A Transient Overcooling in the Early Universe? Clues from Globular Cluster Formation

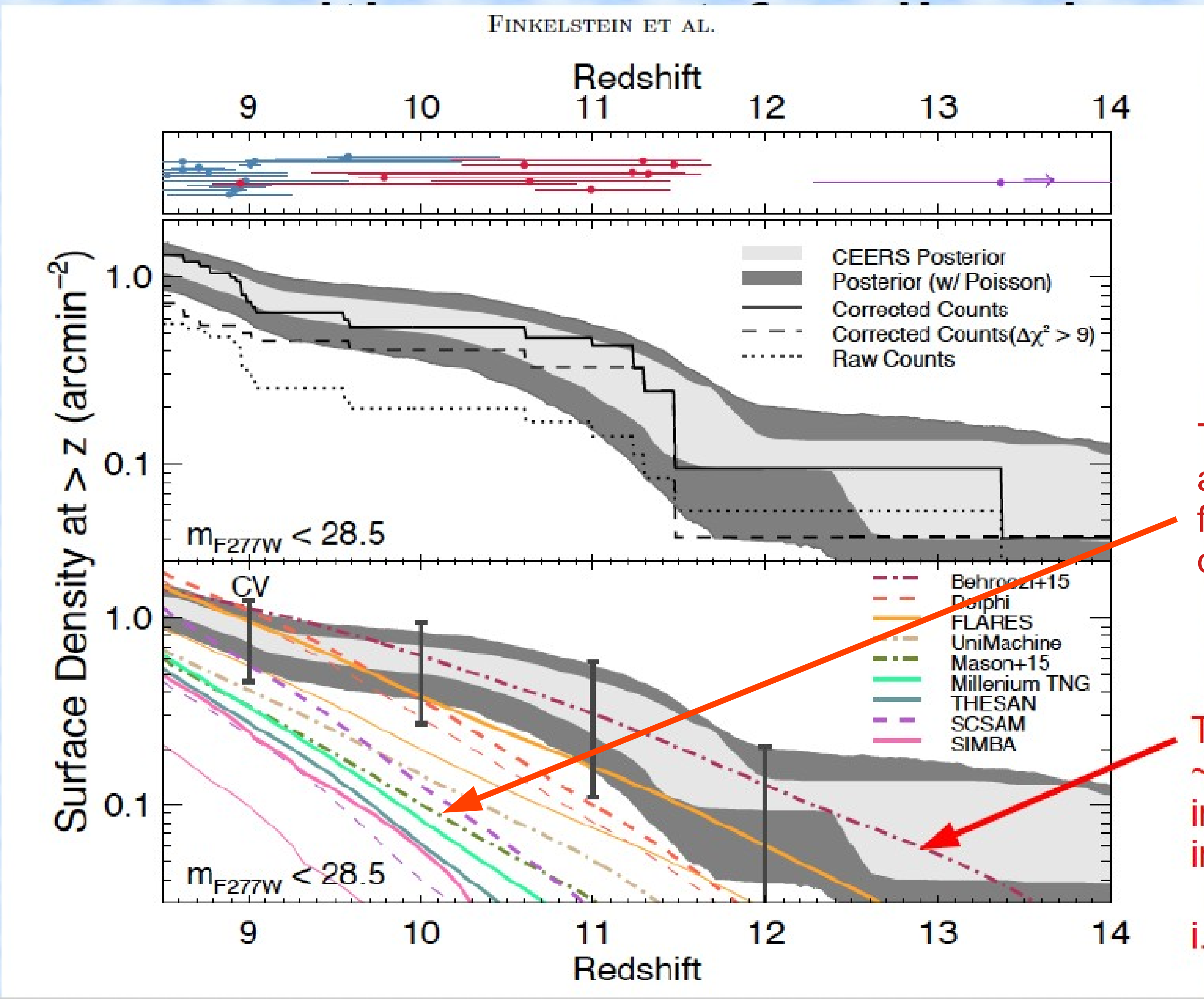
The Outlook

- JWST reveals more activity at z~5-16 than “expected”
- A phenomenological scenario for GC Formation
- That imay help understanding what was going on at such high redshifts.

Alvio Renzini, INAF Milano, May 20, 2024

Background from Evans+2018

Apparent excess of massive galaxies at high z over theoretical simulations

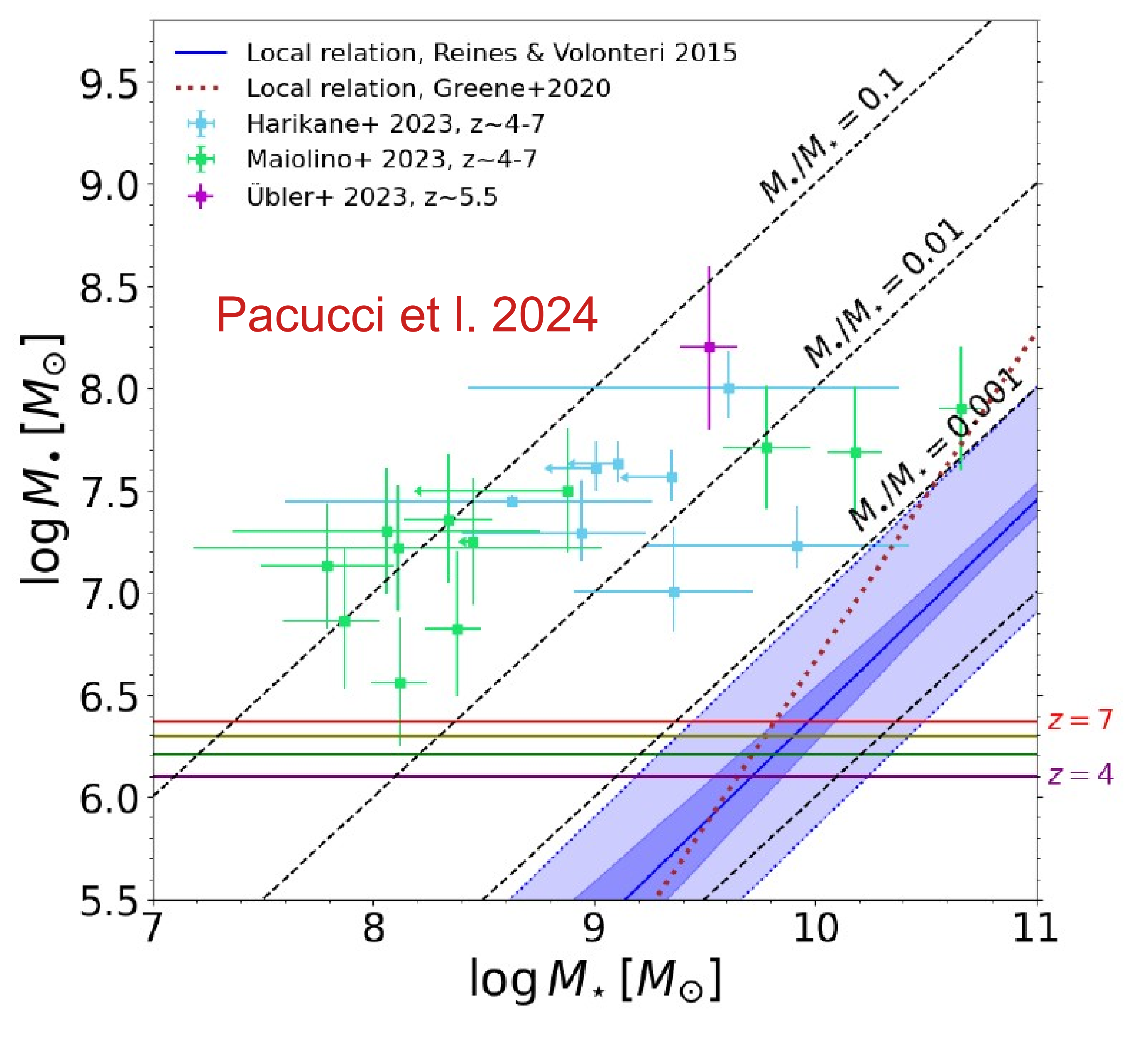


The models adopted strong feedback to avoid overcooling

This assumes ~100% efficiency in converting gas into stars

i.e., overcooling

More and more massive SMBH than expected



Seing GCs in formation at high redshift!

With HST

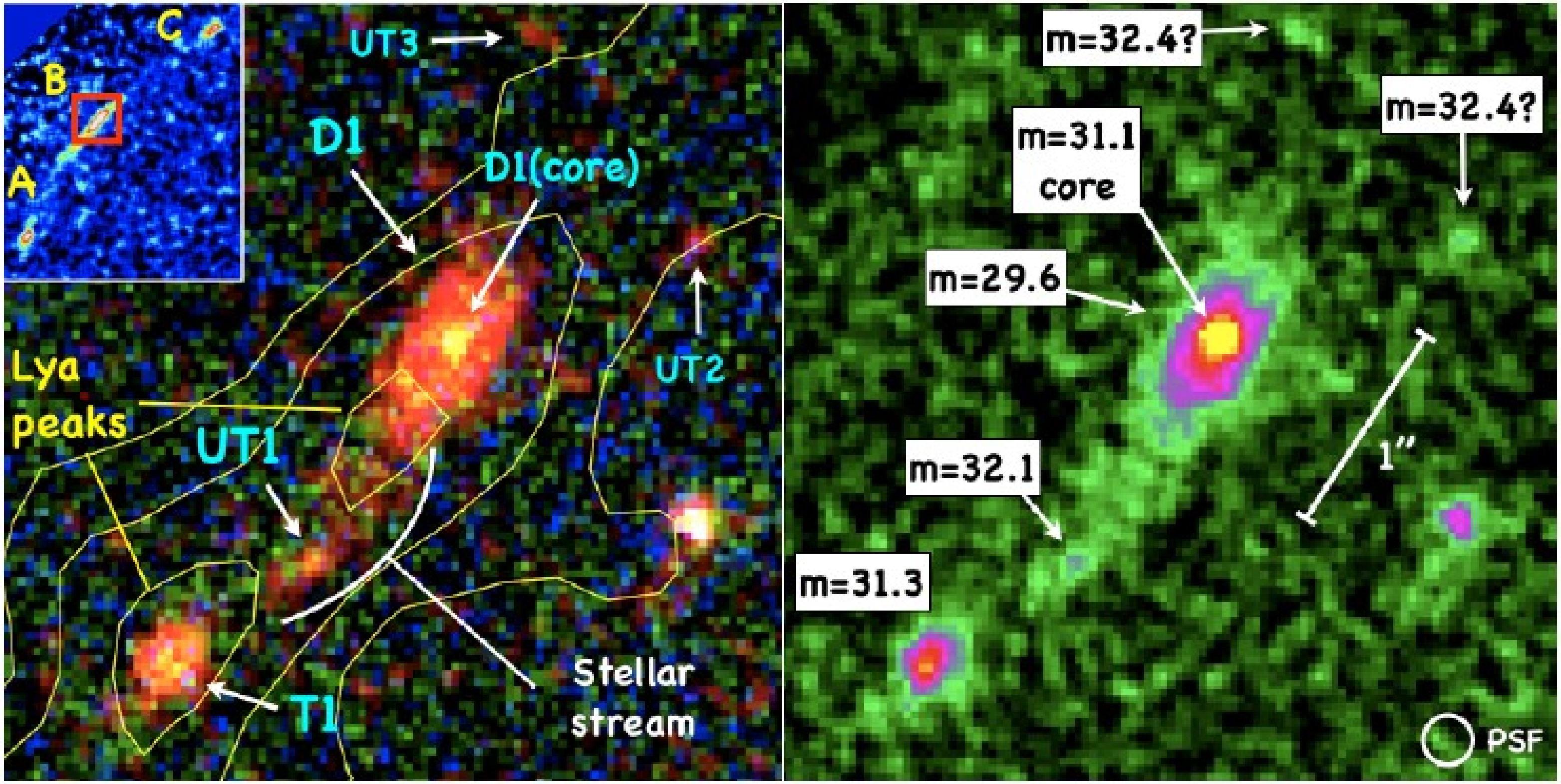


Figure 2. Color composite (left) and the WFC3/F105W image (right) of the field under study containing the sources D1 and T1. This region corresponds to the red square in the top-left inset which shows the extended Lyα arc from MUSE (see Figure 1). Sources are labelled (left), along with their de-lensed F105W magnitudes (right). Note the prominent symmetric core of D1 despite the large tangential magnification and the presence of a stellar stream possibly connecting D1 and T1, also including a star-forming knot, dubbed UT1. Other faint knots are shown, UT2 and UT3, with de-lensed magnitudes fainter than 32. The HST F105W PSF is shown in the bottom right.

A ~2x10^{7} z=6 Dwarf hosting a 10^{6} M$_{\odot}$ unresolved nucleus with Re < 13 pc.

The best example so far of a forming GC at high redshift.

Assembly lines of Globular Clusters at z=4

THE ASTROPHYSICAL JOURNAL LETTERS, 940:L53 (8pp), 2022 December 1 Vanzella et al.

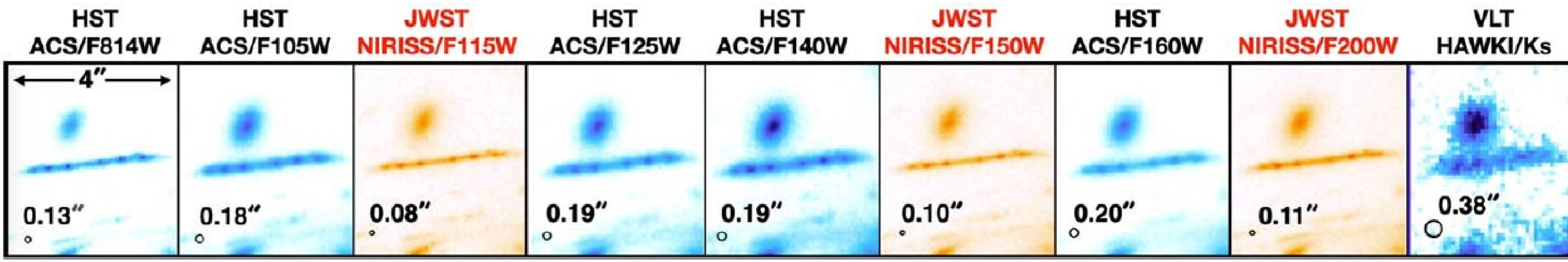
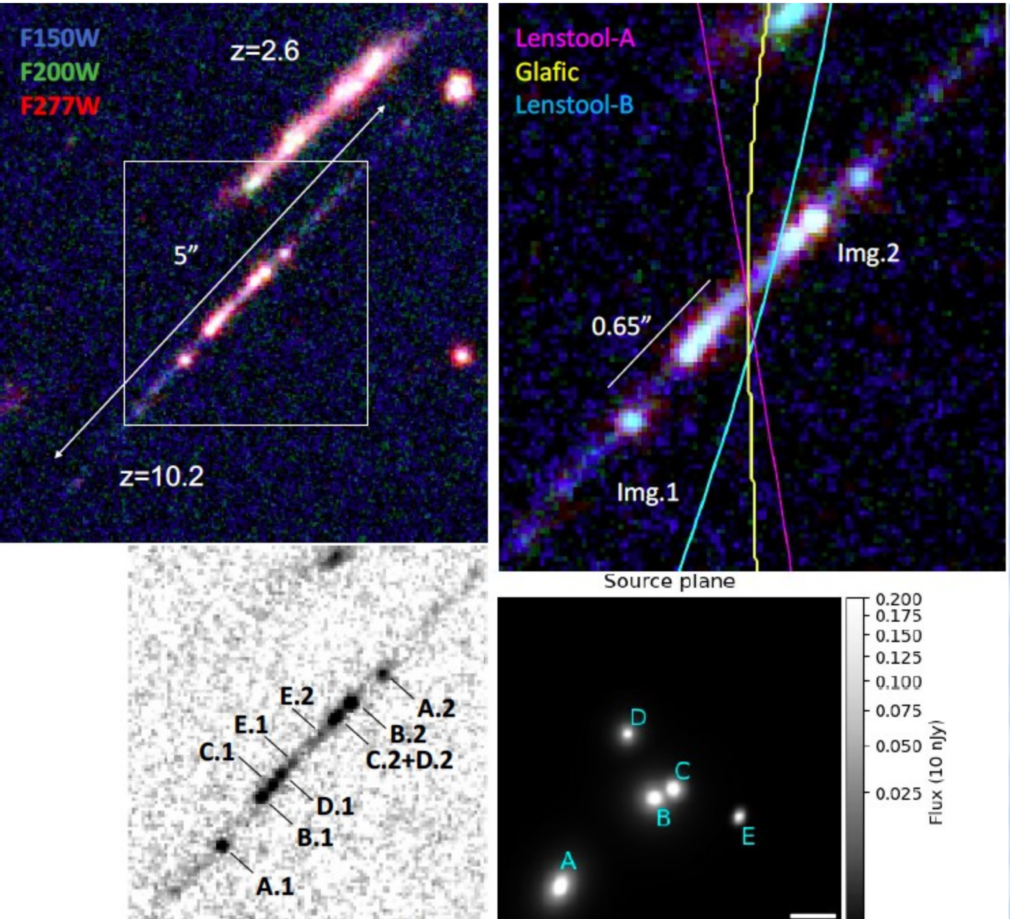


Figure 2. Cutouts of the arclet as observed with HST, JWST, and VLT filters. Small circles in the bottom left corner indicate the PSF size in each instrument/band (for Hubble and VLT they are taken from Merlin et al. 2016, whereas for JWST the PSFs are estimated with available nonsaturated stars).



Vanzella+2023

With JWST

And at z=10
Adamo+2024

The densest baryon concentrations we know of: Globular Clusters, Nuclear Star Clusters, SMBHs

Formed easily in the early Universe

Apparently, not much was contrasting a tendence of Baryons to cool, sink, reach extreme densities and deepen potential wells

Understanding how globular clusters formed may help to understand z=9-16 galaxies and early SMBH formation as revealed by JWST

Several possible origins of the discrepancy have been proposed, the most widely considered is an excess of stellar feedback in the models; e.g., Finkelstein+23; Yung+23; Dekel+23; Harikane+23; Quin+23; ...

Circumstantial evidence from globular clusters gives some support to the notion of a feedback-free early phase in star formation, as advocated in

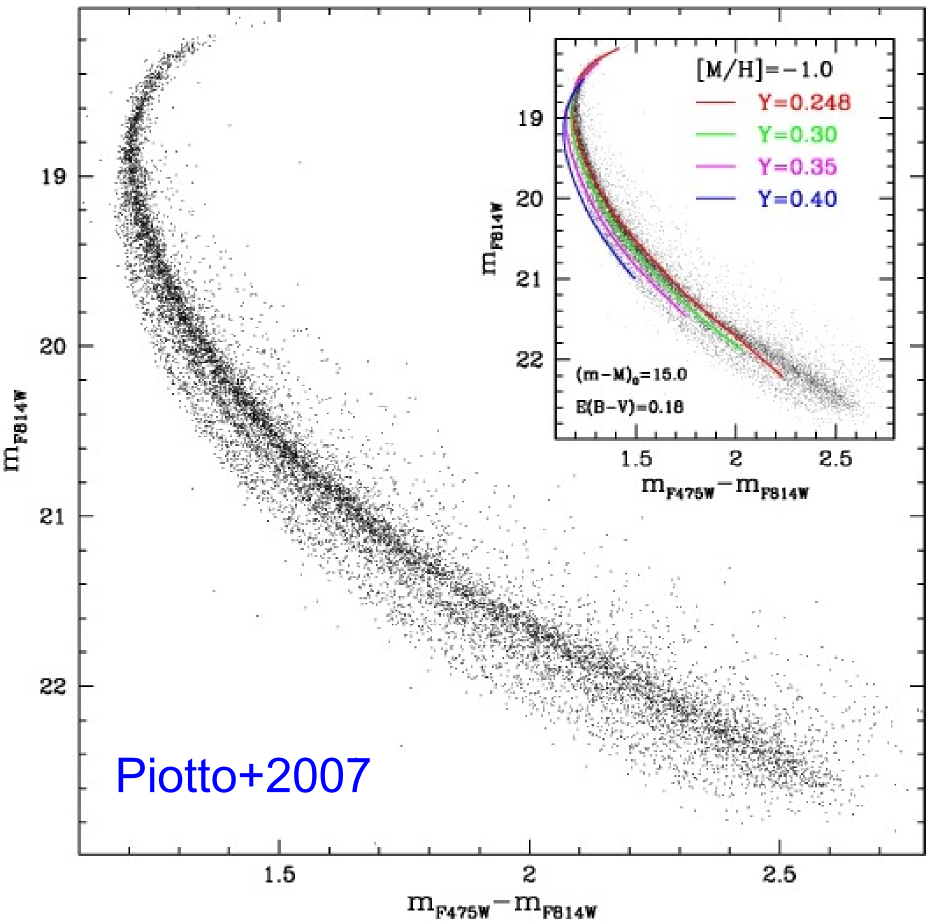
“Globular cluster formation as a case of overcooling” (A.R., Marino & Milone, 2022)

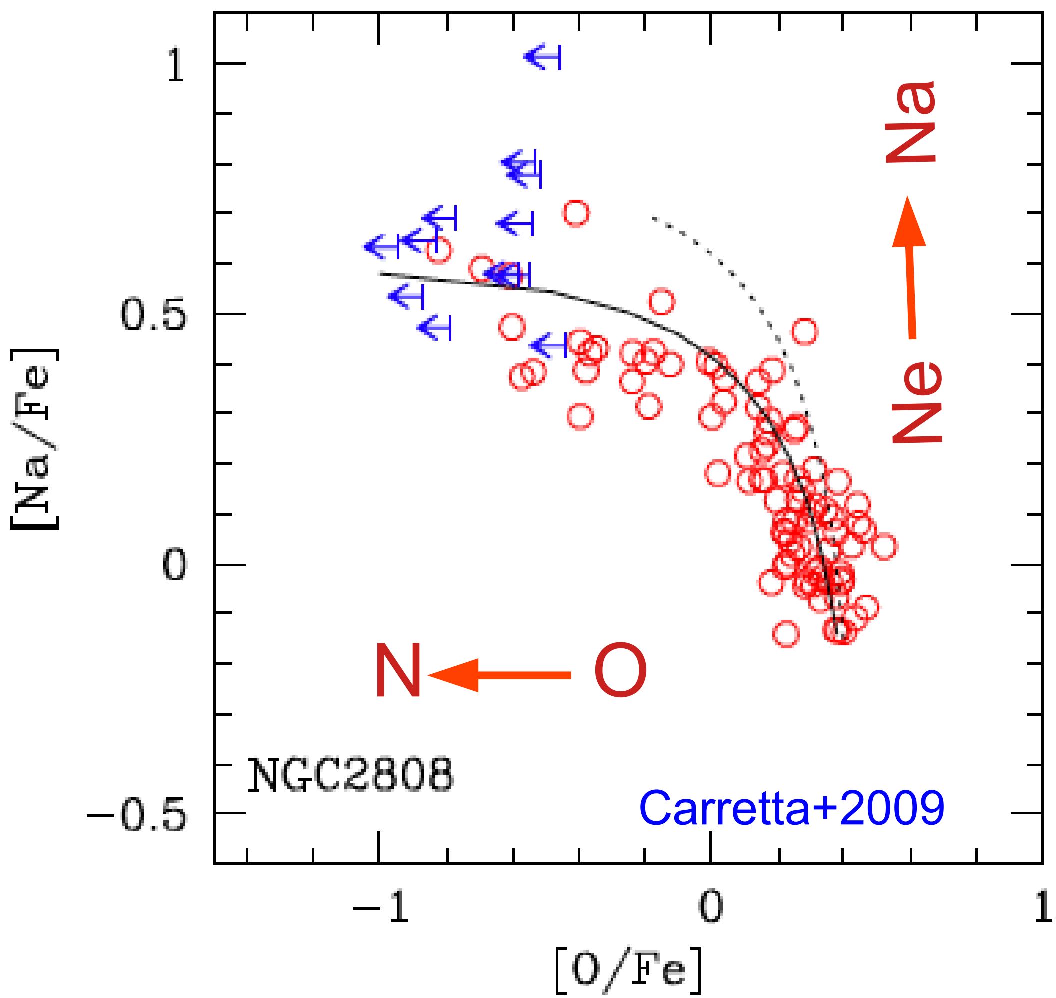
White & Rees1978

The Multiple Stellar Generations of GCs

One of many possible examples: NGC 2808: at least 3 main sequences with the same metallicity: hence with different helium content:

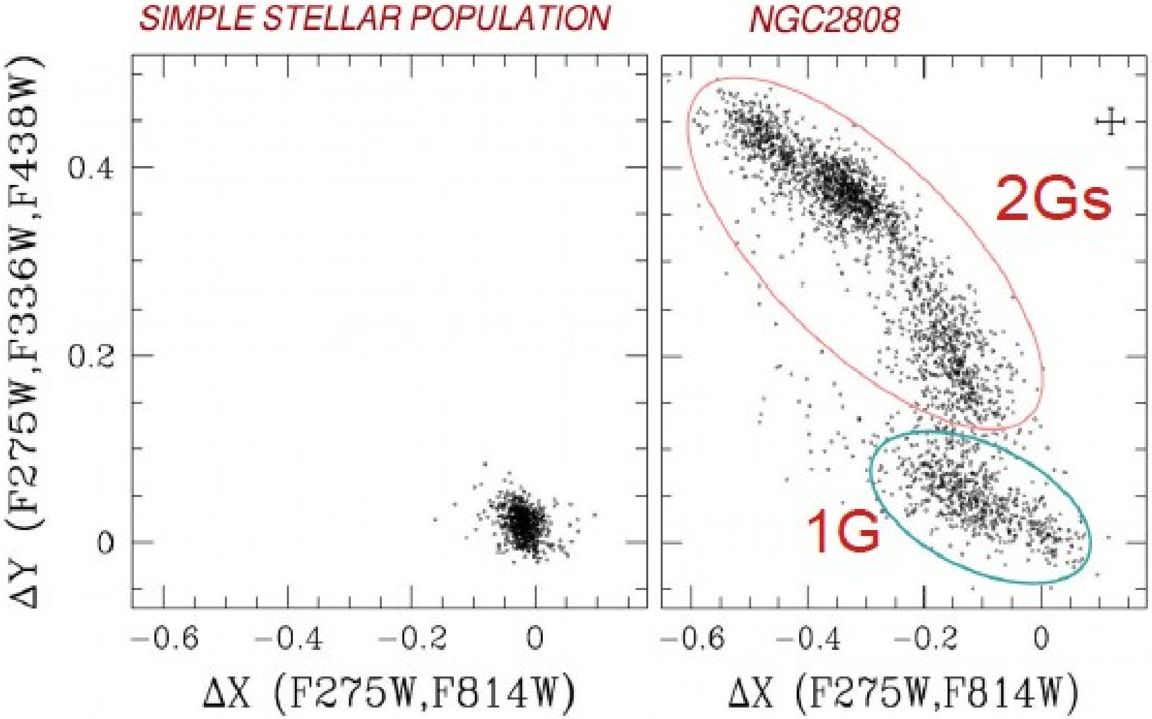
Second (third) generation stars are made of material
Exposed to high temperature (up to ~10^8 K) *p*-captures + CNO cycling





"Chromosome Maps" of this kind now exists for 57 GCs

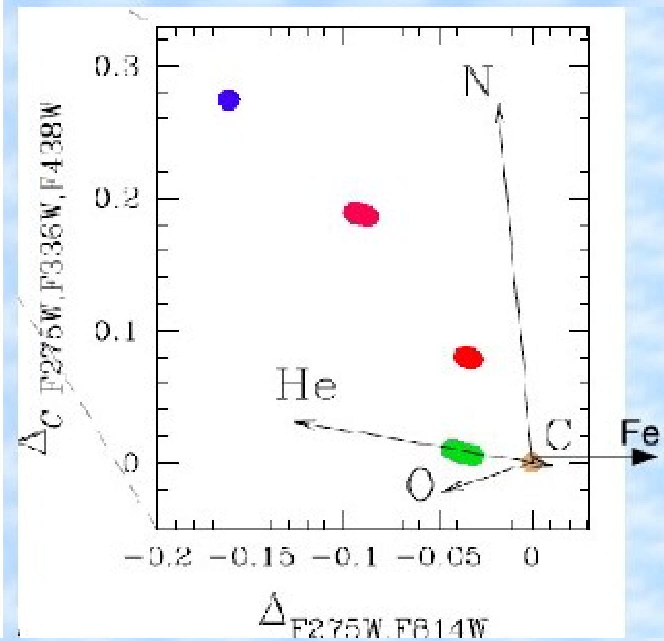
No extra Supernova products in 2G stars!



Courtesy of Tonino Milone

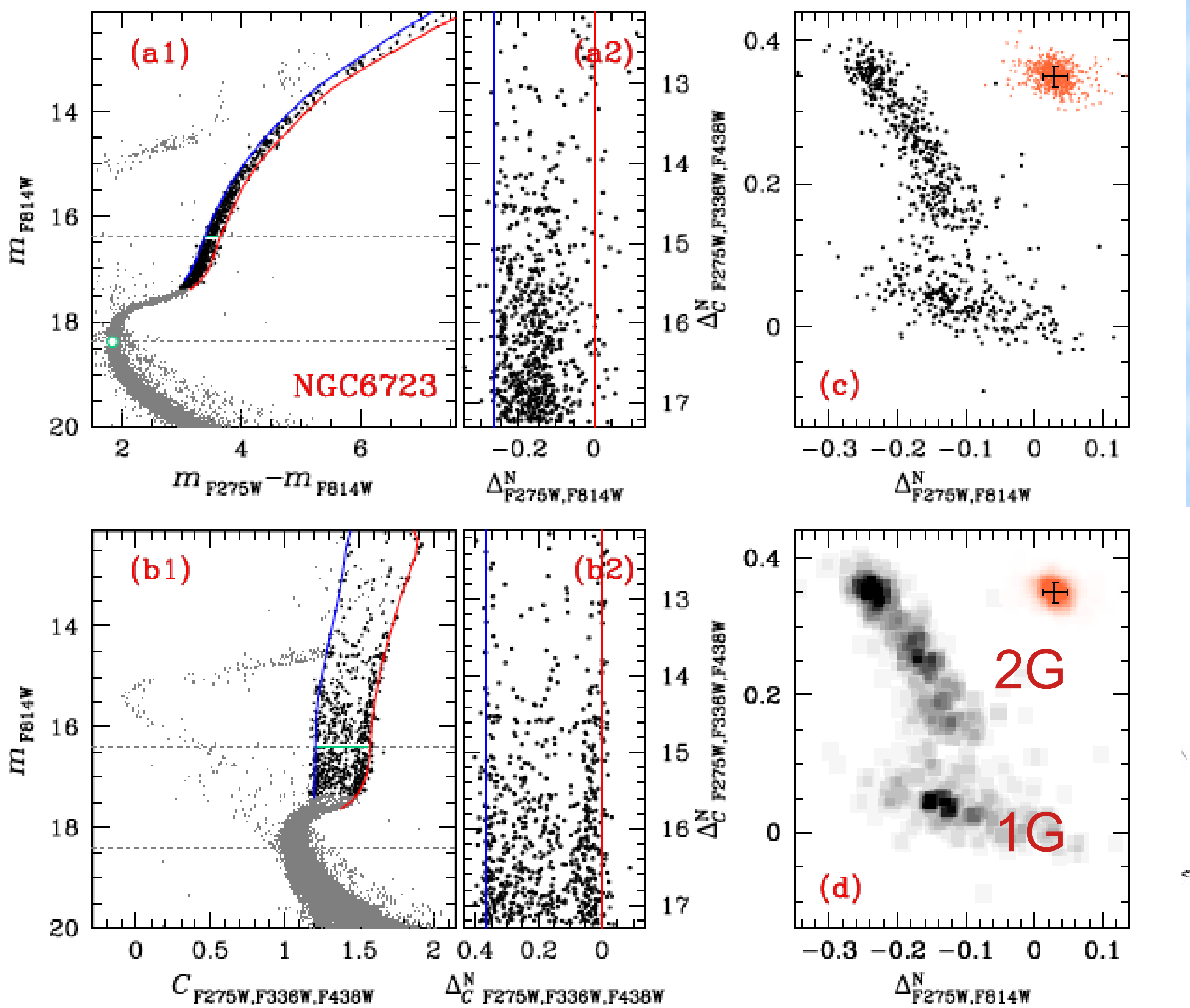
2G stars are enriched in Nitrogen, Helium, and Sodium and depleted in Carbon and Oxygen

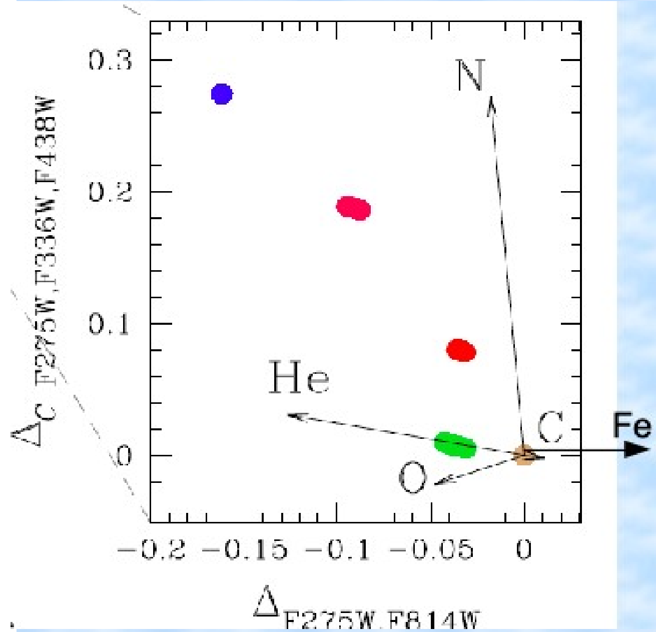
Molecular bands of NH, OH, CN, CH, and H_2O tell the difference

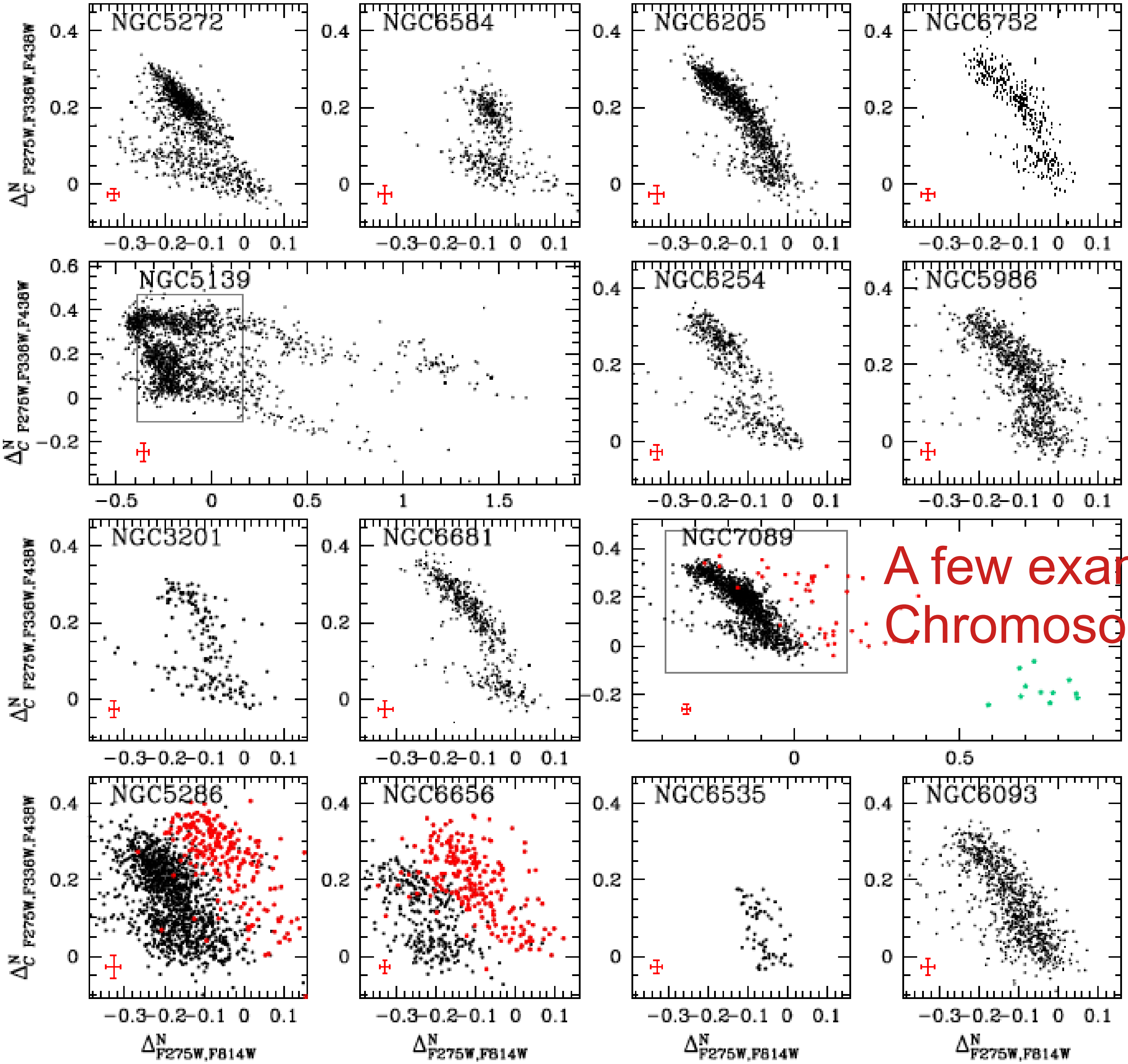


“Chromosome Maps” of this kind now exists for 57 GCs

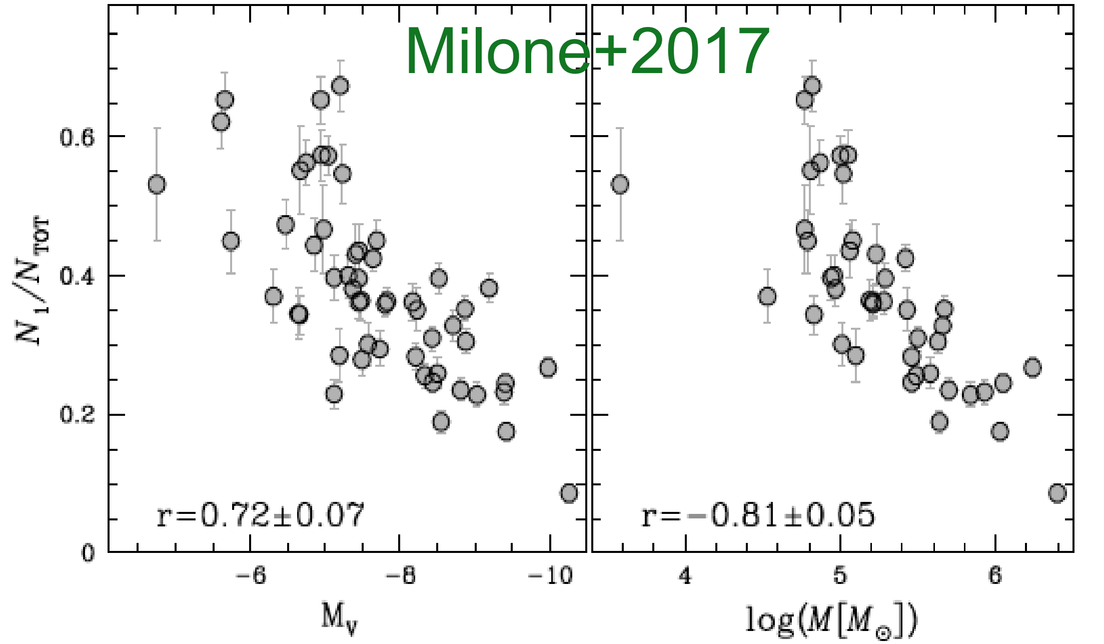
Piotto et al. 2015
Milone et al. 2017





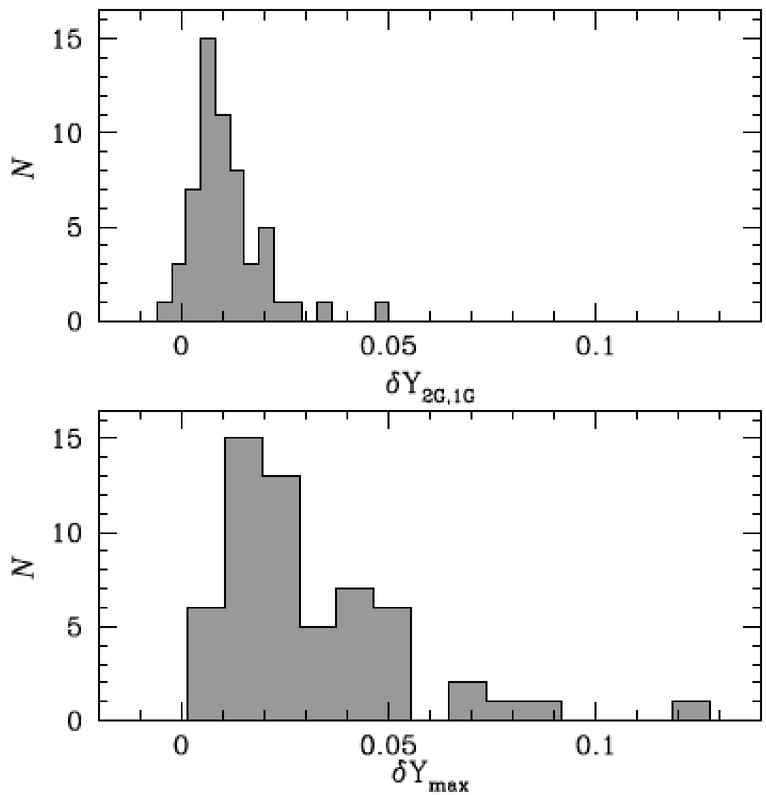


A few examples of Chromosome Maps



Most Massive GCs are 2G dominated
(2G ~ 80% of the cluster)

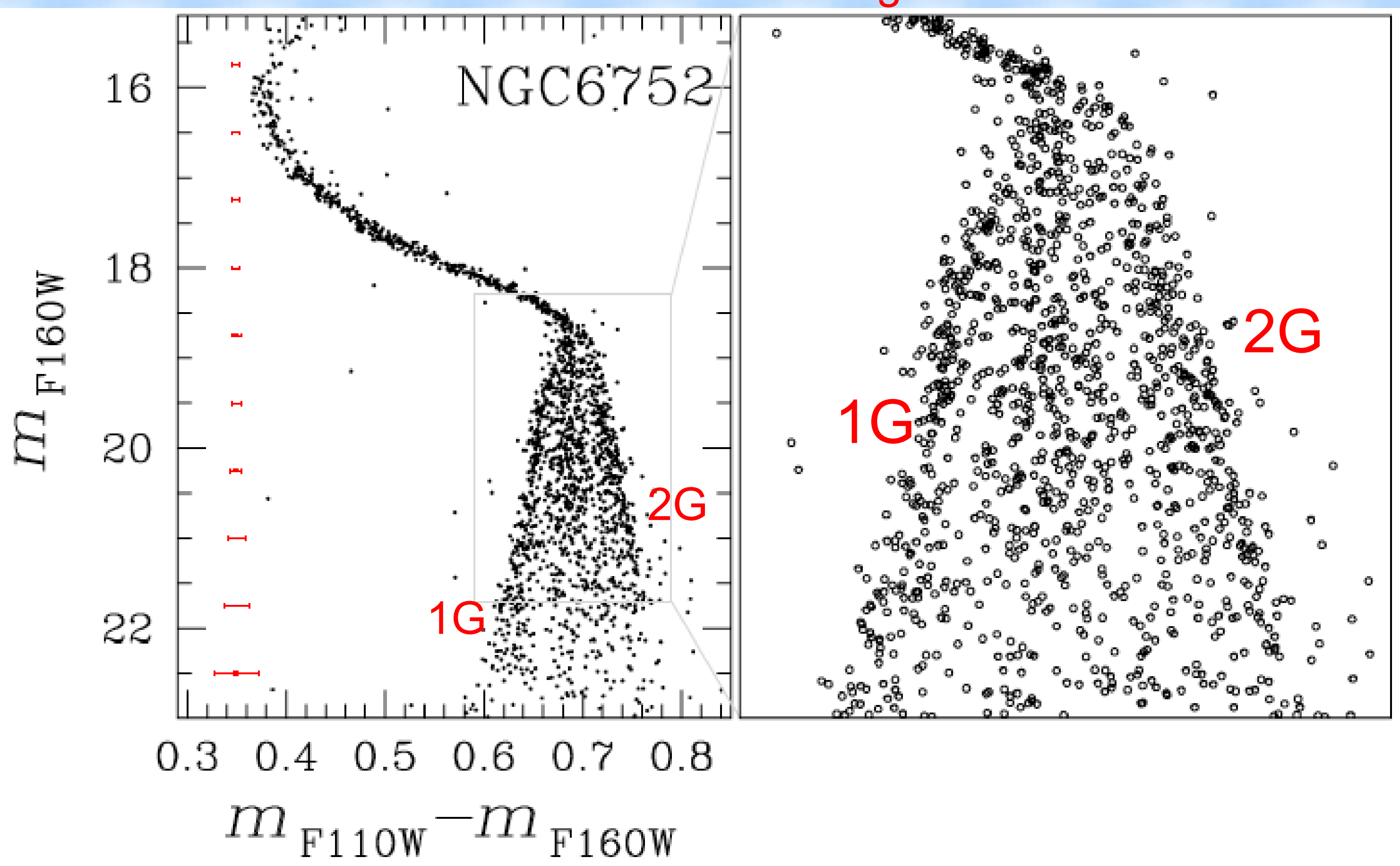
Even less massive GCs are ~50% 2G



Helium enrichment in 2G stars typically small (δY ~ 0.02)
but in extreme cases it can be very high (δY ~ 0.1)
(Milone+2018)

Multiple Pop.s exist down to the bottom of the Main Sequence

Dondoglio+2022

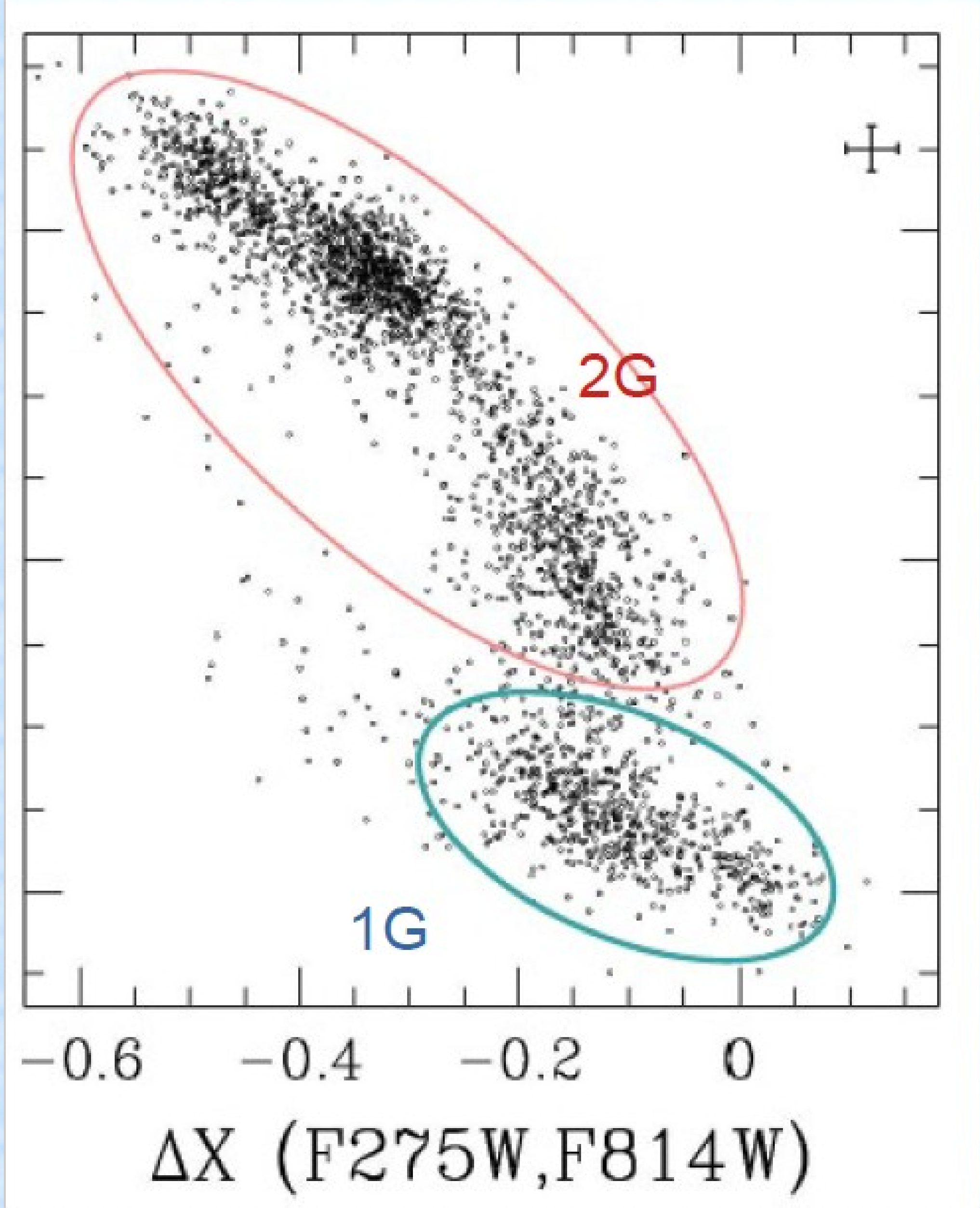


Strong Water Vapor blanketing in the F160W band:

2G stars are redder in F110W-F160W because they are oxygen depleted. Hence brighter in F160W (less water)

1G stars are bluer, because they are oxygen rich, so fainter in F160W (more water)

How to read the Chromosome Map



- The formation of the first generation did not prevent the formation of second generations

  → There was no Negative Feedback!

- Stars kept forming out of gas with varying composition, but without supernova products

  → No Feedback, No SN products

- No supernovae during 2G formation!

Making multiple generations was

PREDOMINANT AND UNAVOIDABLE!

ie. it was not the result of special conditions

If formation was completed before SNe begun to explode, this leaves only massive (binary, de Mink+2009) stars as those making the material for the 2G stars

The evidence is that GCs kept forming stars as in a Runway Process, difficult to stop once started, and with star formation efficiency close to unity, as expected for an *Overcooling* event

In absence of Feedback, processed gas from the surroundings kept flowing in, feeding the nascent GC to form its 2Gs

White & Rees 1978

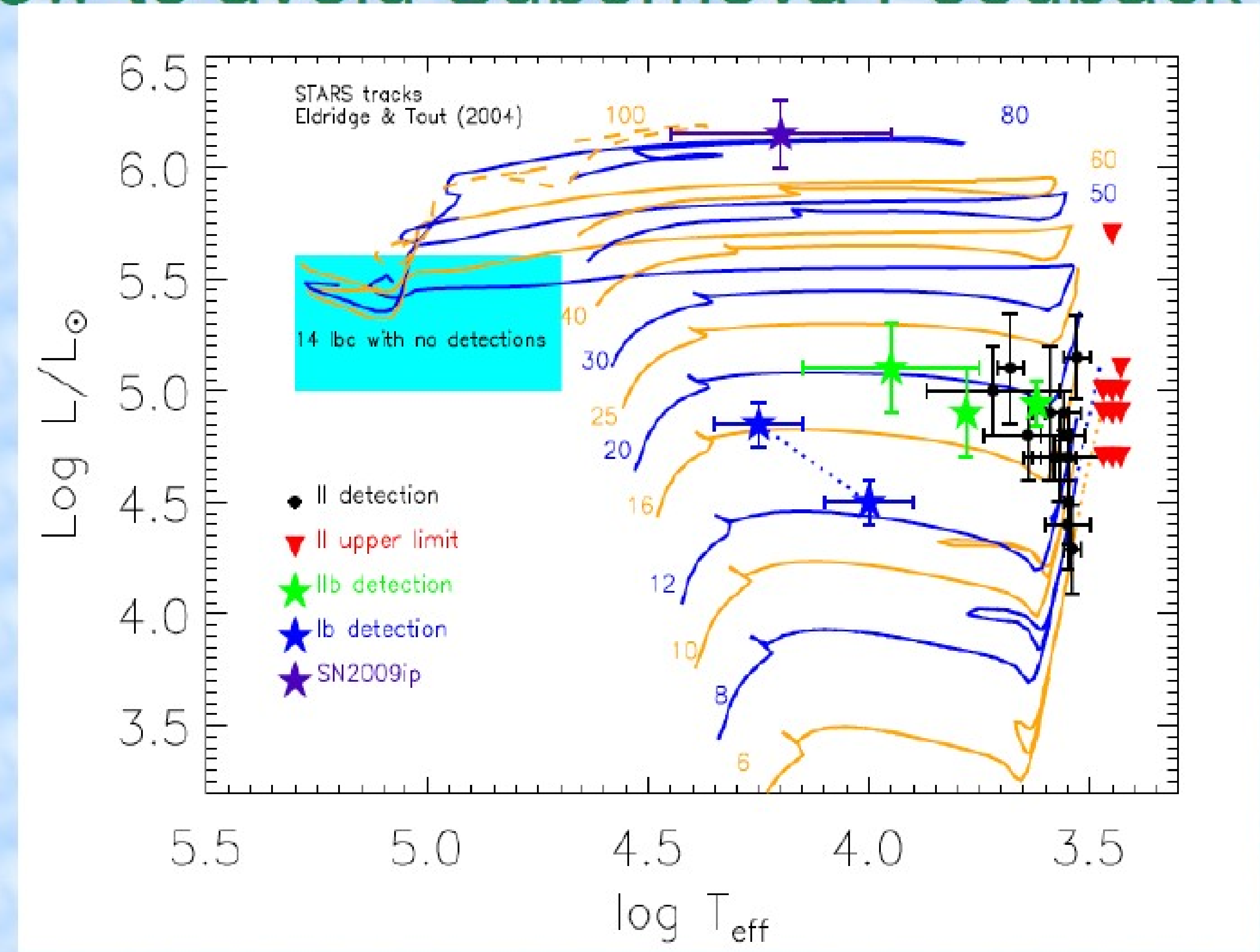
How to avoid Supernova Feedback and Supernova products

In our 2022 paper we endorse the assumption according to which, above a certain mass (~20 $M_\odot$), stars don't explode but at core collapse silently sink into a black hole, without ejecting metals (Krause+2013) and kinetic energy. (!)

Independent supporting arguments in Smartt 2015; Li+2023; Sukhbold+2016; Adams+2017; Eldridge & Stanway 2022, ARAA

If so, supernova feedback is delayd ~10 Myr after a burst of star formation!

How to avoid Supernova Feedback & products



Smartt 2015: no SN precursor more massive than ~18 $M_\odot$

Limong & Chieffi 2018
Recommend no SNe above ~25$M_\odot$

Independent supporting arguments in Smartt 2015; Li+2023; Sukhbold+2016; Adams+2017; Eldridge & Stanway 2022, ARAA

If so, supernova feedback is delayd ~10 Myr after a burst of star formation!

What if this is the “right” Scenario of GC formation?

- A 10 Myr Delayed FEEDBAK/transient overcooling

- will facilitate local burstiness in star formation

- may facilitate the formation of giant clumps

- may help to form extreme baryon Concentrations... such as early seeds to form SMBH (?)

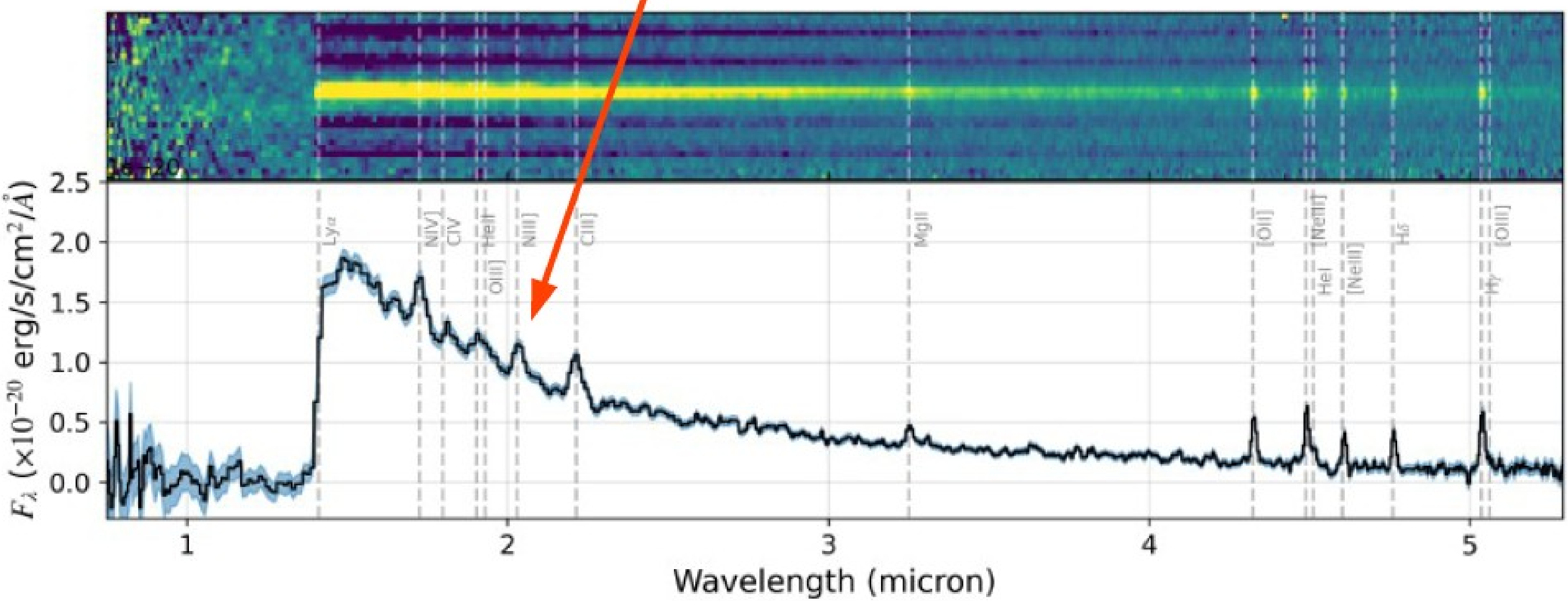
- It could help making the massive galaxies at z=9-16 detected by JWST (e.g. Finkelstein+2023) and the

- Oversized SMBHs @ z=4-7 (Maiolino+2023; Pacucci+2024)

The NIRSpec spectrum of GN-z11 at z=10.6 (Bunker at al. 2023)

Strong NIII] line, weak OIII] line
Indicative of supersolar N/O ratio

As expected for the ISM of a GC while forming its 2G stars (see also Senchyna+2023, Belokurov & Kravtsov 2023).



The NIRSpec spectrum of GN-z11 at z=10.6 (Bunker at al. 2023)

But the emission may be dominated by the BLR of an AGN (Maiolino+2023)

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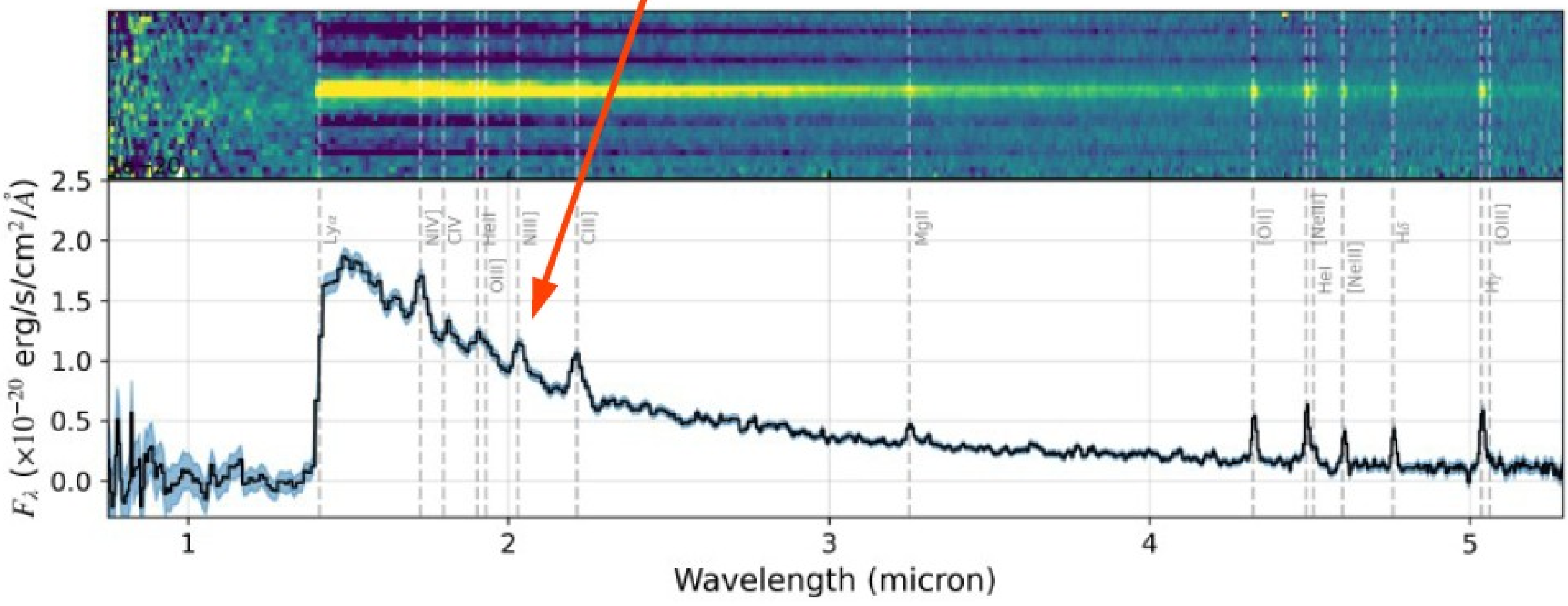
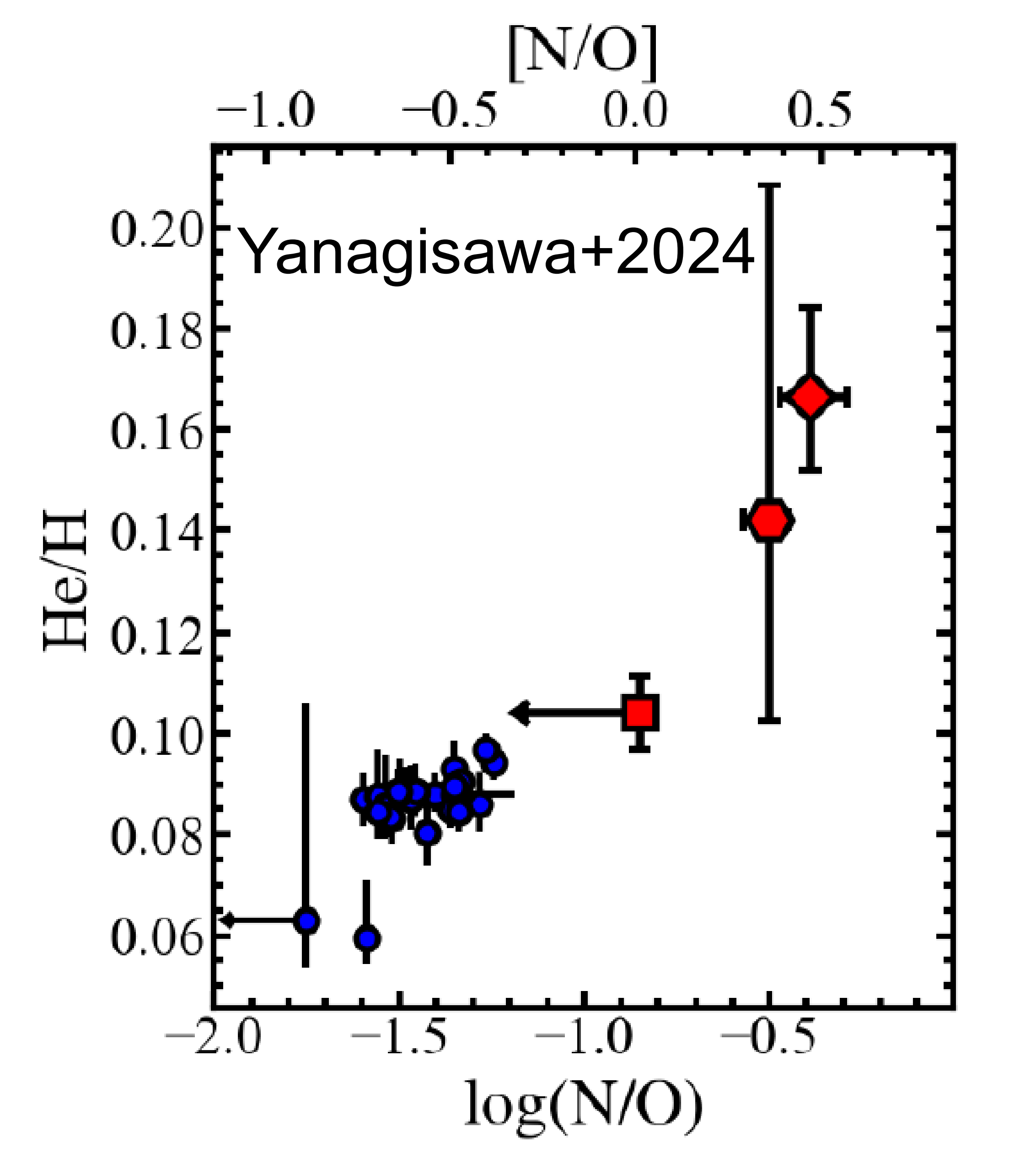


More evidence of a connection with globular cluster formation in high-z galaxies



High Helium and Nitrogen in three star-forming galaxies at z~6, just the typical composition of second generation stars in globular clusters!

Wrap Up

- The ubiquity of the multiple generation phenomenon in Globular Clusters argues for their formation having taken place as an extended (~10 Myr) feedback-free event (*transient overcooling*)

- Overcooling may result from massive stars (>~20 $M_{\odot}$) failing to end with a supernova explosion but silently sink into black holes.

- May this help accounting for the excess of UV-bright galaxies at z=9-16?

- And help making SMBHs at z>4?

GCs: A key that may help opening many doors


Thank You!

Some Caveats

- With no massive supernovae the chemical yield is reduced by a factor ~2
- In some high-z dwarfs light/mass is dominated by the young clusters (I would prefer the opposite)
- Do massive binaries deliver the right chemicals to make 2G stars?