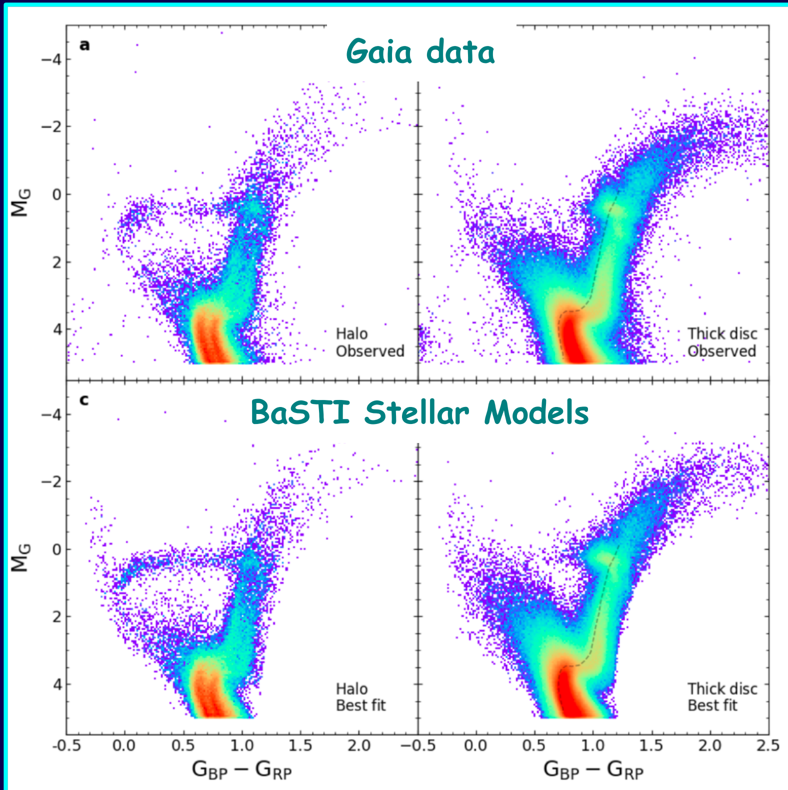
Hunting the oldest stars in the Galactic halo



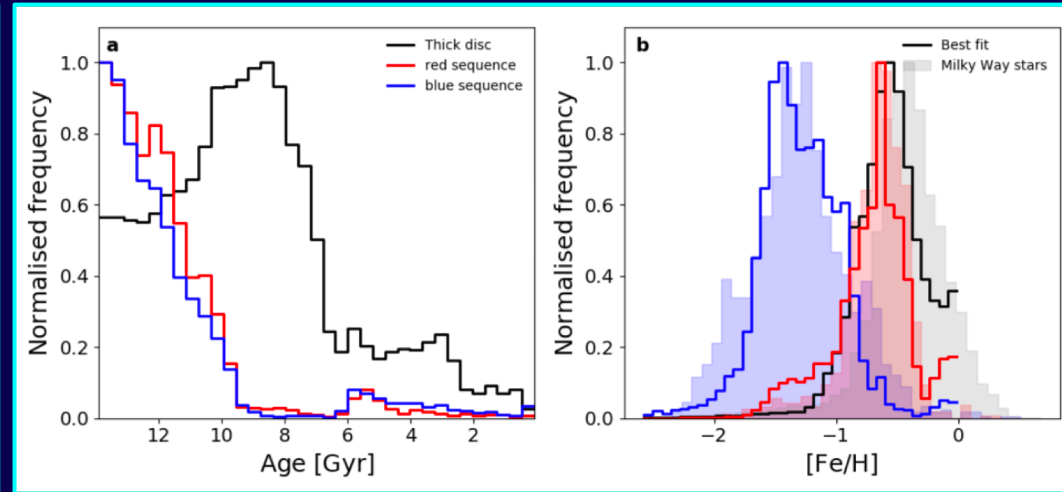
The blue sequence: related to the Gaia-Enceladus accretion event (Belokurov+18, Haywood+18);

The red sequence has been associated with the MW thick disk (Haywood+18 on the basis of its chemical composition - Schuster+12);

This interpretation is in contrast with the hot kinematic properties of the RS population



Gallart et al. (2019, in press)



- ✓ The red and the blue sequences are coeval and very old – peak age@13.4Gyr;
- ✓ The red and the blue sequences have quite different metallicity distribution, with the RS being more metal rich;
- ✓ The thick disc pop. is younger – peak age@8.7Gyr;
- ✓ The retrieved [Fe/H] distributions are in good agreement with the spectroscopic determination from LAMOST and GALAH for the same pops...;

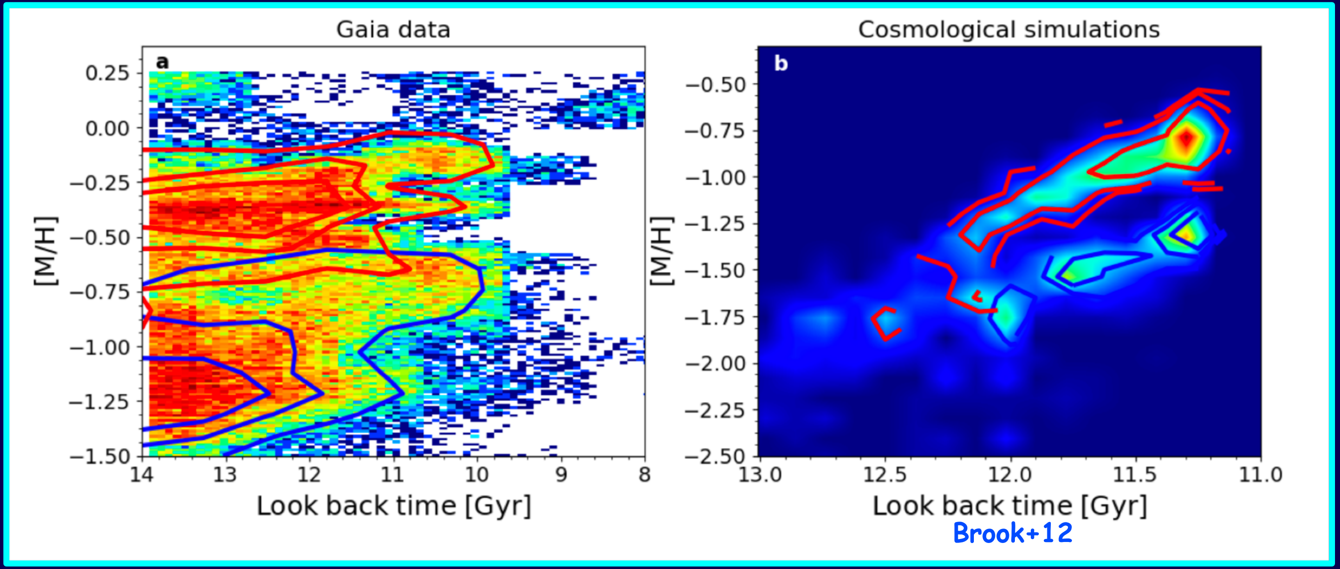
Implications:

- Due to the existence of a relation between galaxy's mass and metallicity, RS stars formed in a galaxy more massive than the one where BS stars formed;
- The fact that the 2 pops. are coeval means that their parent galaxies <u>formed stars at similar times, and also they stopped forming at similar times</u>;

These findings correspond to what is expected if these two populations were involved in a merger event, with:

- Red sequence belonging to the main progenitor of the MW → in-situ halo. These stars would be heated to halo-like velocities by dynamical interactions related with the merger process;

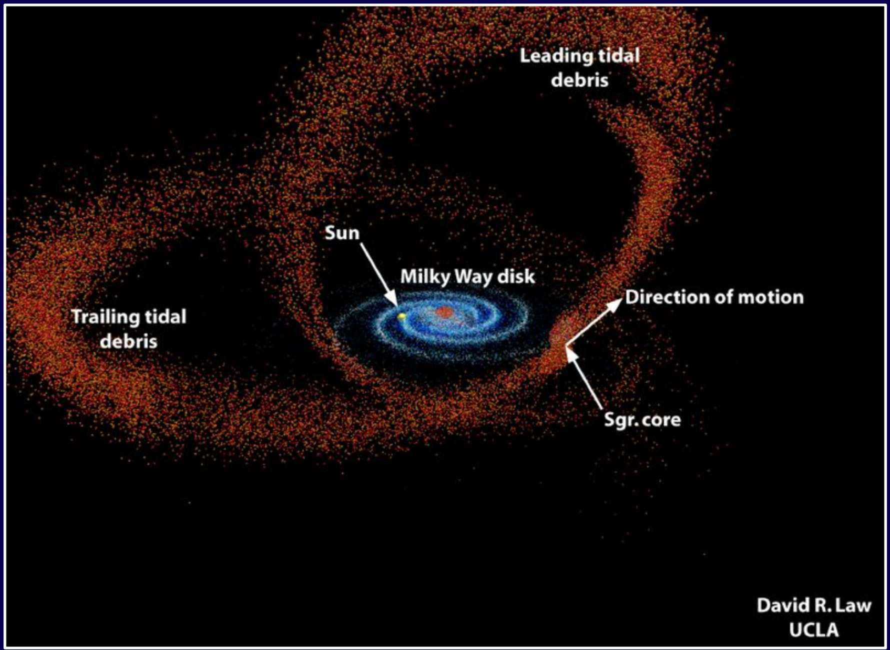
- Blue sequence belonging to a smaller accreted galaxy, possibly Gaia-Enceladus;



The cosmological simulations have been performed by assuming the properties of MW- and Gaia-Enceladus-analogue galaxies…

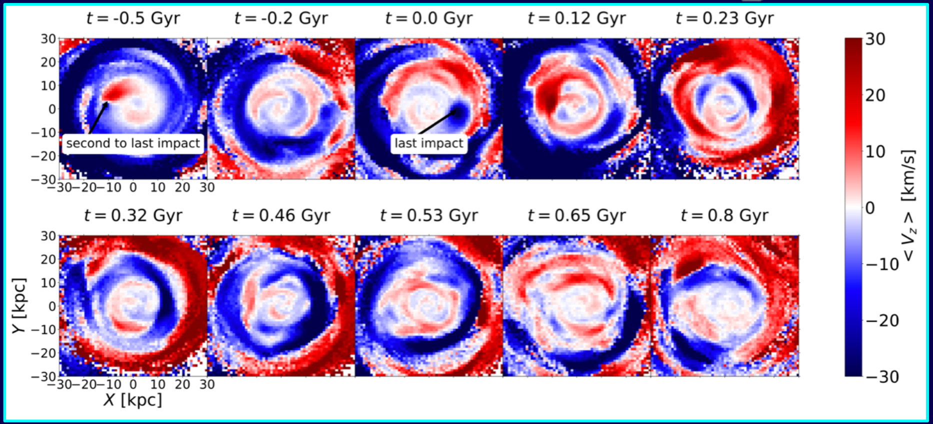
The agreement – only expected to be qualitative - is remarkable…

Merging processes and their impact on Galaxy formation



Can we identify the fingerprints of these interactions in the Galactic disk SFH?

Work in progress

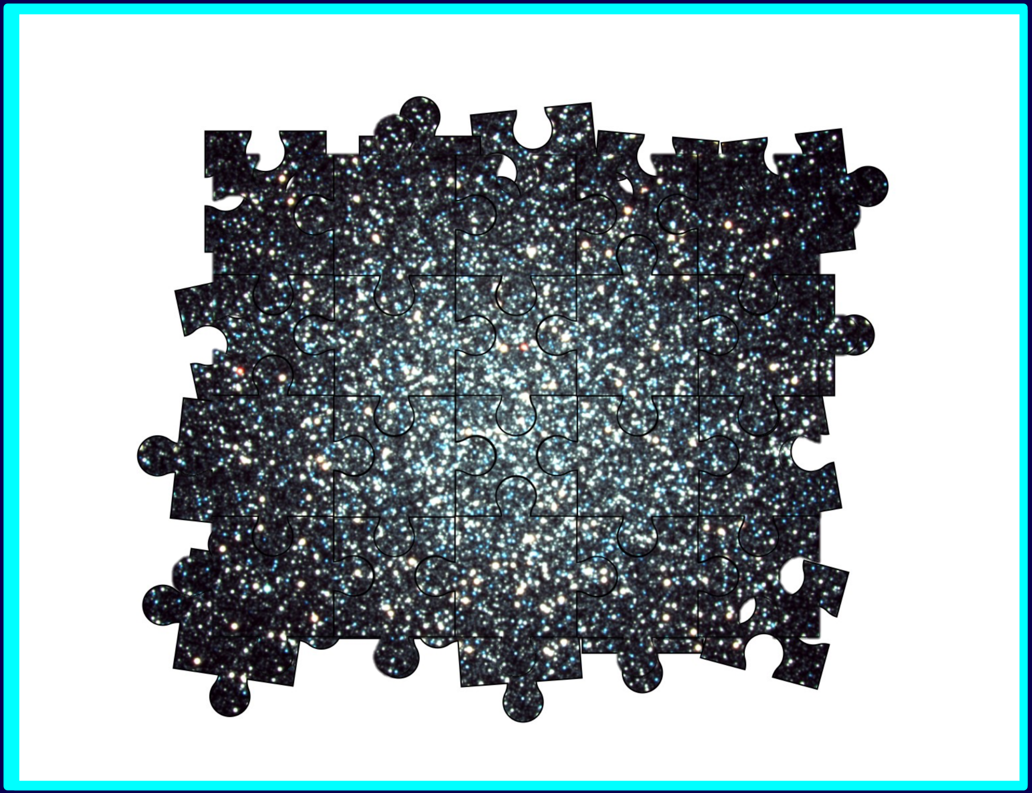


Simulations show that satellites closely orbiting disc galaxies can induce phase space features such as spirality, vertical heating or phase wrapping in their disc;

Such features have been observed in the Galaxy but the complexity of the Milky Way disc phase space has only been fully unveiled recently thanks to Gaia DR2 data;

This complex behaviour is ascribed to the repeated perturbations induced by the Sagittarius dwarf galaxy along its orbit, pointing to this satellite as the main dynamical architect of the Milky Way disc (Laporte+19)

Conclusions



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

Many thanks for your attention