RGB mass loss: inferences from CMD-fitting and asteroseismology

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In collaboration with:

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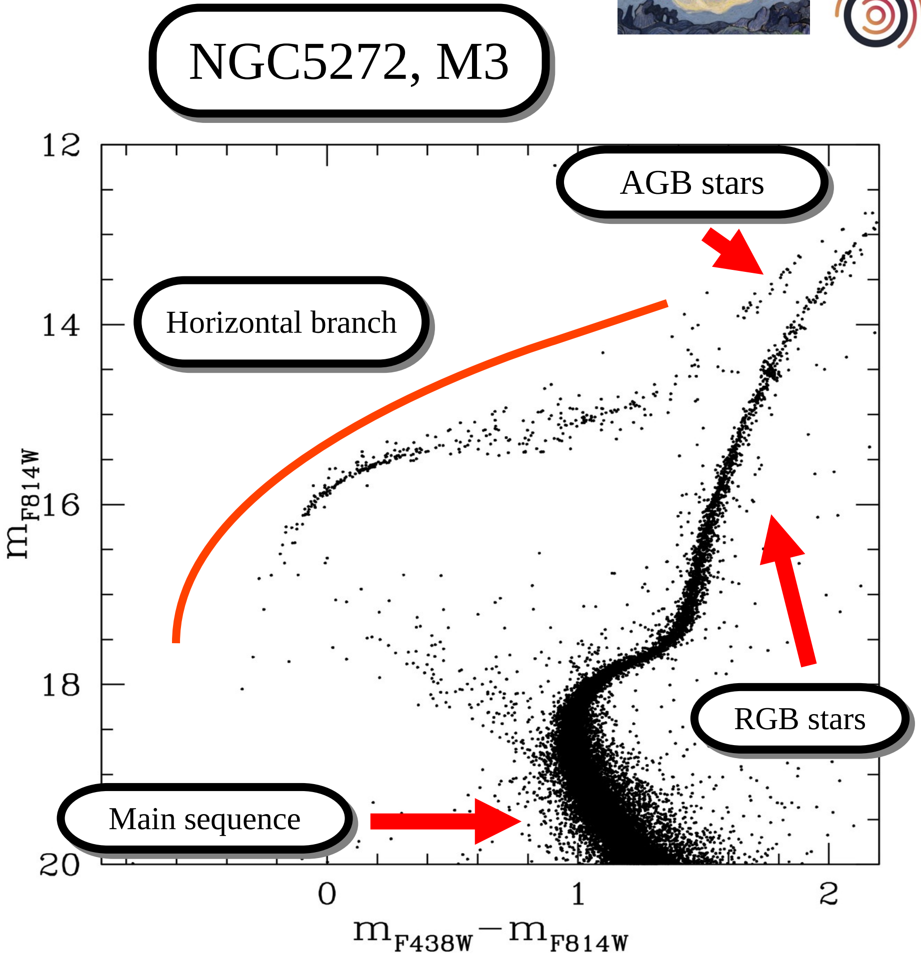
INAF Roma and Catania

Outline

- Inferring the integrated RGB mass loss from the CMD and the study of the horizontal branch stars
  - Possible hints of a universal mass loss relation for old, metal poor stars
- What happens at higher metallicity and lower ages?
- The case of M4

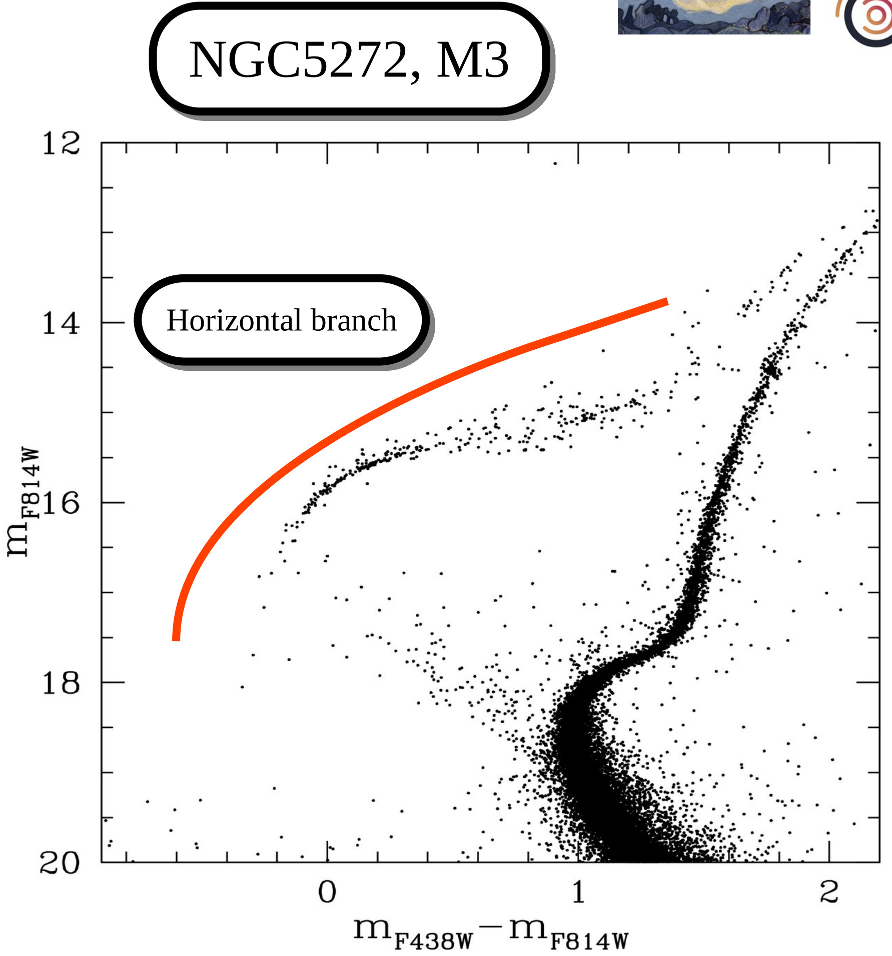
Globular clusters

- Large number (order 10^6) of old (>6-8 Gyr), low mass ($< 1.0\ M_{sun}$) stars.
- Stars have the same age (within few 10^2 Myr).
- Generally, no internal variation of [Fe/H] (iron content, but there are some exceptions, like M22, Omega Centauri).



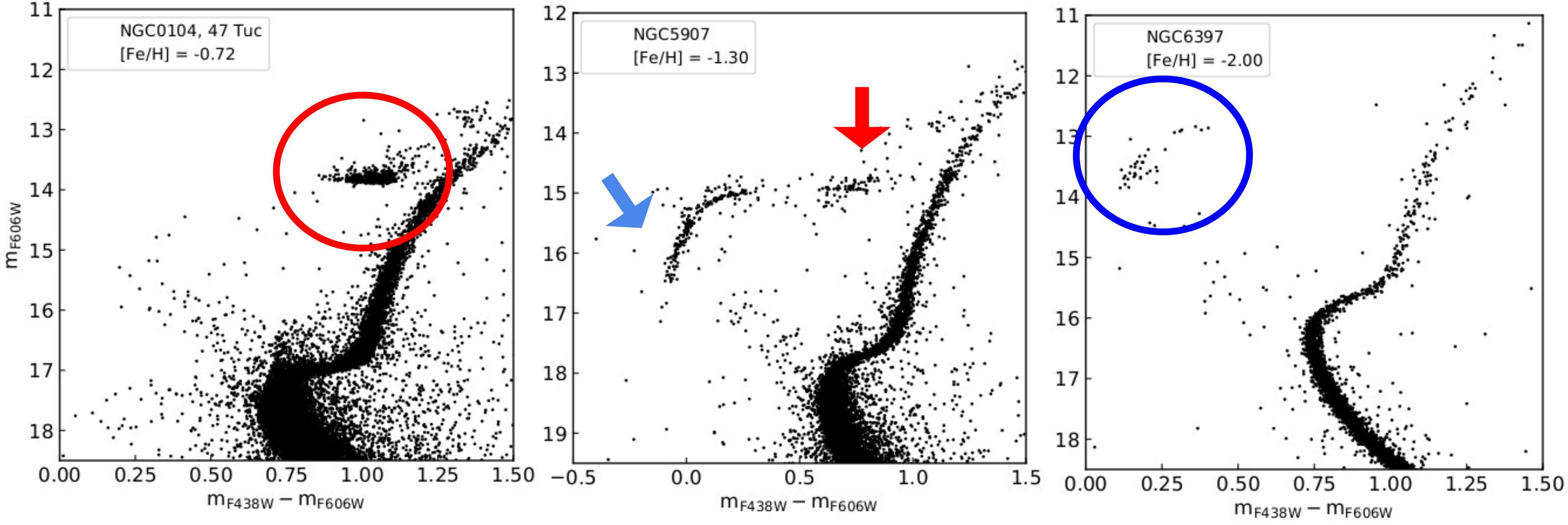
Horizontal Branch

- The HB is the locus of the helium burning stars of old stellar populations.
- Product of the helium flash at the Tip of the RGB.
- Historically connected to the, still unsolved, second parameter problem.

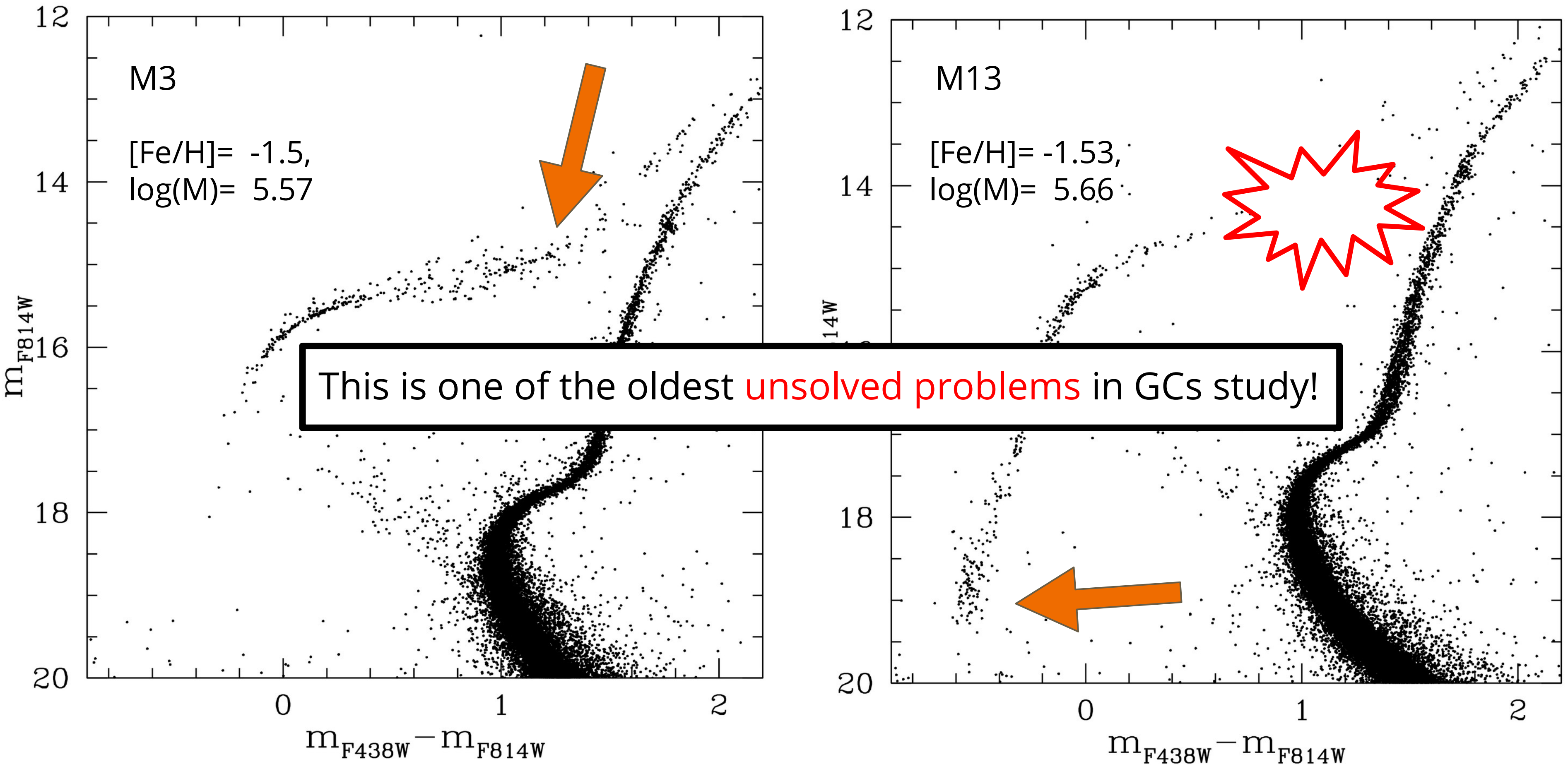


Second parameter problem

from Nardiello et al. (2018) data



Metallicity (here in [Fe/H]) is the defining parameter for the HB morphology



This is one of the oldest unsolved problems in GCs study!

Why these HB are so different despite the general similarities between the two GCs?

Multiple populations

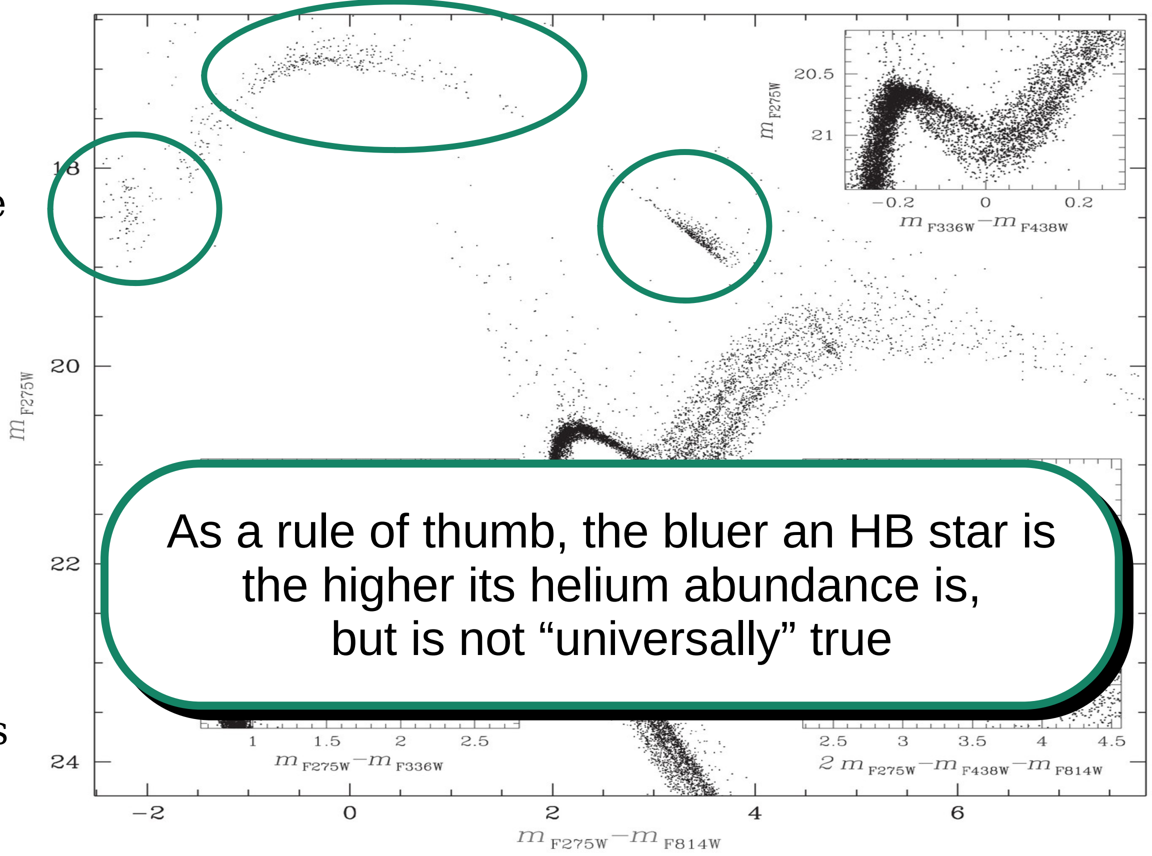
- Globular clusters are composed of a collection of stellar populations.

- First generation (1G, stars with the same chemical pattern of the field stars) and a Second generation (2G, stars with radically different pattern)

- One distinctive feature is the presence of multiple sequences on the CMD in all evolutionary phases.

- On the HB the multiple populations show themselves as different groups of stars.

NGC2808,Milone et al. 2015



As a rule of thumb, the bluer an HB star is the higher its helium abundance is, but is not “universally” true

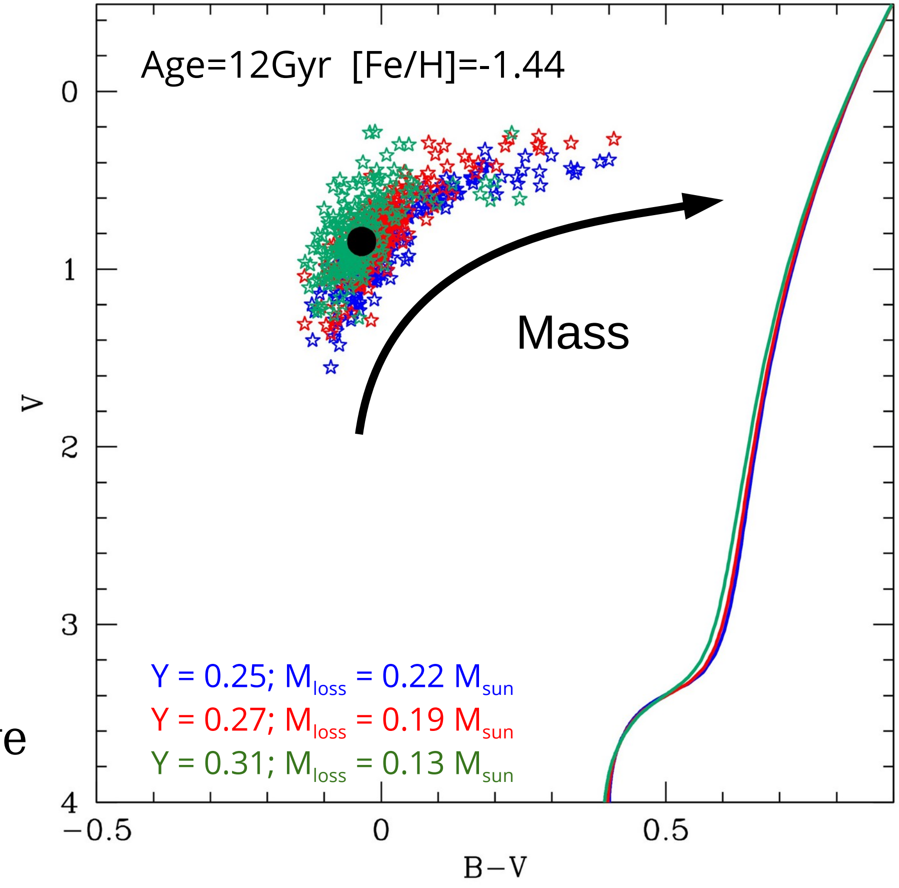
Why?

The position of these stars is affected by 4 main parameters:

- Cluster Age
- Metallicity ([Fe/H])
- Helium abundance
- Mass loss during the RGB

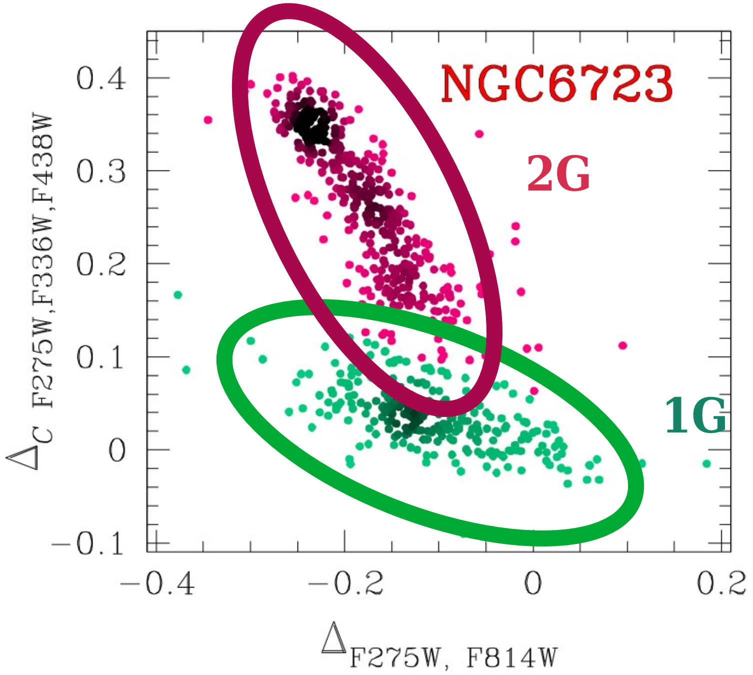
The age of the cluster stars and [Fe/H] can be evaluated independently.

Until recently, helium and mass loss have been degenerate.

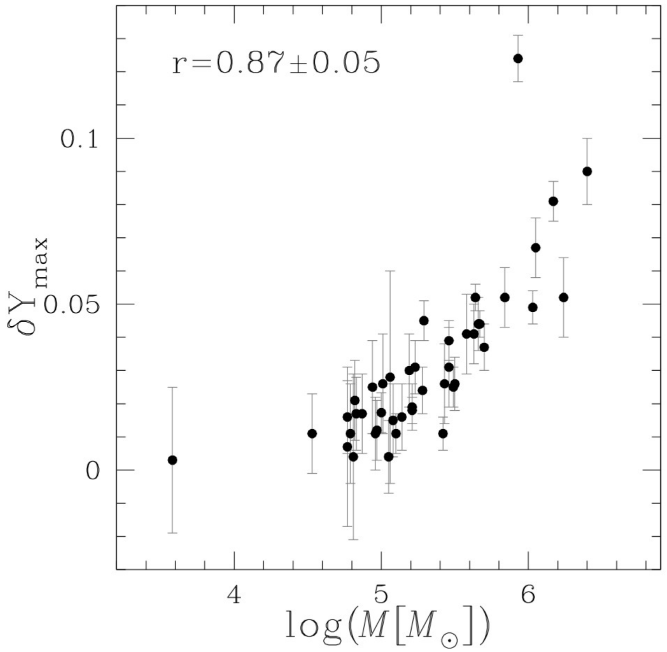


Helium and Chromosome maps

Special combination of HST filters able to separate the populations inside a GC.



Milone et al. 2018



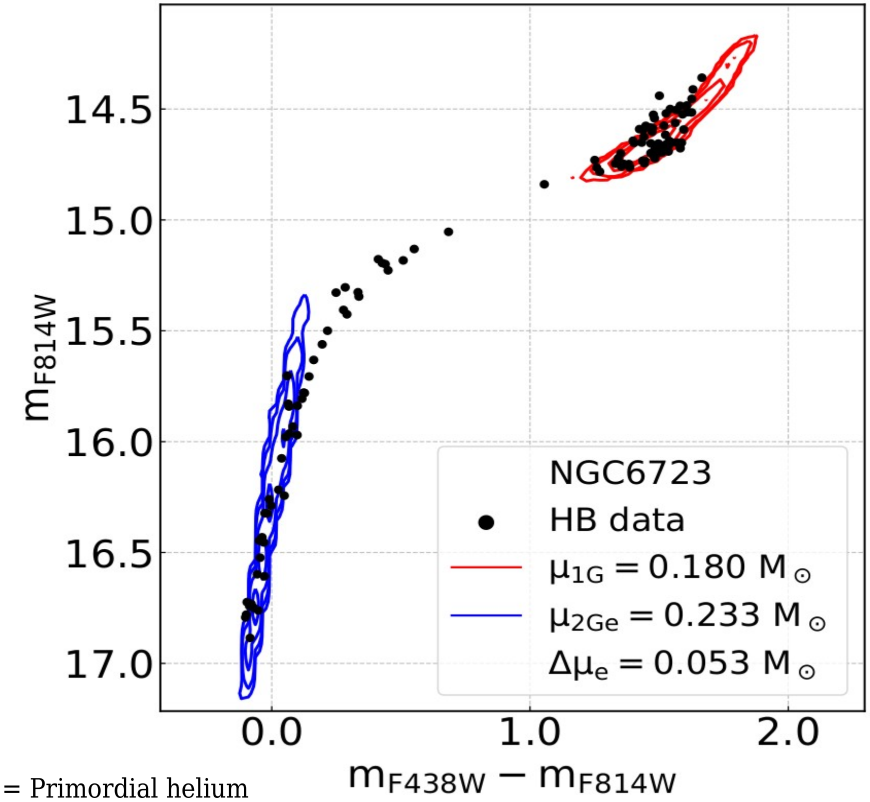
Combining this with stellar models and synthetic spectra a link with helium can be found.
Breaking a decades long parameters degeneracy!

HB modeling

Tailo et al. 2020

- The last parameter to evaluate is the integrated RGB mass loss (μ).
- For most clusters we have the helium values for two groups of stars : the first and the extreme part of the second generation stars (**1G*** and **2Ge**)
- In most cases, these correspond to the **reddest (1G)** and **bluest (2Ge)** groups of stars along the branch.

We *only* need to identify these two groups and to associate them a mass and a mass loss value… Seems easy!

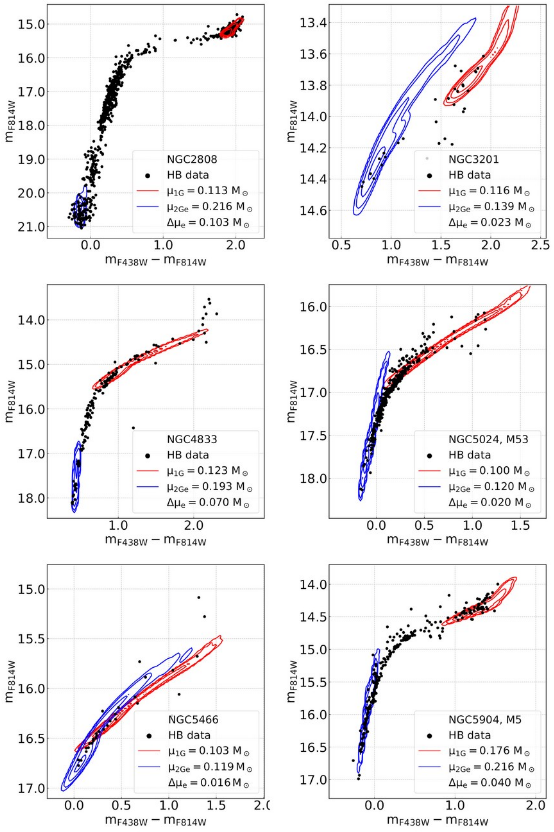


* 1G helium = Primordial helium

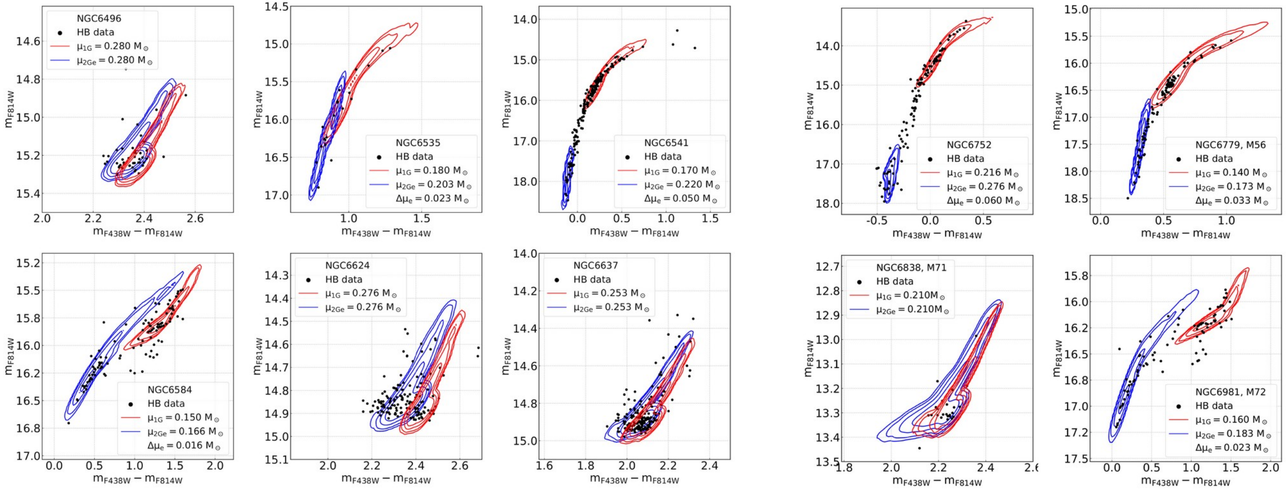
Spoiler: it wasn't

Doing that for a large sample of GCs

- Analyzed 53 clusters:
  - Included both regular and second parameter clusters.
  - Also analyzed those cluster without any trace of multiple populations



Tailo et al. 2020, Tailo et al 2021



Doing that for a large sample of GCs

Tailo et al. 2020

Looking at our results from a wide perspective we notice an intricate web of relations between different structural parameters of the host clusters.

Few generate all the others.

Correlation of μ_{1G} against 56 GC parameters

Age (MF09) 0.13 (44) 0.384	Age (D10) -0.45 (44) 0.001	Age (V1[illegible]) -0.51 (4[illegible]) <0.00[illegible]	Age (This work) -0.43 (44) 0.003	$\delta Y_{2G,1G}$ [illegible].04 (44) 0.789	δY_{max} -0.02 (44) 0.879	HBR -0.40 (44) 0.005	$\bar{M}^{HB}_{1G}$ -0.66 (44) <0.001
W_{F275W} 0.61 (44) <0.001	$W_{C,F275W}$ 0.71 (44) <0.001	$\Delta W_{C,F27[illegible]}$ -0.15 (44) 0.311	[illegible] 0.07 (41) 0.677	S_{RR} -0.42 (44) [illegible]	L_1 -0.41 (44) 0.005	L_2 -0.44 (44) 0.002	μ_{2Ge} 0.86 (33) <0.001
$f_{bin,c}$ 0.24 (30) 0.185	$f_{bin,hm}$ 0.07 (38) 0.649	$f_{bin,ohm}$ -0.10 (33) 0.575	$W_{C,F336[illegible]}$ 0.73 (44[illegible] <0.001	[Fe/H] 0.88 (44) <0.001	M_v [illegible].13 (44) 0.402	c -0.00 (44) 0.978	$\bar{M}^{HB}_{2Ge}$ -0.49 (33) 0.003
ρ_0 0.14 (44) 0.364	τ_{HB} -0.46 (42) 0.002	$\log(M/M_\odot)$ -0.17 (44) 0.264	$\log(M_i/M$[illegible] 0.04 (44) 0.770	[illegible] -0.05 (44) 0.735	r_c -0.13 (44) 0.384	r_{hl} -0.10 (44) 0.529	$\Delta\mu_e$ 0.18 (33) 0.309
r_{hm} -0.20 (44) 0.172	r_t -0.51 (44) <0.001	$\log(\rho_c)$ 0.08 (44) 0.606	$\log(\rho_{hm})$ 0.11 (44) 0.474	$\log(T_{rh})$ -0.34 (44) 0.019	MF slope 0.60 (44) <0.001	F_{remn} 0.48 (44) <0.001	ε -0.11 (42) 0.486
σ_0 0.01 (44) 0.960	v_{esc} 0.00 (44) 0.983	η_c 0.06 (44) 0.699	η_{hm} 0.08 (44) 0.606	R_{GC} -0.59 (44) <0.001	$\Delta W_{C,F336W}$ -0.19 (44) 0.199	R_{apog} -0.59 (44) <0.001	SB_0 -0.03 (44) 0.848
X -0.22 (44) 0.150	Y 0.05 (44) 0.760	Z -0.07 (44) 0.625	U 0.21 (44) 0.154	V 0.09 (44) 0.540	W -0.13 (44) 0.395	R_{perig} -0.15 (44) 0.326	RV -0.21 (44) 0.157

Correlation of μ_{2Ge} against 56 GC parameters

Age (MF09) -0.11 (33) 0.548	Age (D10) -0.24 (33) 0.160	Age (V13) -0.13 (30) 0.484	Age (This work) -0.17 (33) 0.324	$\delta Y_{2G,1G}$ 0.23 (33) 0.178	δY_{max} 0.21 (33) 0.224	HBR 0.10 (33) 0.550	μ_{1G} 0.86 (33) <0.001
W_{F275W} 0.59 (33) <0.001	$W_{C,F275W}$ 0.77 (33) <0.001	$\Delta W_{C,F275W}$ 0.41 (33) 0.014	N_{1G}/N_T -0.24 (32) 0.164	S_{RR} -0.23 (33) 0.174	L_1 0.07 (33) 0.671	L_2 0.19 (33) 0.262	$\bar{M}^{HB}_{1G}$ -0.70 (33) <0.001
$f_{bin,c}$ -0.22 (22) 0.301	$f_{bin,hm}$ -0.33 (28) 0.075	$f_{bin,ohm}$ -0.41 (26) 0.030	$W_{C,F336W}$ 0.71 (33) <0.001	[Fe/H] 0.70 (33) <0.001	M_v -0.21 (33) 0.224	c 0.17 (33) 0.329	$\bar{M}^{HB}_{2Ge}$ -0.81 (33) <0.001
ρ_0 0.36 (33) 0.034	τ_{HB} 0.16 (32) 0.359	$\log(M/M_\odot)$ 0.21 (33) 0.220	$\log(M_i/M_\odot)$ 0.42 (33) 0.011	M/L 0.10 (33) 0.568	r_c -0.29 (33) 0.094	r_{hl} -0.37 (33) 0.027	$\Delta\mu_e$ 0.60 (33) <0.001
r_{hm} -0.49 (33) 0.003	r_t -0.26 (33) 0.136	$\log(\rho_c)$ 0.33 (33) 0.051	$\log(\rho_{hm})$ 0.48 (33) 0.004	$\log(T_{rh})$ -0.40 (33) 0.016	MF slope 0.60 (33) <0.001	F_{remn} 0.38 (33) 0.026	ε -0.25 (31) 0.154
σ_0 0.38 (33) 0.024	v_{esc} 0.37 (33) 0.028	η_c -0.03 (33) 0.846	η_{hm} -0.04 (33) 0.810	R_{GC} -0.51 (33) 0.002	$\Delta W_{C,F336W}$ 0.21 (33) 0.220	R_{apog} -0.61 (33) <0.001	SB_0 -0.34 (33) 0.049
X -0.18 (33) 0.301	Y 0.06 (33) 0.738	Z -0.01 (33) 0.936	U 0.02 (33) 0.921	V 0.00 (33) 0.994	W -0.22 (33) 0.195	R_{perig} -0.38 (33) 0.023	RV -0.11 (33) 0.519

Correlation of $\Delta\mu_e$ against 56 GC parameters

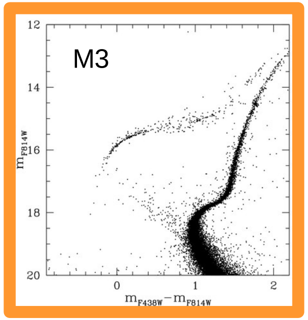
Age (MF09) -0.11 (33) 0.526	Age (D10) -0.11 (33) 0.523	Age (V13) -0.02 (30) 0.898	Age (This work) 0.12 (33) 0.480	$\delta Y_{2G,1G}$ 0.46 (33) 0.006	δY_{max} 0.61 (33) <0.001	HBR -0.01 (33) 0.938	μ_{1G} 0.18 (33) 0.309
W_{F275W} 0.67 (33) <0.001	$W_{C,F275W}$ 0.58 (33) <0.001	$\Delta W_{C,F275W}$ 0.76 (33) <0.001	N_{1G}/N_T -0.51 (32) 0.002	S_{RR} -0.08 (33) 0.667	L_1 -0.07 (33) 0.696	L_2 0.46 (33) 0.005	$\bar{M}^{HB}_{1G}$ -0.09 (33) 0.617
$f_{bin,c}$ -0.41 (22) 0.049	$f_{bin,hm}$ -0.56 (28) 0.001	$f_{bin,ohm}$ -0.49 (26) 0.009	$W_{C,F336W}$ 0.49 (33) 0.003	[Fe/H] 0.21 (33) 0.228	M_v -0.62 (33) <0.001	c 0.21 (33) 0.219	μ_{2Ge} 0.60 (33) <0.001
ρ_0 0.49 (33) 0.003	τ_{HB} 0.33 (32) 0.057	$\log(M/M_\odot)$ 0.61 (33) <0.001	$\log(M_i/M_\odot)$ 0.73 (33) <0.001	M/L -0.10 (33) 0.573	r_c -0.32 (33) 0.057	r_{hl} -0.53 (33) 0.001	$\bar{M}^{HB}_{2Ge}$ -0.82 (33) <0.001
r_{hm} -0.54 (33) <0.001	r_t 0.20 (33) 0.261	$\log(\rho_c)$ 0.43 (33) 0.009	$\log(\rho_{hm})$ 0.74 (33) <0.001	$\log(T_{rh})$ -0.22 (33) 0.213	MF slope 0.31 (33) 0.069	F_{remn} 0.05 (33) 0.771	ε -0.02 (31) 0.927
σ_0 0.69 (33) <0.001	v_{esc} 0.68 (33) <0.001	η_c -0.09 (33) 0.595	η_{hm} -0.07 (33) 0.673	R_{GC} -0.16 (33) 0.346	$\Delta W_{C,F336W}$ 0.62 (33) <0.001	R_{apog} -0.26 (33) 0.125	SB_0 -0.59 (33) <0.001
X 0.05 (33) 0.766	Y -0.00 (33) 0.992	Z -0.01 (33) 0.976	U 0.03 (33) 0.843	V 0.00 (33) 0.985	W -0.11 (33) 0.527	R_{perig} -0.42 (33) 0.012	RV -0.10 (33) 0.584

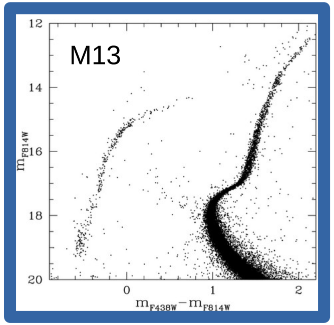
Complexity within complexity within complexity.

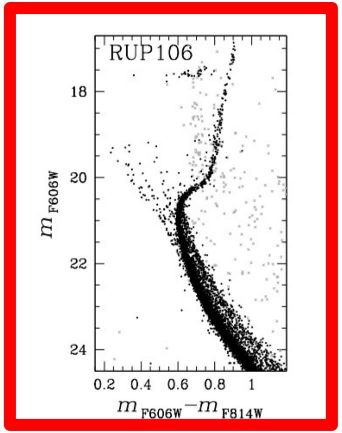
A mass loss law?

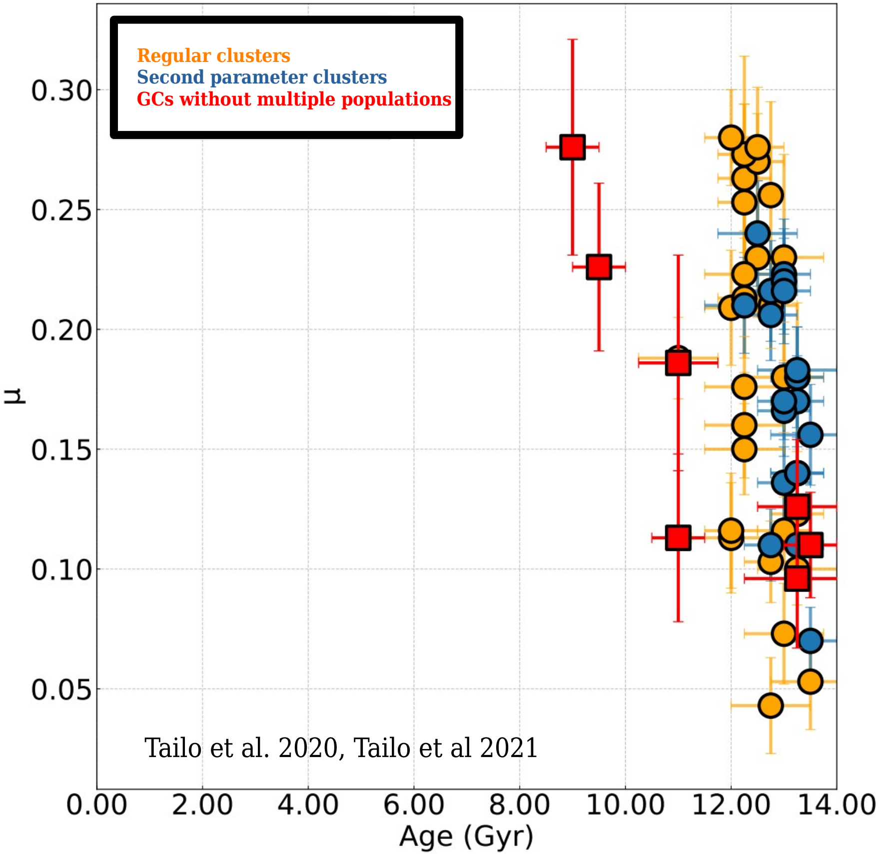
Looking at our results as a function of age it seems that there are two relations at play.

The simple populations clusters follow a distinct sequence









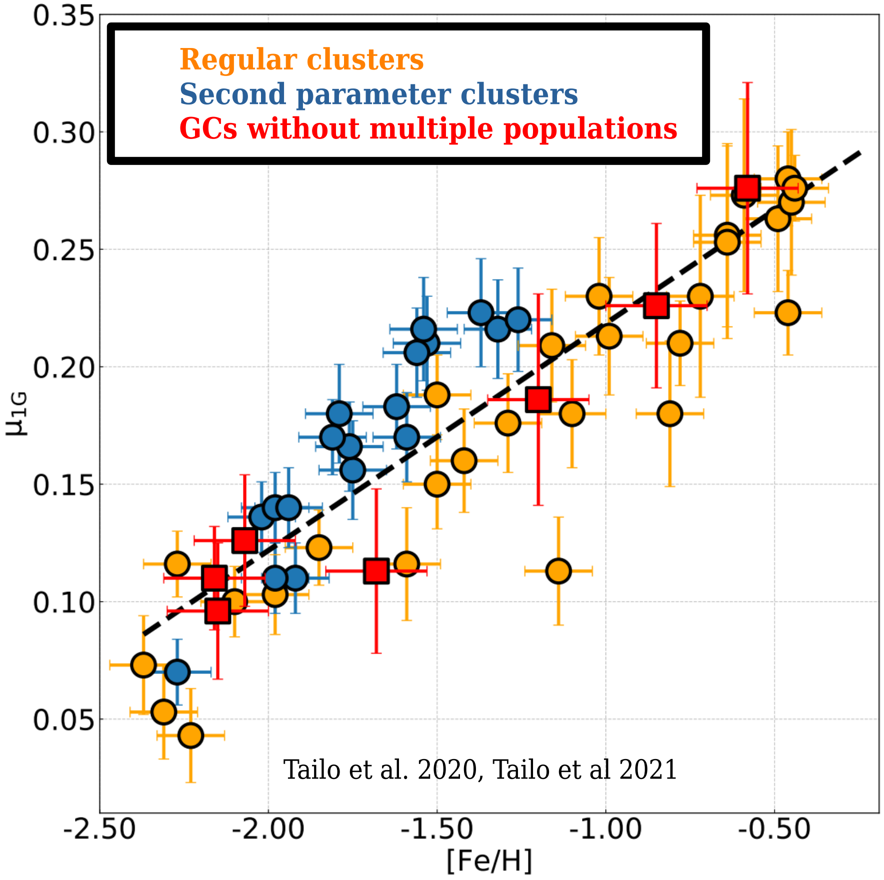
However...

A mass loss law?

The other strong relation is with the metallicity of the host cluster

- All “species” of GCs behave similarly
- Standard models for mass loss can not describe this trend
- The best fit relation is:

$$\mu_{1g}=0.95\cdot[Fe/H] + 0.312$$

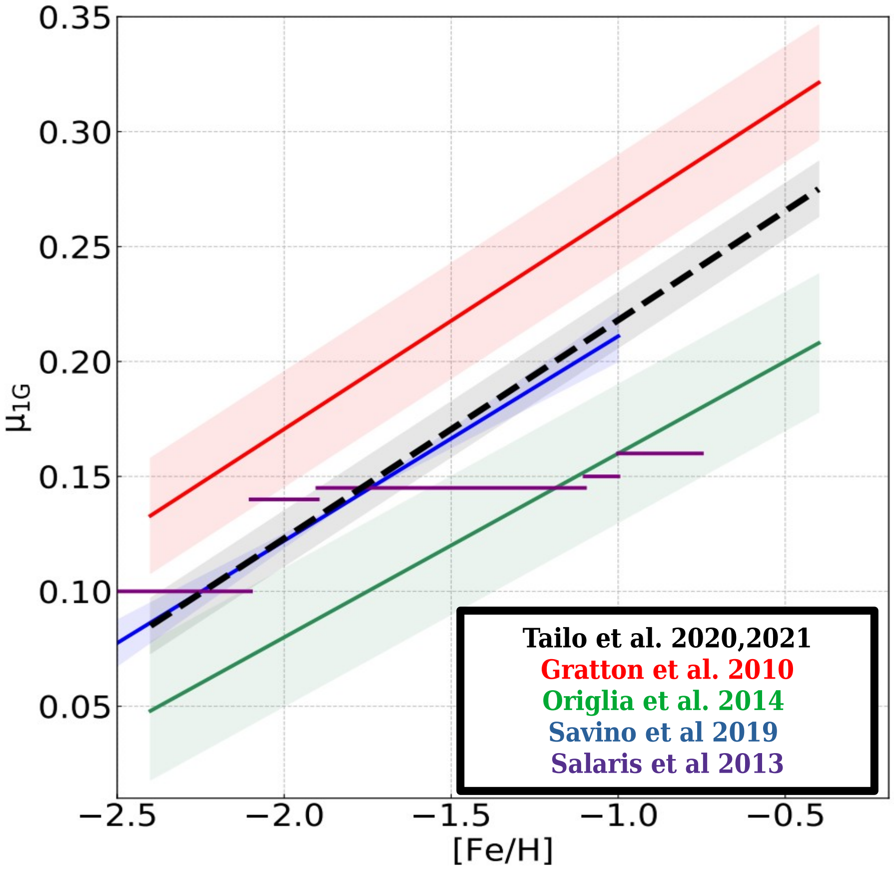


A *universal* mass loss law?

- Slopes of other mass loss relations in the literature are compatible

- We also compared with other few relations coming from **Tucana** and **Sculptor** dSph galaxies (Savino et al. 2019, Salaris et al. 2013)

    - Is RGB evolution universal for old low metallicity stars?
    - How this impacts the evolution of later stages?
    - What happens at even higher metallicity values or in young populations?



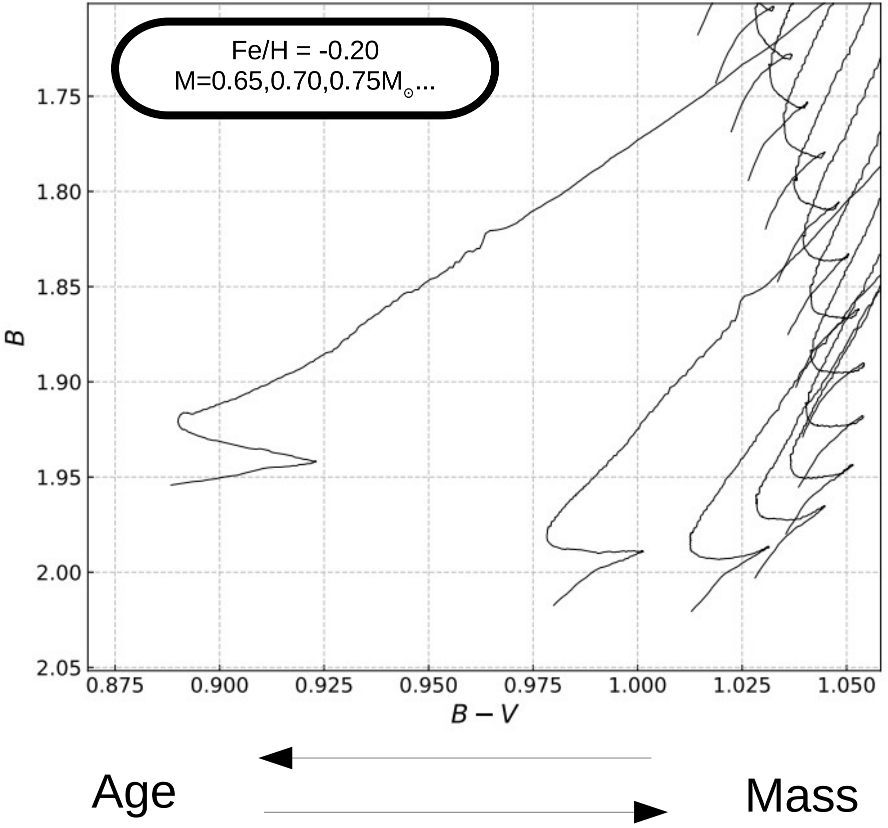
HB to RC: difficult with only photometry!

In younger (<8Gyr) clusters helium burning stars tend to “cluster”* in a small region of the CMD.

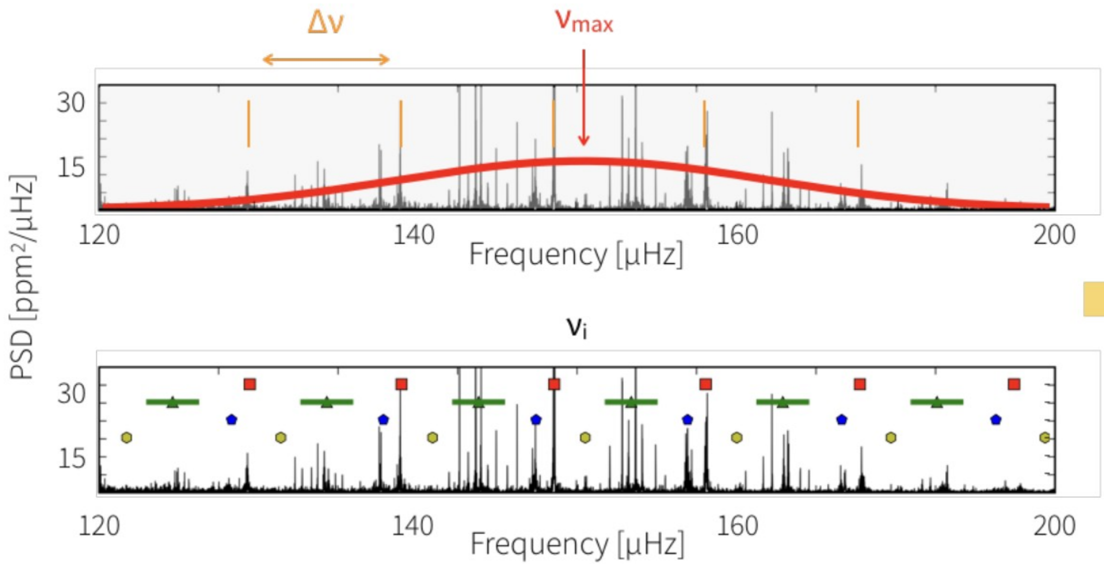
(pun intended)

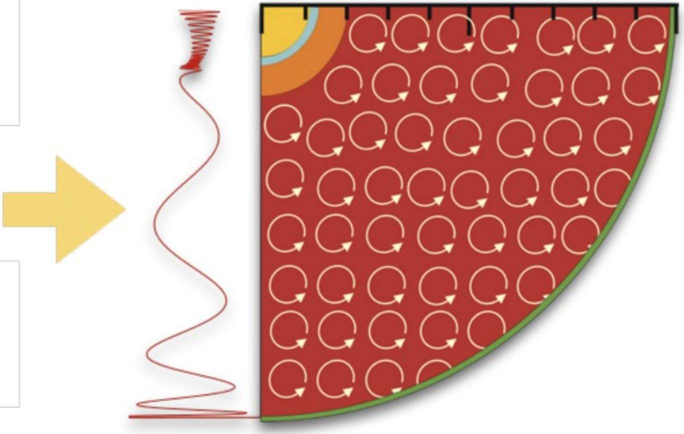
Since this large number of tracks inhabits this region it is difficult to obtain accurate mass estimates with only photometry!

We need to supplement the information coming from photometry and the models!



Asteroseismology

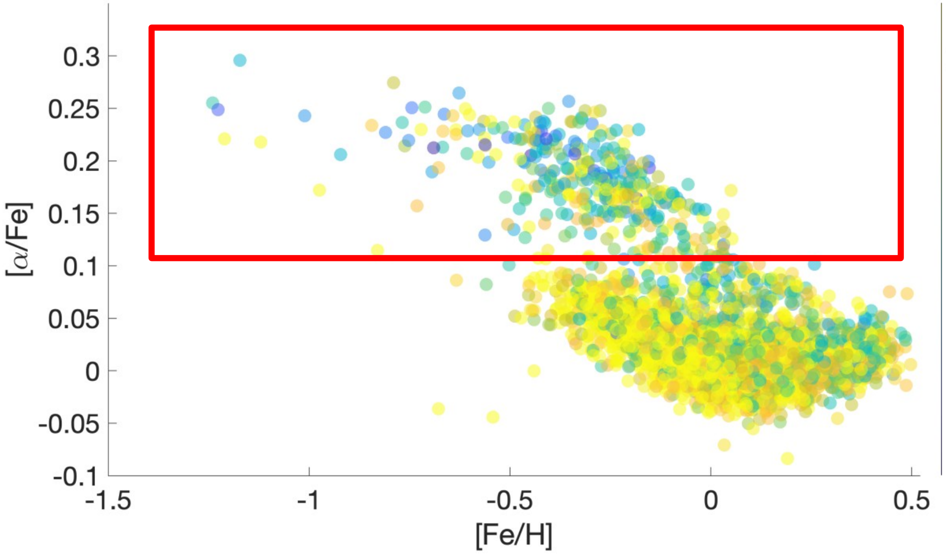


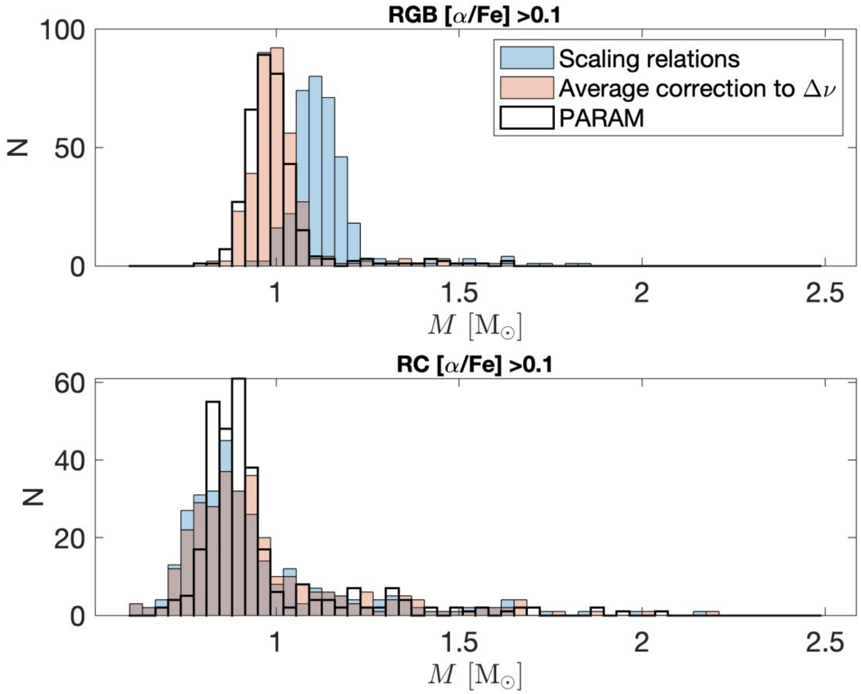


ν_{max} and $\Delta\nu$ can be written in terms of luminosity, mass and temperature

If we observe oscillations in a RGB and a helium burning star we can evaluate their mass ed eventually mass loss

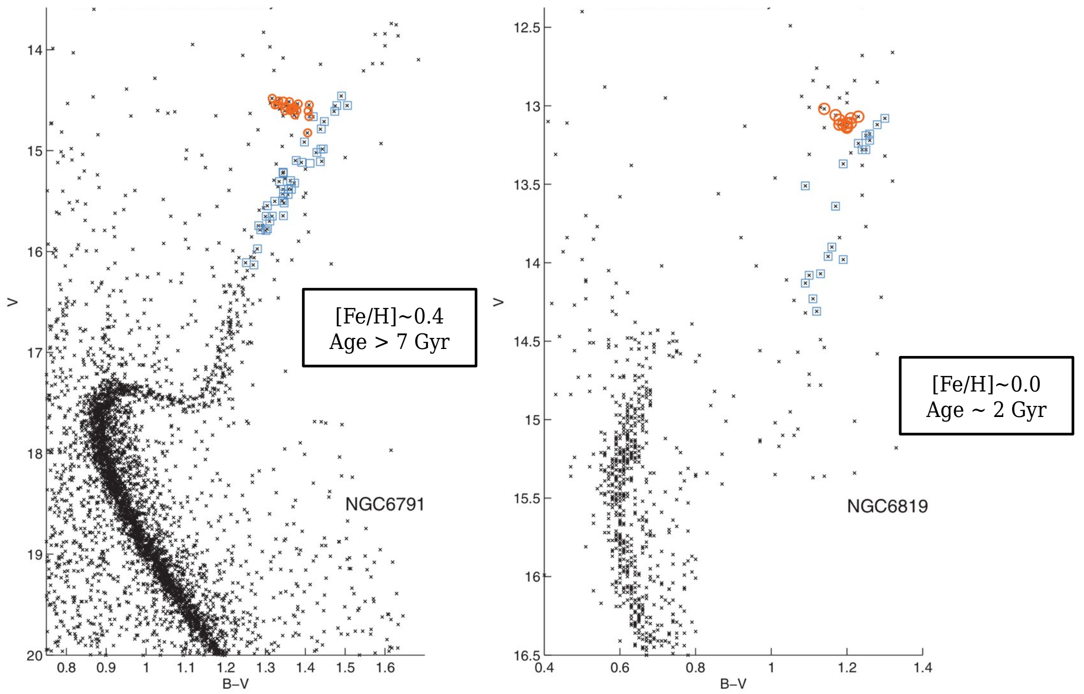
High metallicity / low age regime

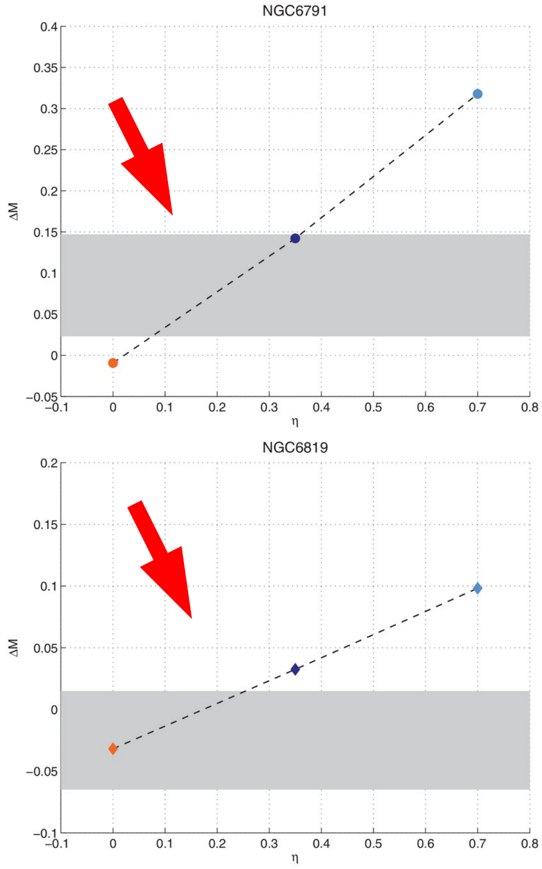




Miglio et al. (2021) found an average 0.1 – 0.12 $M_{\odot}$ mass loss in Kepler field stars

High metallicity / low age regime



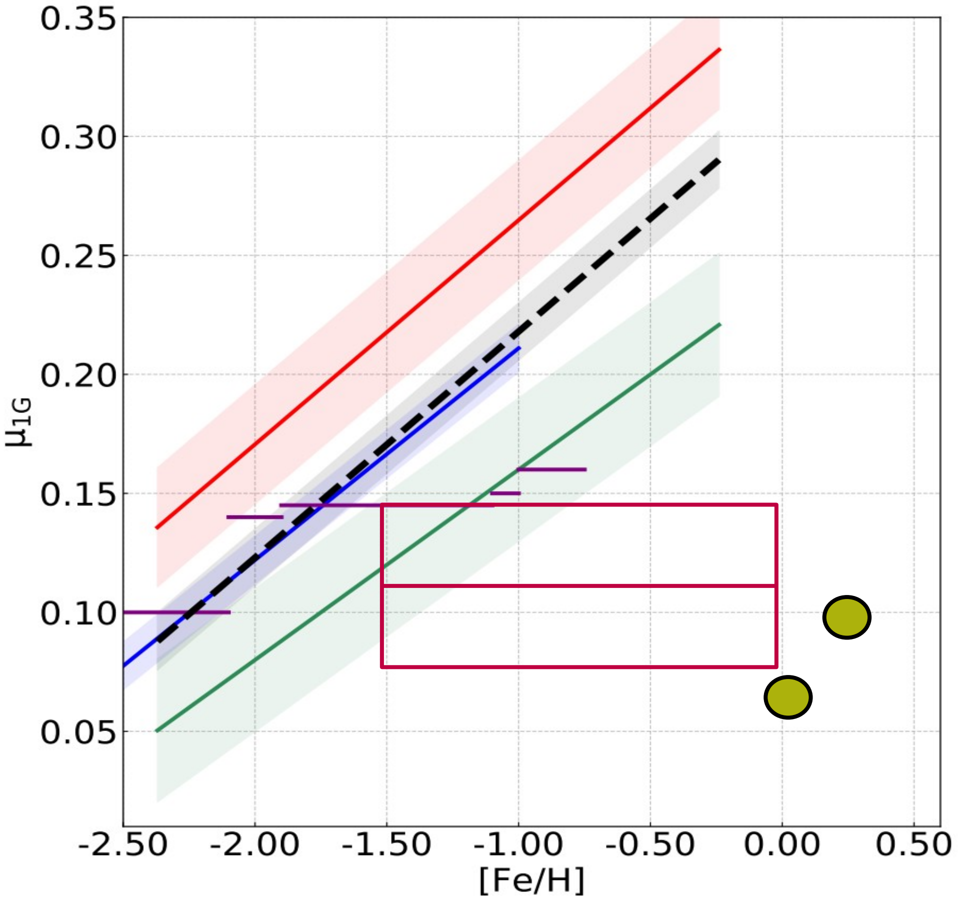


Older measurements from Miglio et al. (2012) show even lower values of integrated mass loss for high [Fe/H]

Tension?

- Seems that the relations found for the old stellar associations (GC and dSph Galaxies) do not agree with the one for the field (Kepler stars) and younger clusters

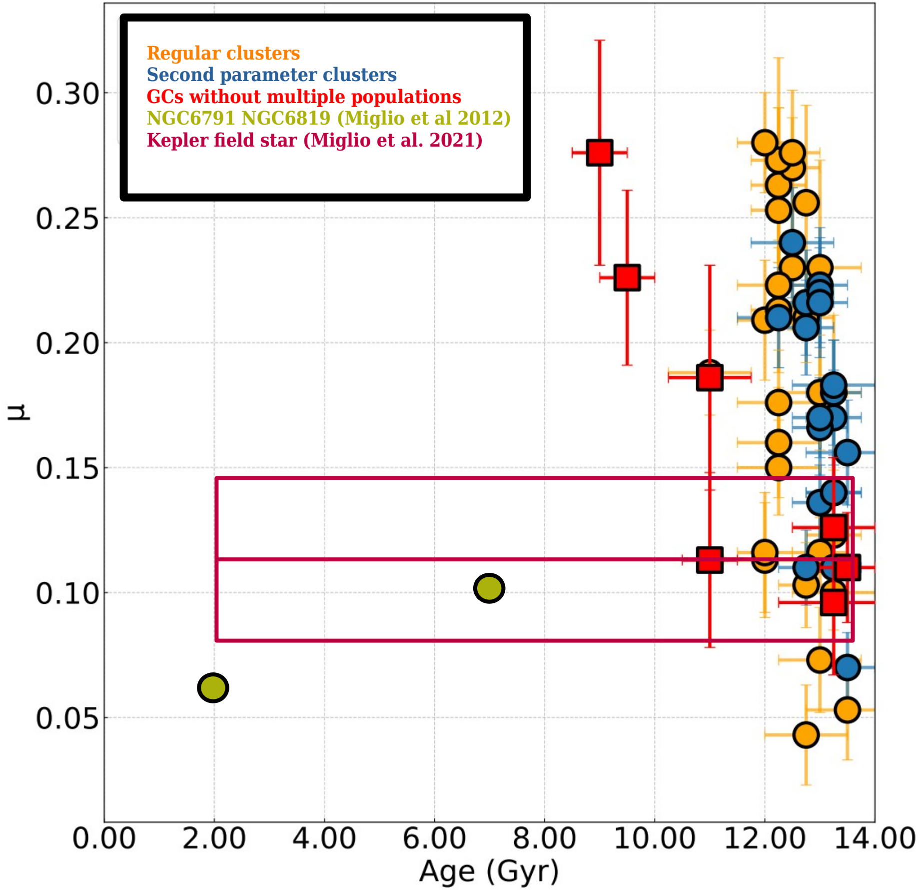
Tailo et al. 2021
Gratton et al. 2010
Origlia et al. 2014
Savino et al 2019
Salaris et al 2013
Miglio et al. 2021
Miglio et al. 2012



Tension?

- This is even more evident if we look and the Age – Mass loss relation.

- Does the environment and the age play a role in altering RGB mass loss?

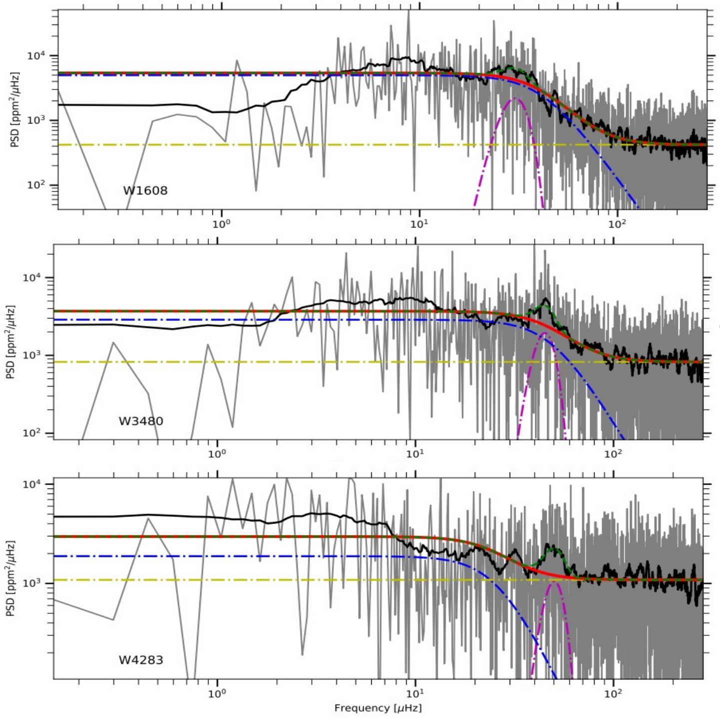


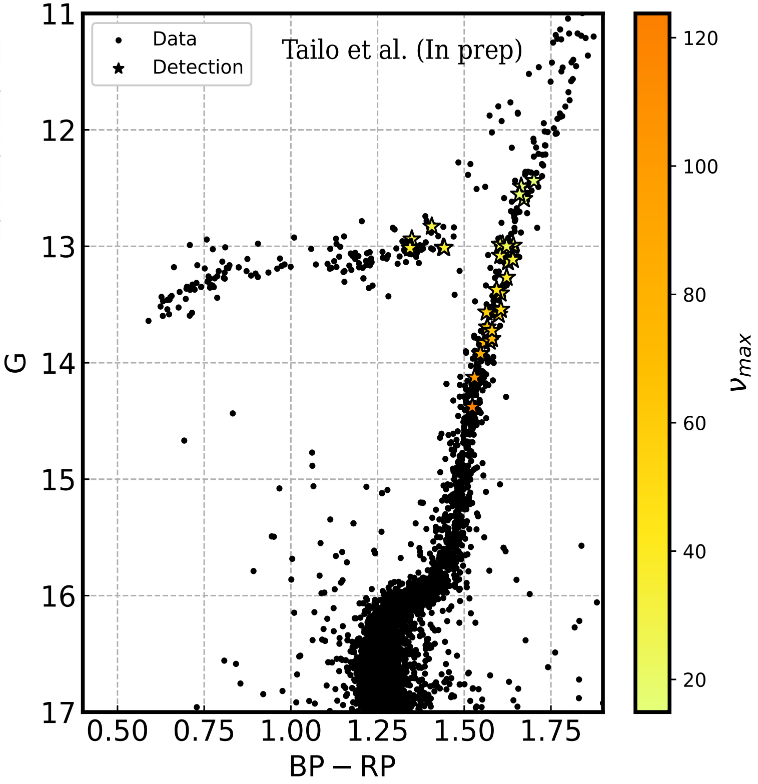
M4: bridging the gap

Combining K2 and Gaia observations of M4 we obtained detection of stellar oscillations in RGB and HB stars.

With this we derived those parameter (ν_{max} and $\Delta\nu$) to estimate the mass of our those stars.

Early results from our team!



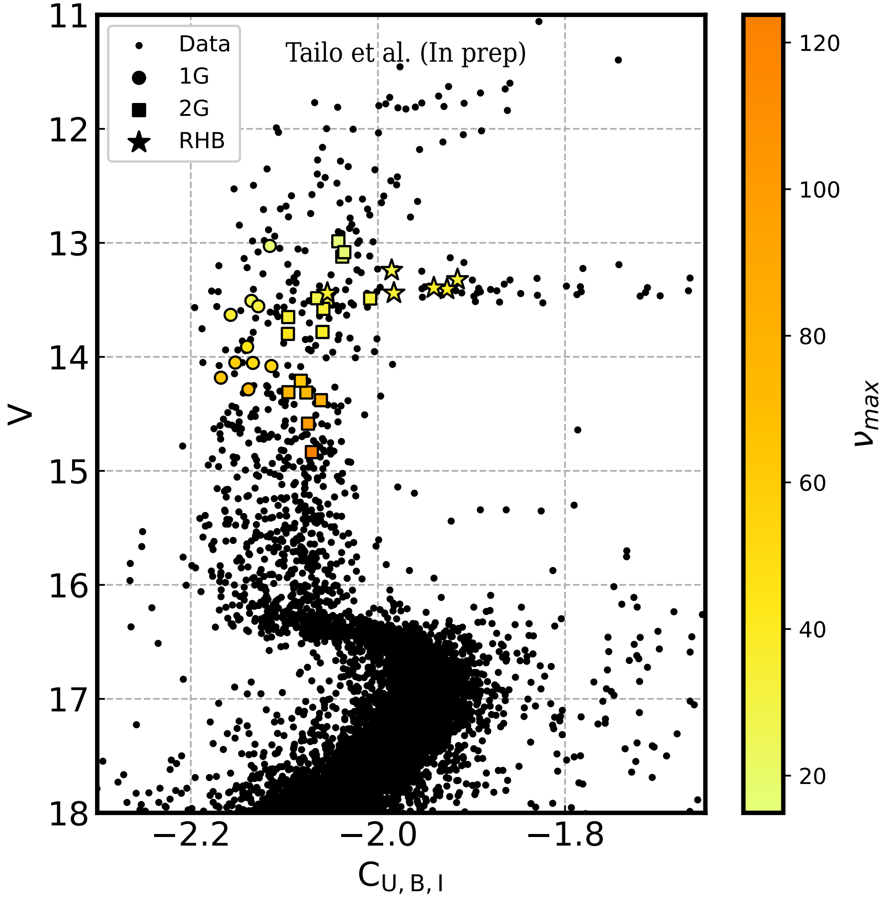


M4: bridging the gap

M4 is a multiple populations system:

- The $C_{U,B,I}$= (U-B)-(B-I) index is an effective way to separate stellar populations
- We cross matched the data from Gaia and K2 with the data from Stetson at al.
- Overall we have 10/26 1G stars and 16/26 2G stars (40 to 60 ratio)
- The 6 HB stars we have are all 1G (according to spectroscopy) and will provide a measure of mass loss.

Early results from our team!



Conclusions

- With the new abundance estimates available, the analysis of the old helium burning stars can provide a fast way to evaluate integrated RGB mass loss in clusters.
- For old, low metallicity stars it seems a universal relation exists.
- Which, still, does not translate well to the available high metallicity, low age measures. Does the environment and the age of the cluster/stars play a role?
- M4 is a unique GC where a direct asteroseismologic study is possible.
  A unique opportunity to refine the tools for further instruments/missions.

Thank you!