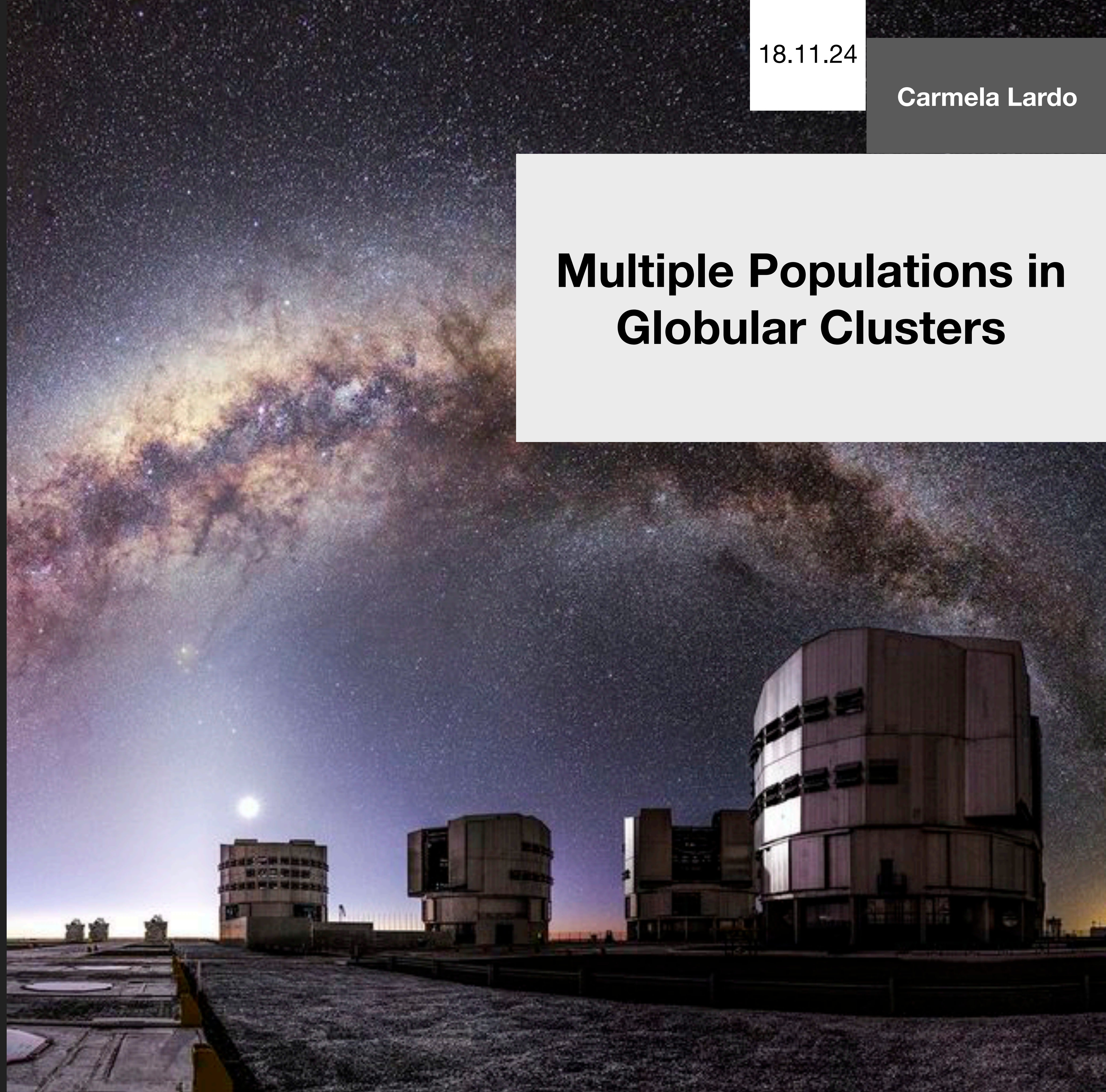
IAUS 395: STELLAR POPULATIONS IN THE MILKY WAY AND BEYOND

A celebration of Beatriz Barbuy' s career in astronomy

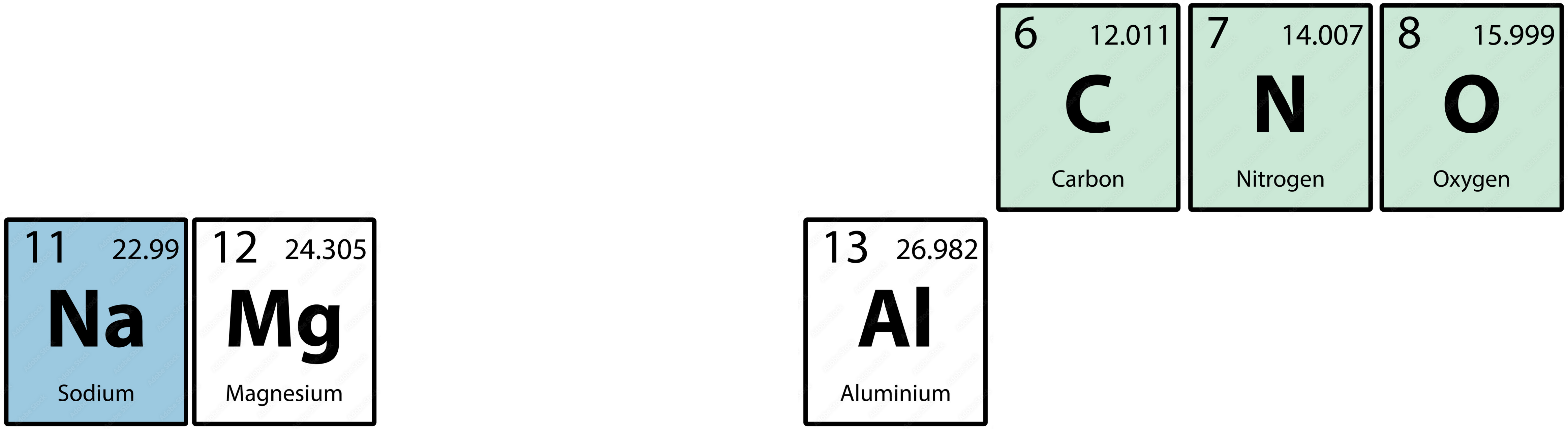


18.11.24

Carmela Lardo

Multiple Populations in Globular Clusters

GCs are not simple stellar populations



MPs are groups of stars born with **different chemical compositions**, but very **similar ages**.

Light element variations

6 12.011 **C** Carbon

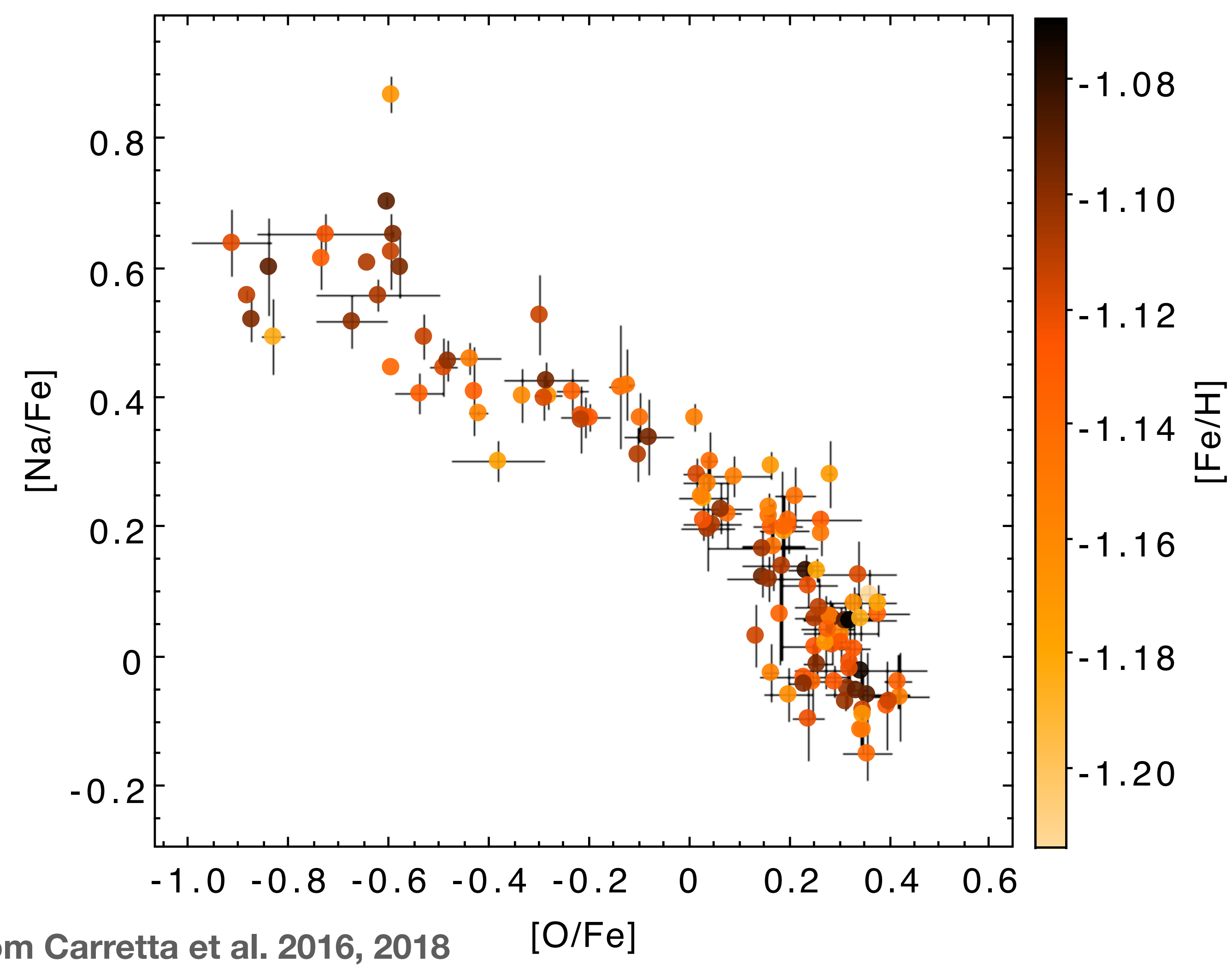
7 14.007 **N** Nitrogen

8 15.999 **O** Oxygen

11 22.99 **Na** Sodium

12 24.305 **Mg** Magnesium

13 26.982 **Al** Aluminium



Adapted from Carretta et al. 2016, 2018

First Population

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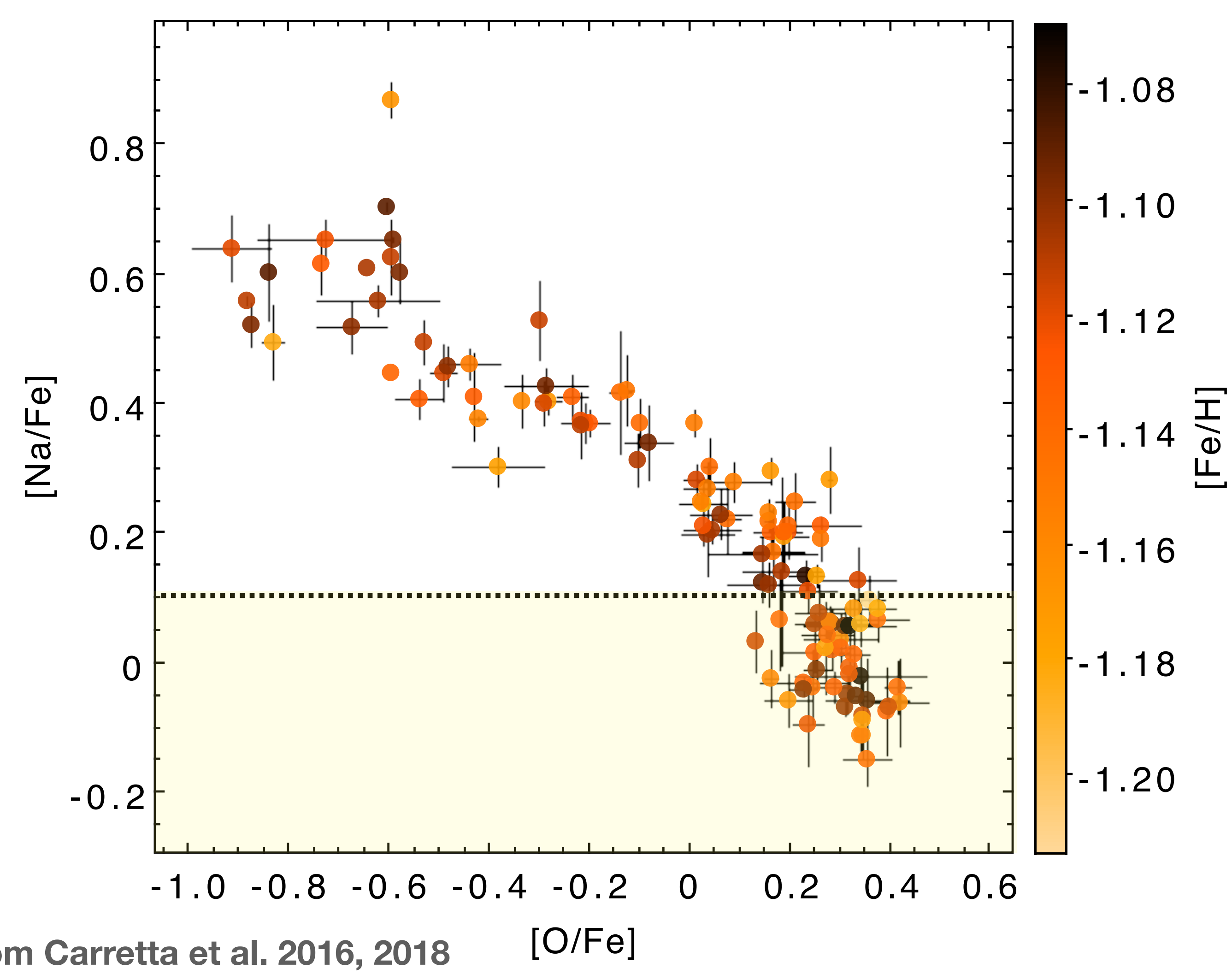


Adapted from Carretta et al. 2016, 2018

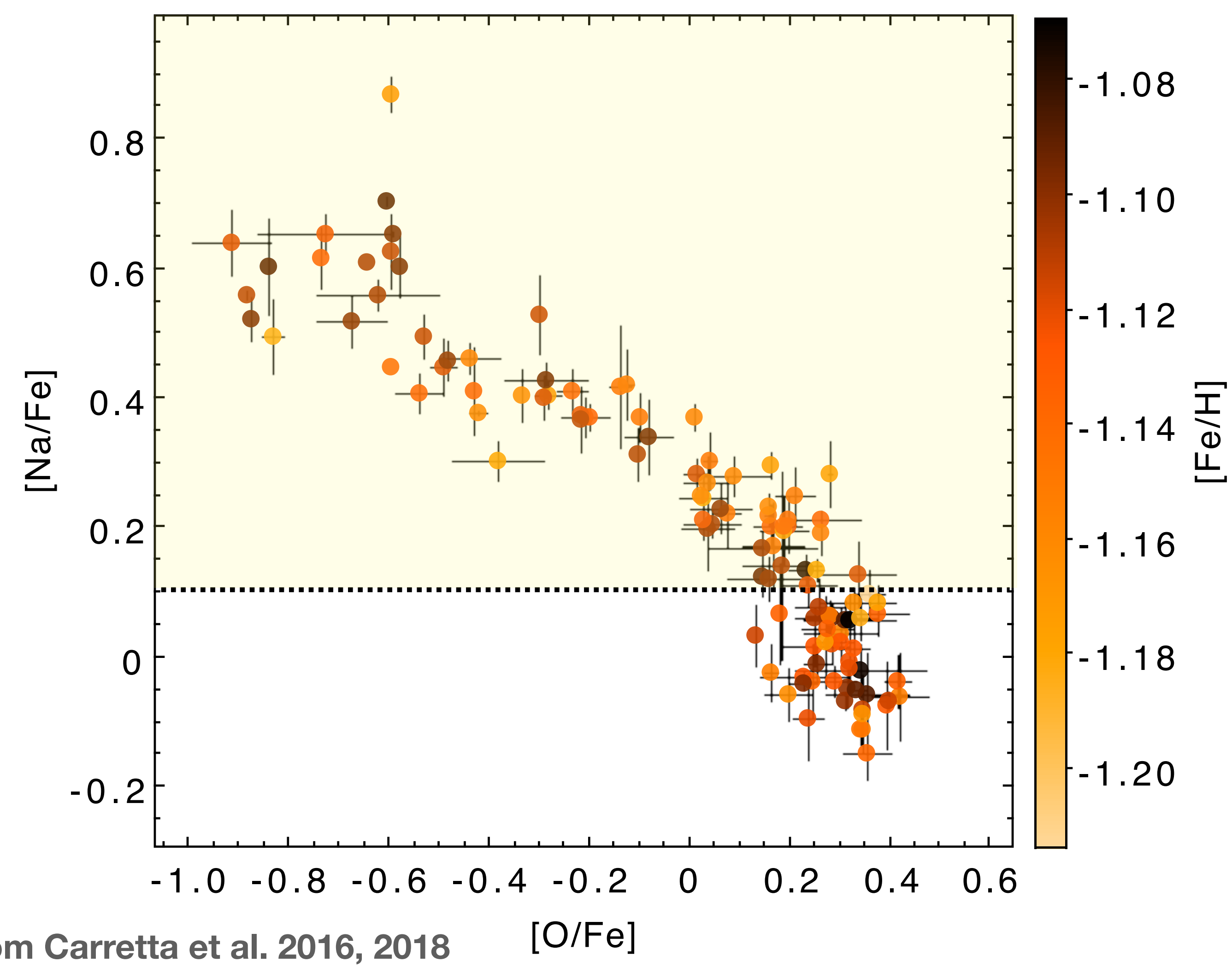
FIRST POPULATION

stars with field-like light-element abundances

Second Population

6 12.011 **C** Carbon	7 14.007 **N** Nitrogen	8 15.999 **O** Oxygen

11 22.99 **Na** Sodium	12 24.305 **Mg** Magnesium	13 26.982 **Al** Aluminium



Adapted from Carretta et al. 2016, 2018

SECOND POPULATION

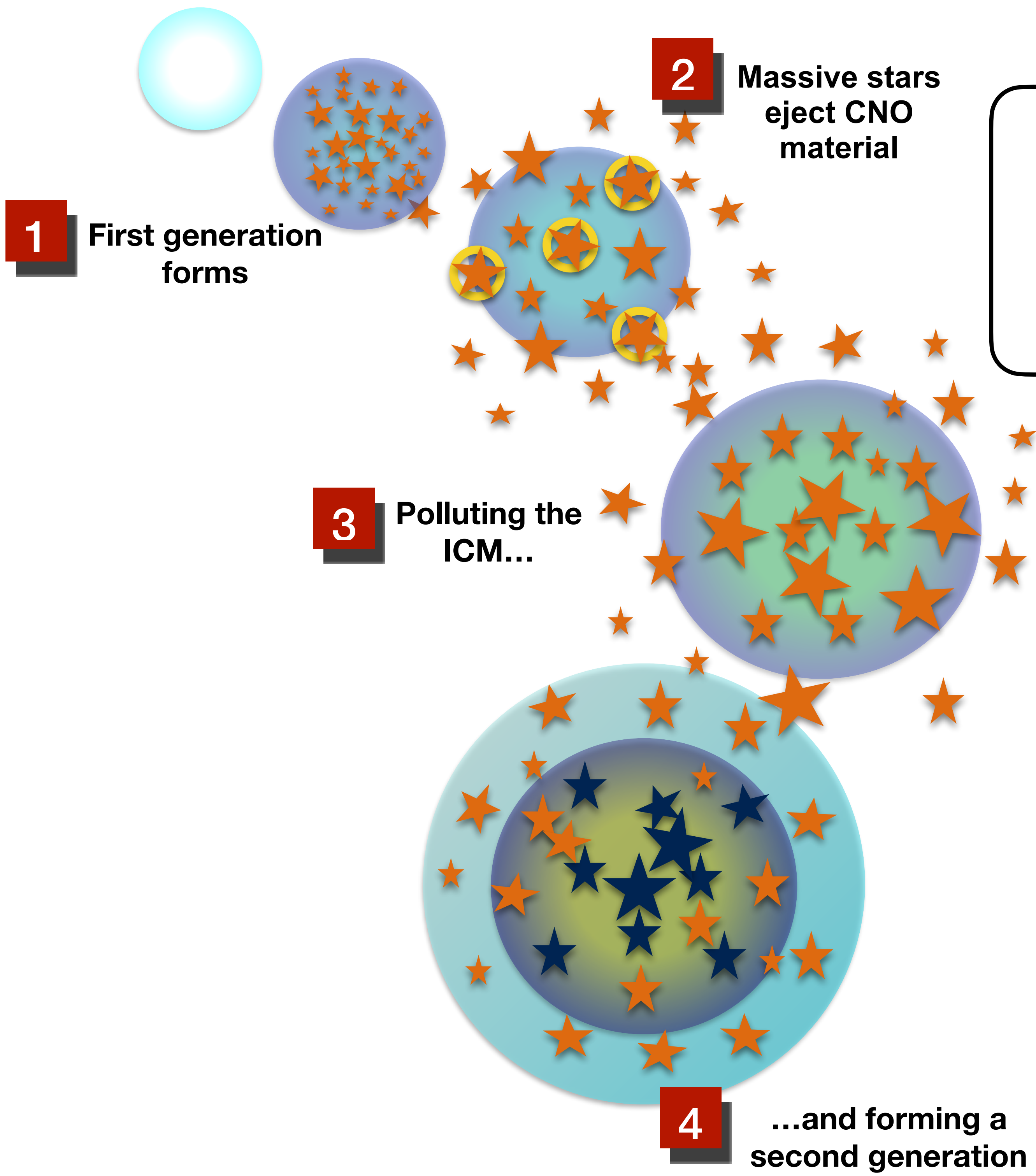
stars with:

- enhanced N, Na, Al
- depleted C, O, Mg

FIRST POPULATION

stars with field-like light-element abundances

Hot-CNO in Massive Stars

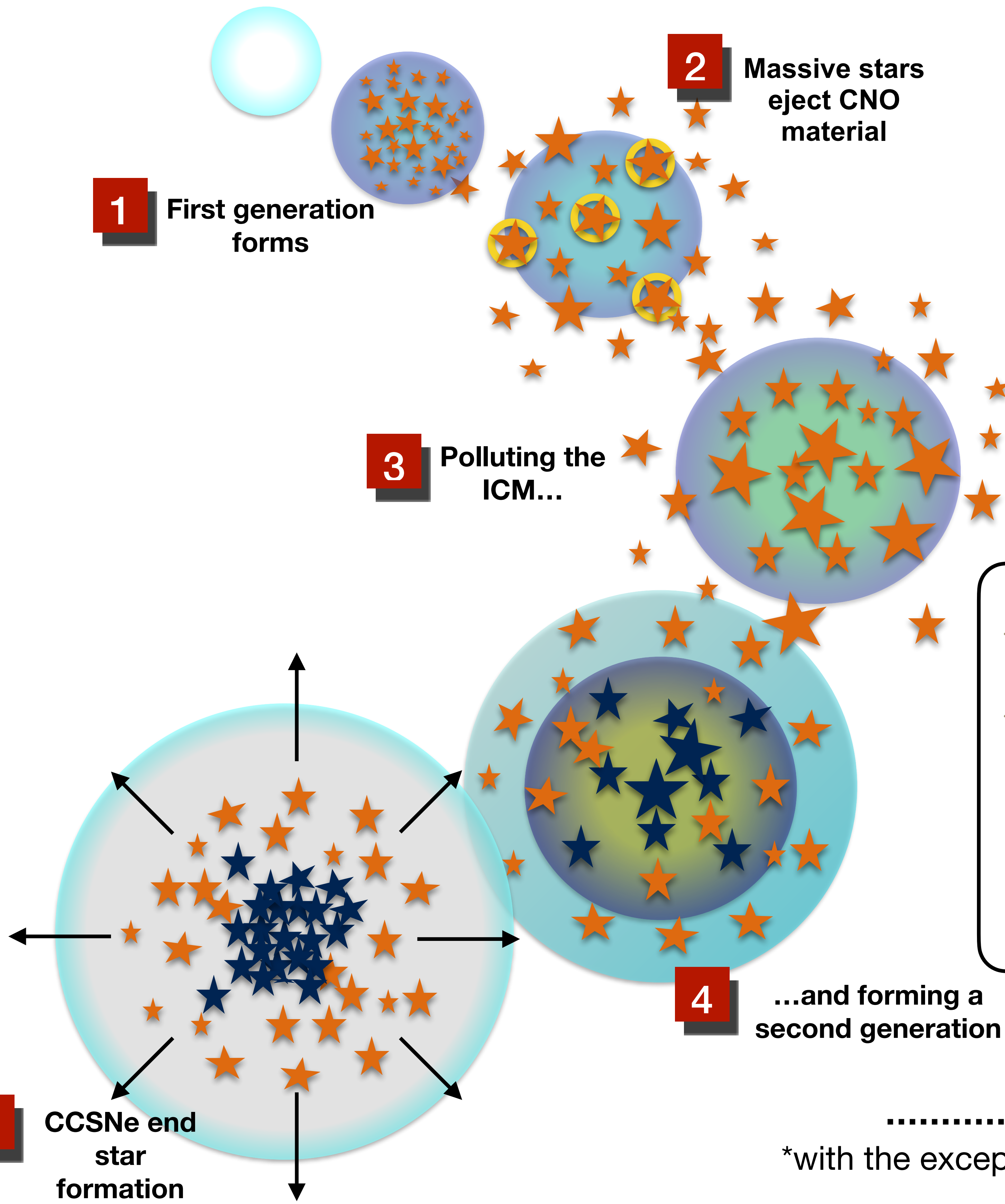


The likely origin is the **CNO cycle**, which converts H into He and includes hotter **Ne–Na** and **Mg–Al** cycles*

- AGBs$(3-8M_\odot)$
- Fast Rotating Massive Stars
- Very massive ($\sim 300M_\odot$) or supermassive ($\lesssim 5000M_\odot$) stars
- Interacting massive binaries

*T > 40MK to produce ^{23}Na and T> 70MK to deplete ^{24}Mg

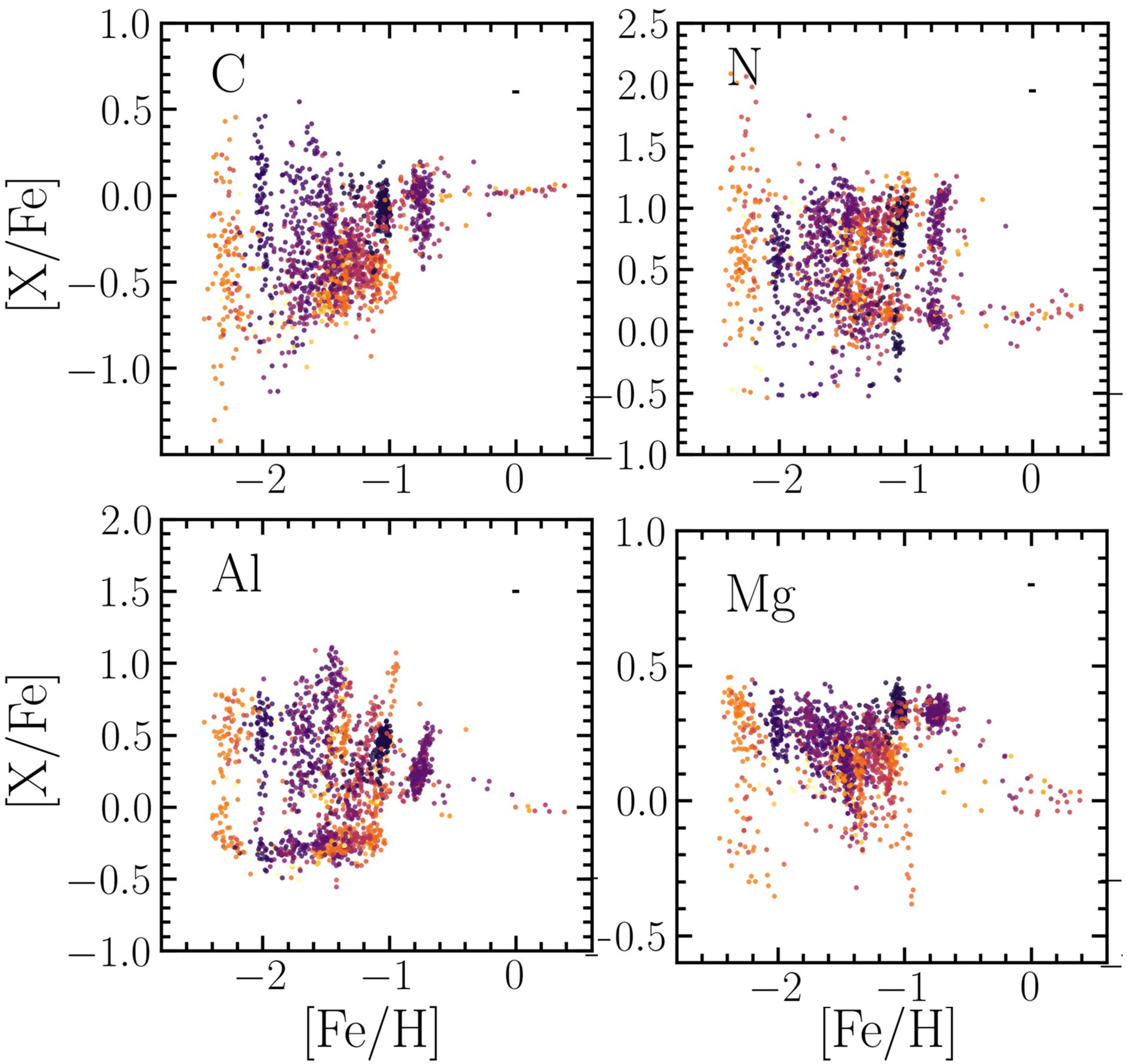
Supernova Avoidance



- GCs are generally **homogeneous in Fe**
- **P2** must **form before** the majority of **CCSNe** (supernova avoidance problem; Renzini et al. 2015)

*with the exception of a small ~0.1 dex spread in [Fe/H] in P1 stars

Spectroscopy of MPs

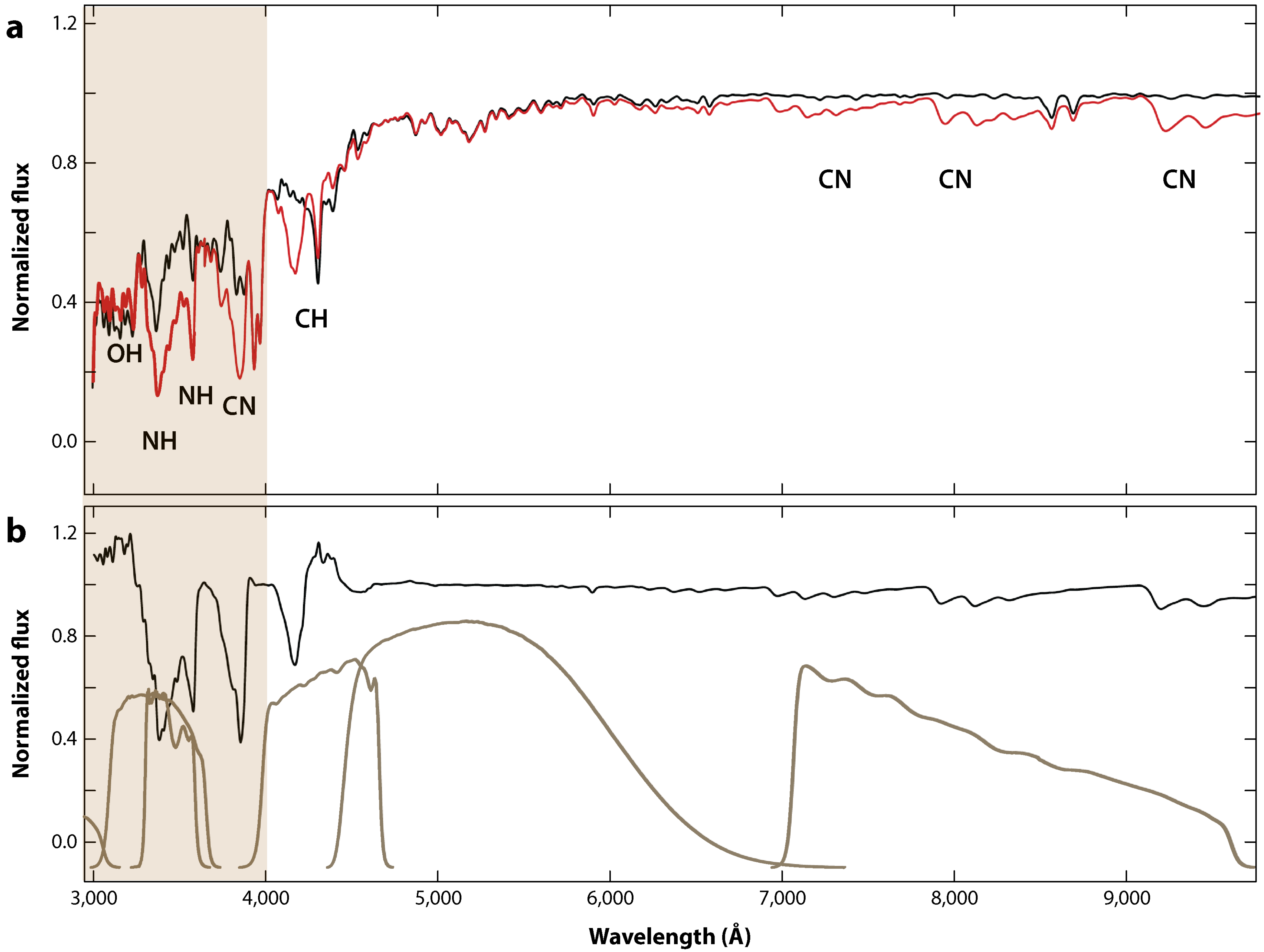


Extensive collection of **spectroscopic data** spanning high to low resolutions, with **homogeneous analyses** provided by various surveys, including:

- **APOGEE Value-Added Catalog of Galactic GC stars** (Schiavon et al. 2024)
- **Gaia-ESO survey** (Pancino et al. 2017)
- **FLAMES survey of Galactic GCs** (Carretta et al. 2009a, b and subsequent papers)

Schiavon et al. 2024

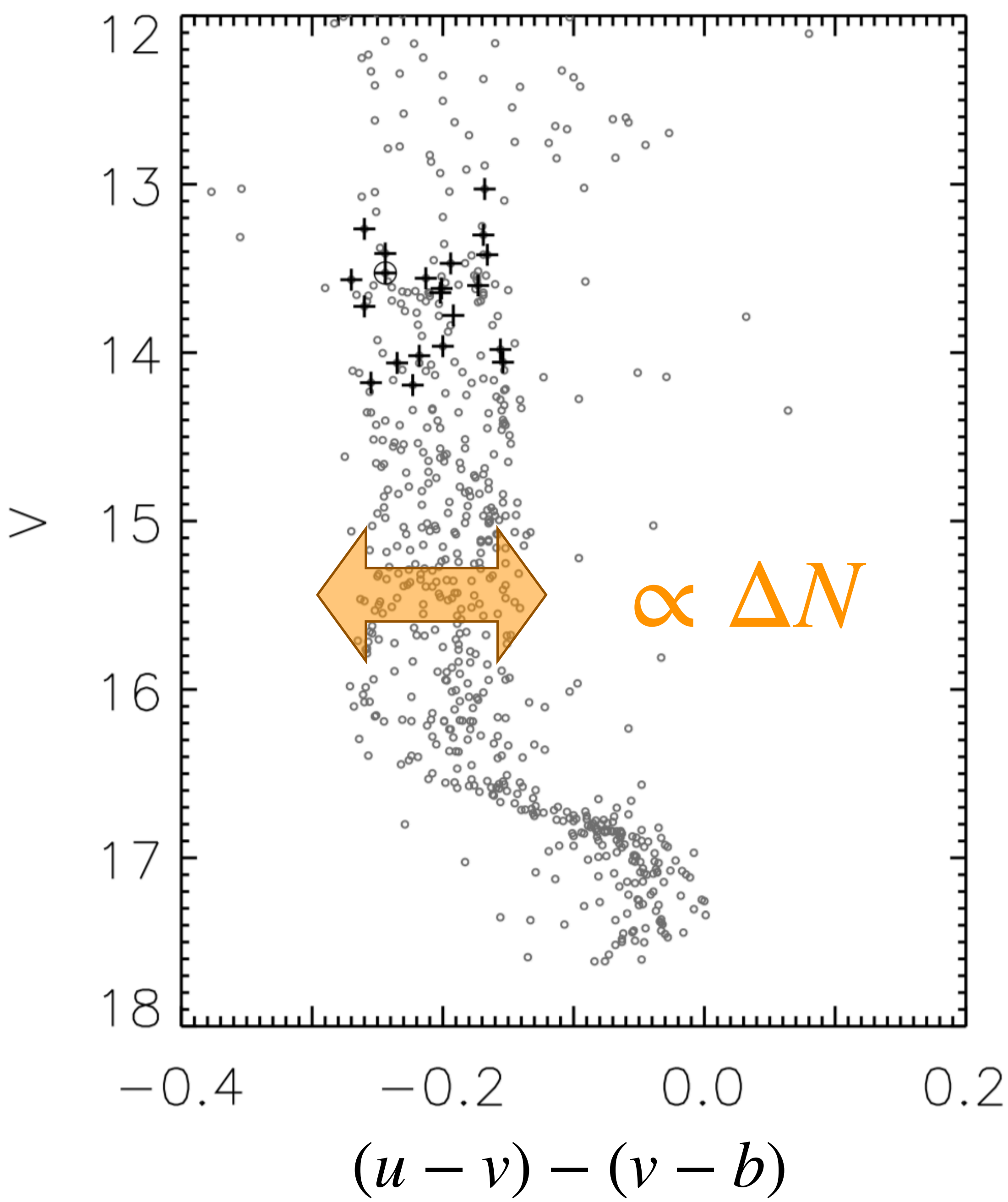
Evidence from photometry

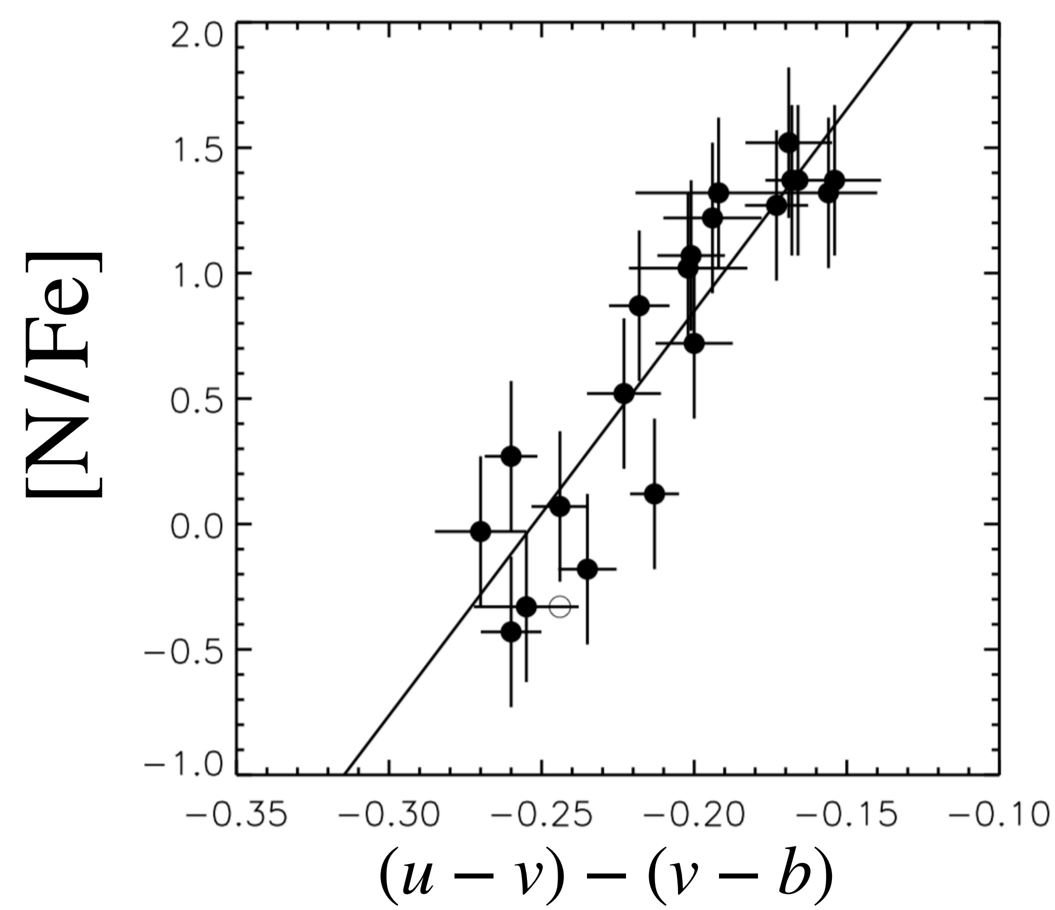


Bastian & Lardo 2018
(see also Cassisi & Salaris 2020; Sbordone et al. 2011)

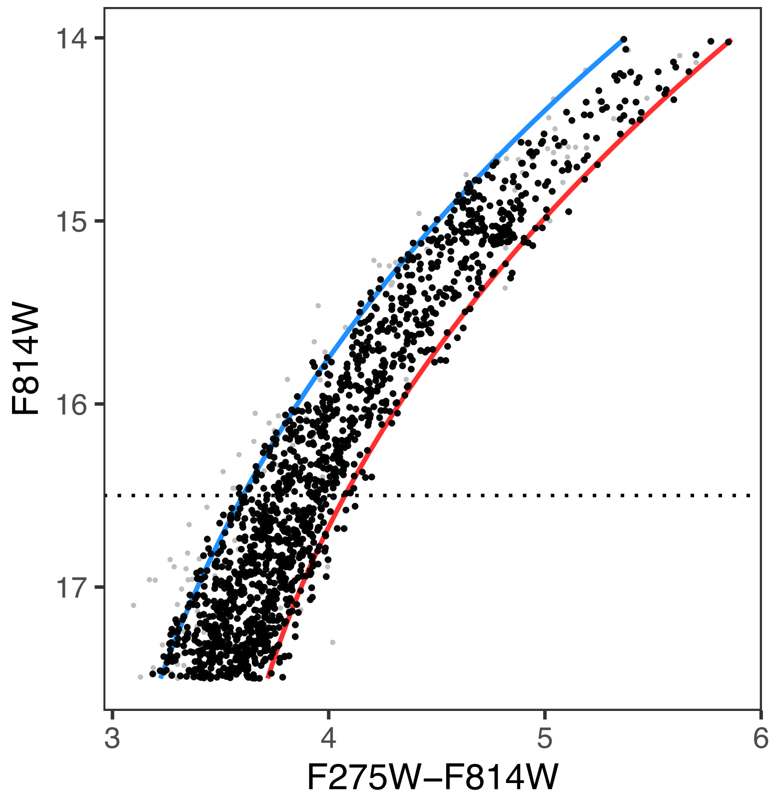
Evidence from photometry

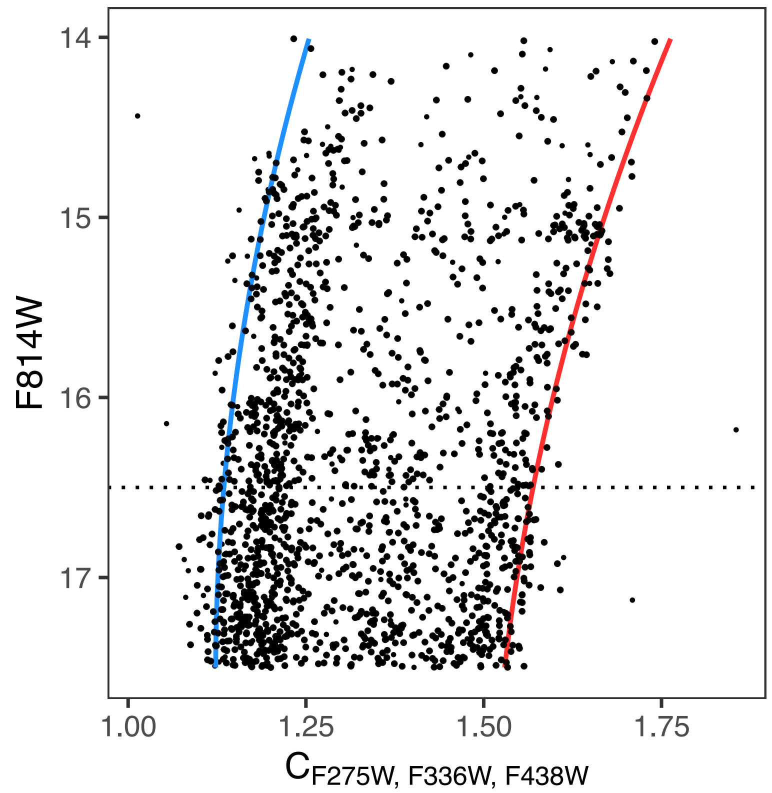
RGB photometric spreads indicate variations in N, suggesting the presence of MPs

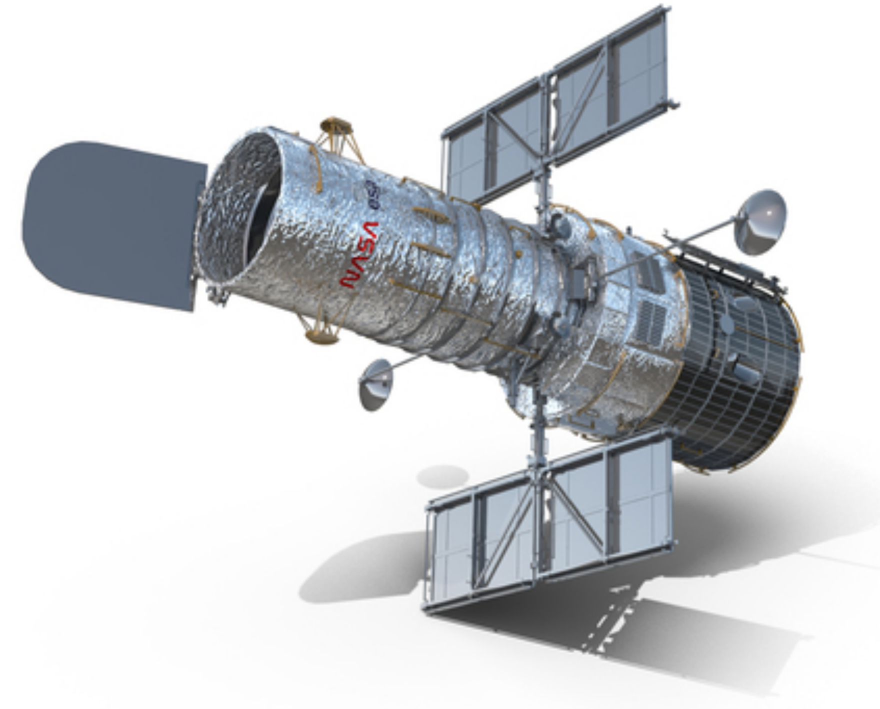




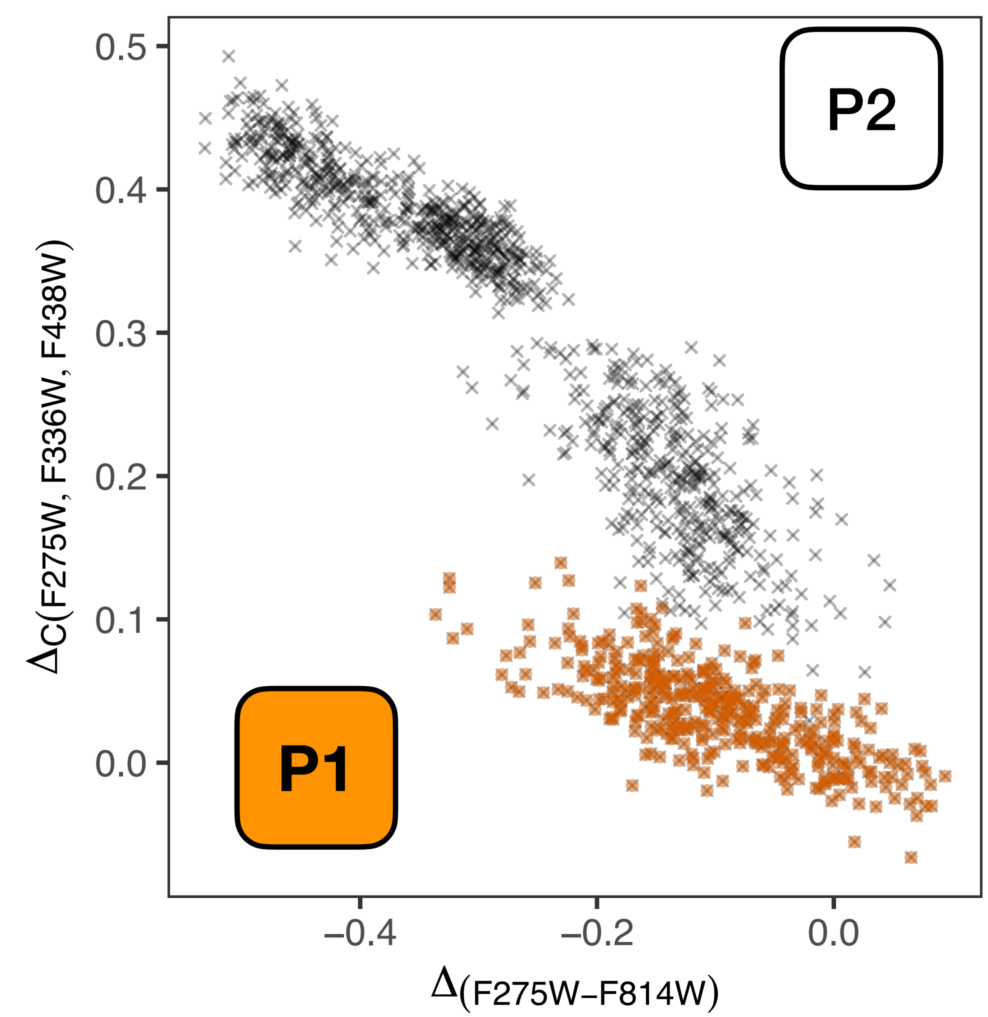
Yong et al. 2012







The Chromosome Map

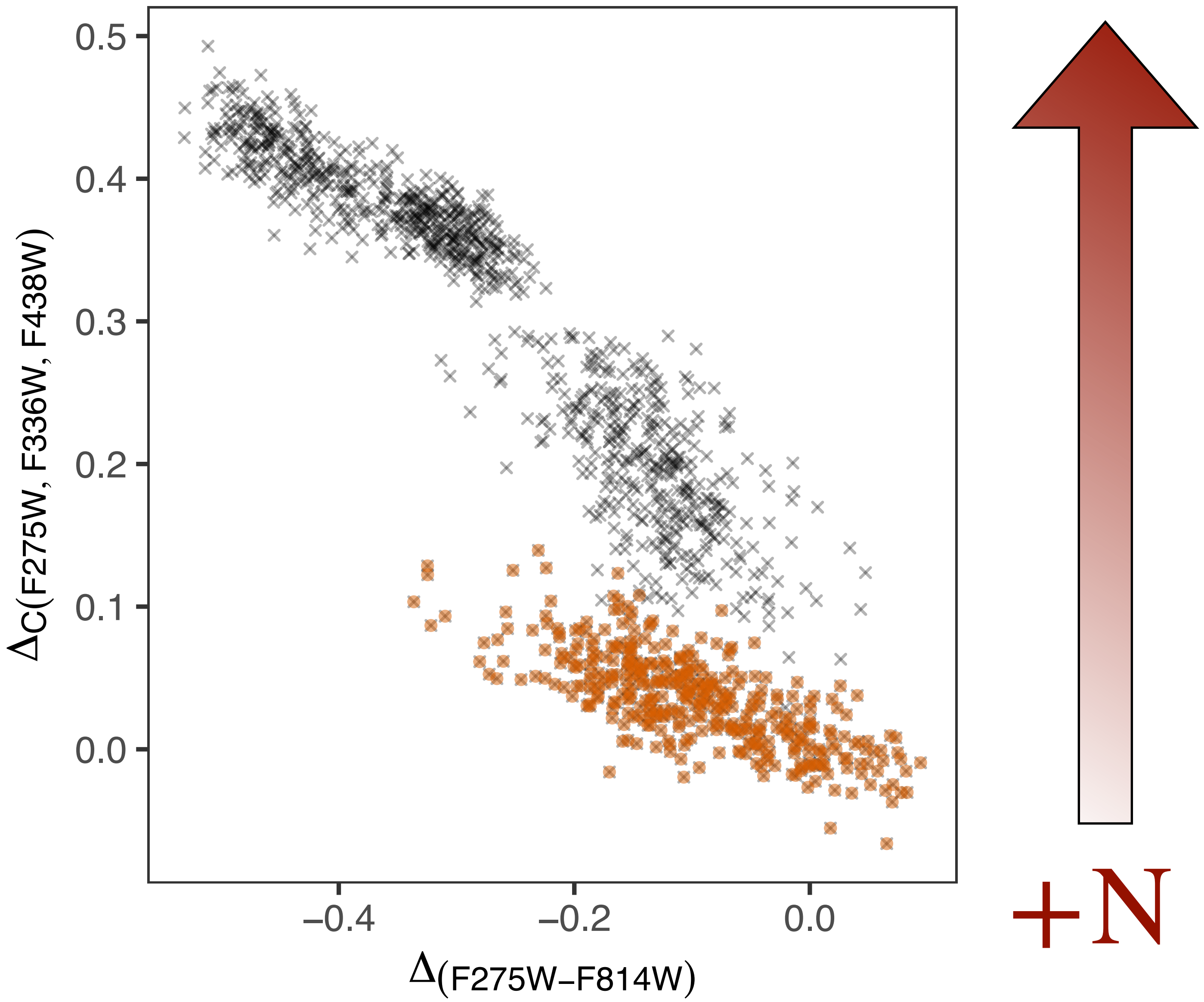


Adapted from Milone et al. 2017

"HST Legacy Survey of Galactic Globular Clusters" (PI: G. Piotto)

- F275W, F336W, F438W HST/WFP3 photometry (Piotto et al. 2015, Milone et al. 2017, Soto et al. 2017; Nardiello et al. 2018)
- F606W, F814W from HST/ACS (Sarajedini et al. 2007)

Abundance Variations: Insights from the ChMap



e.g. Milone et al. 2018, Legnardi et al. 2018, Lardo et al. 2018, Marino et al. 2019

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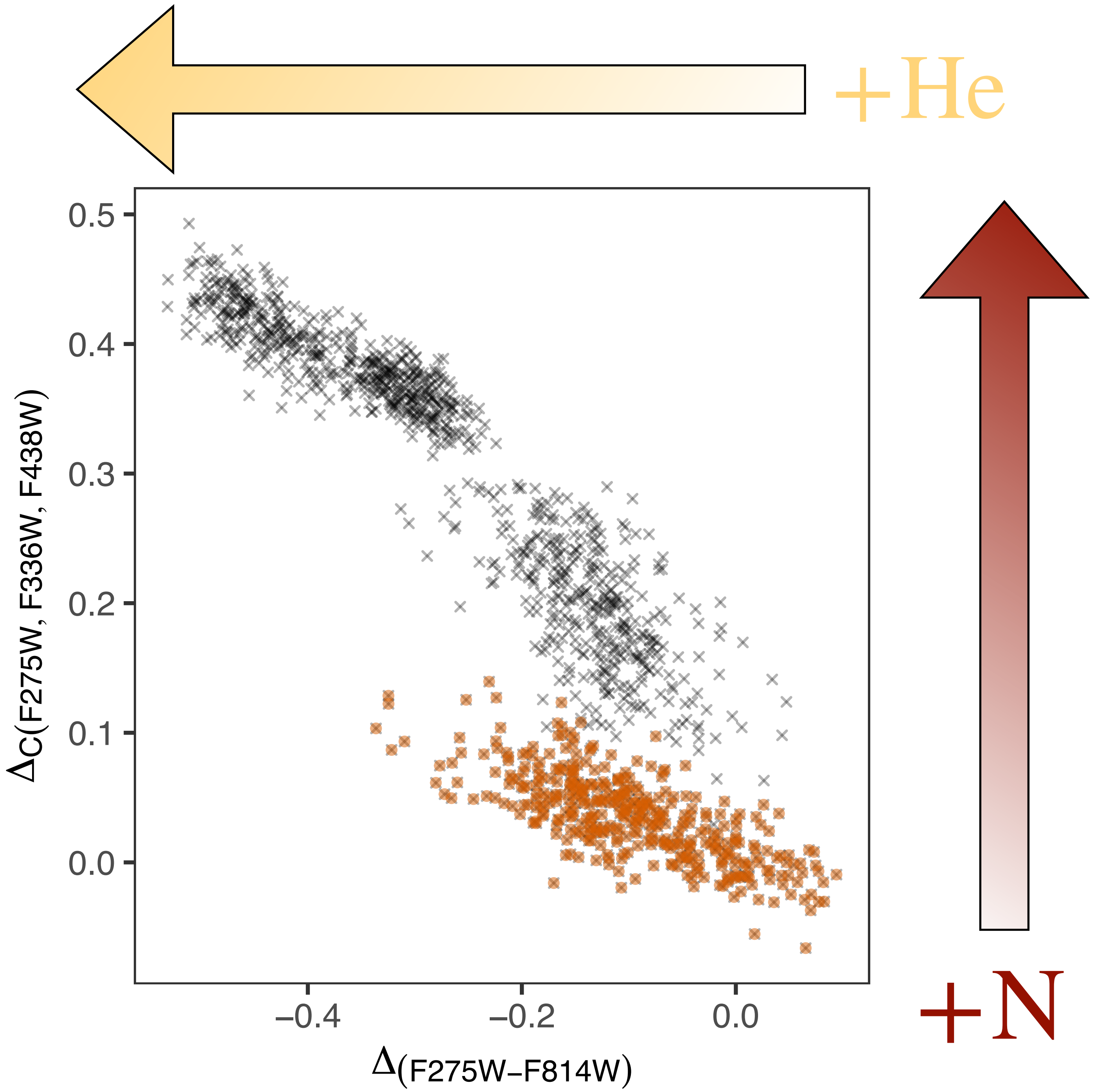

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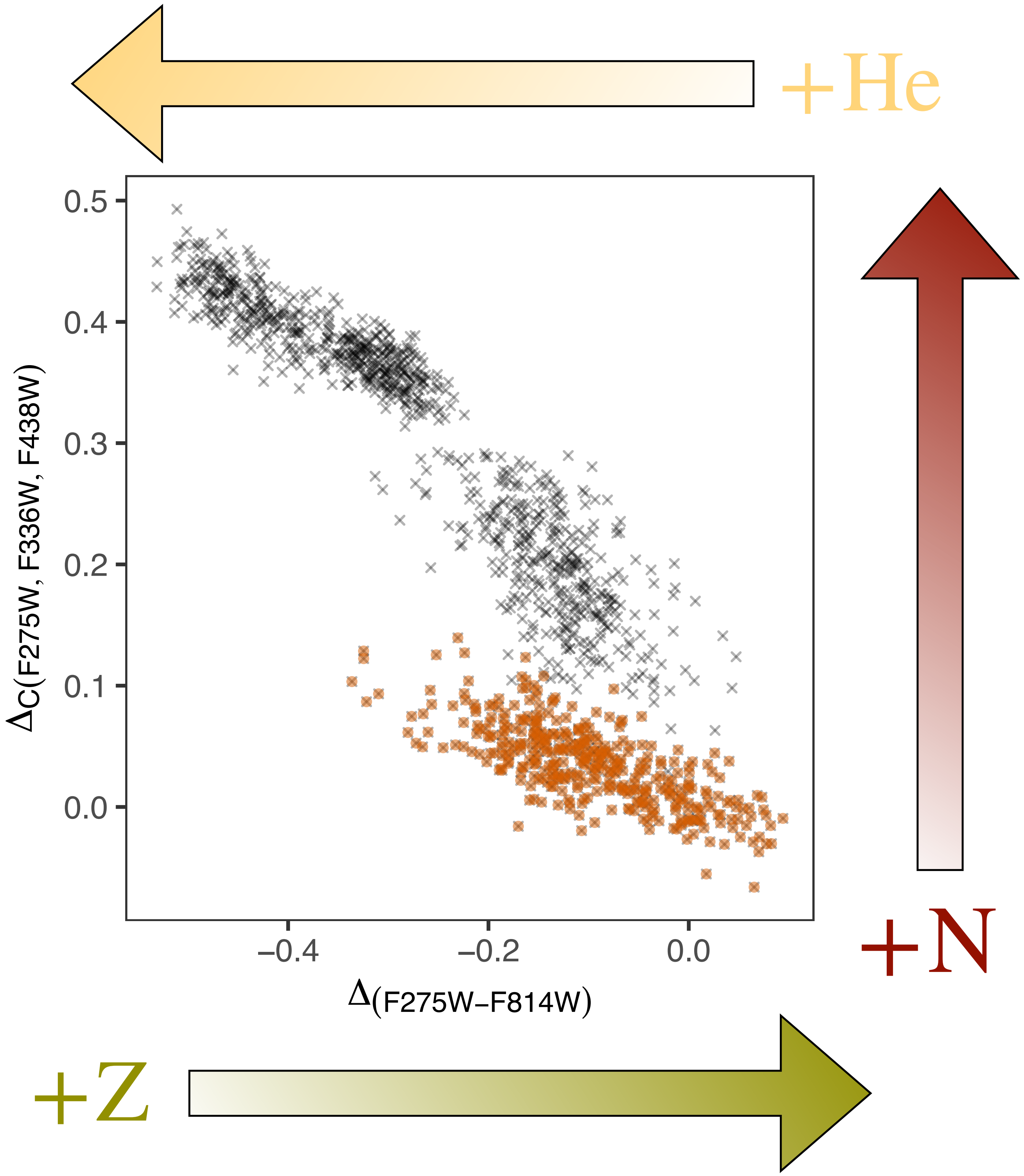
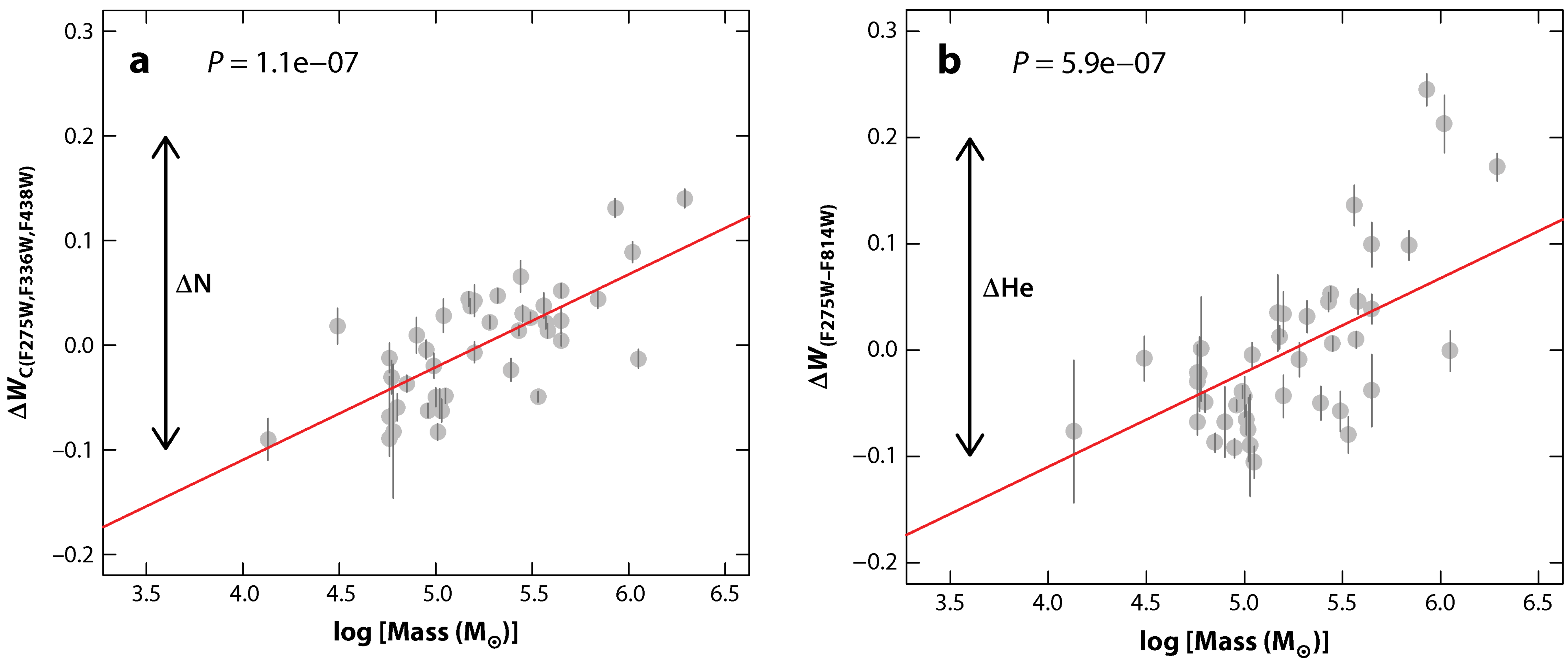


- e.g. Milone et al. 2018, Legnardi et al. 2018, Lardo et al. 2018, Marino et al. 2019

Enrichment vs. Mass

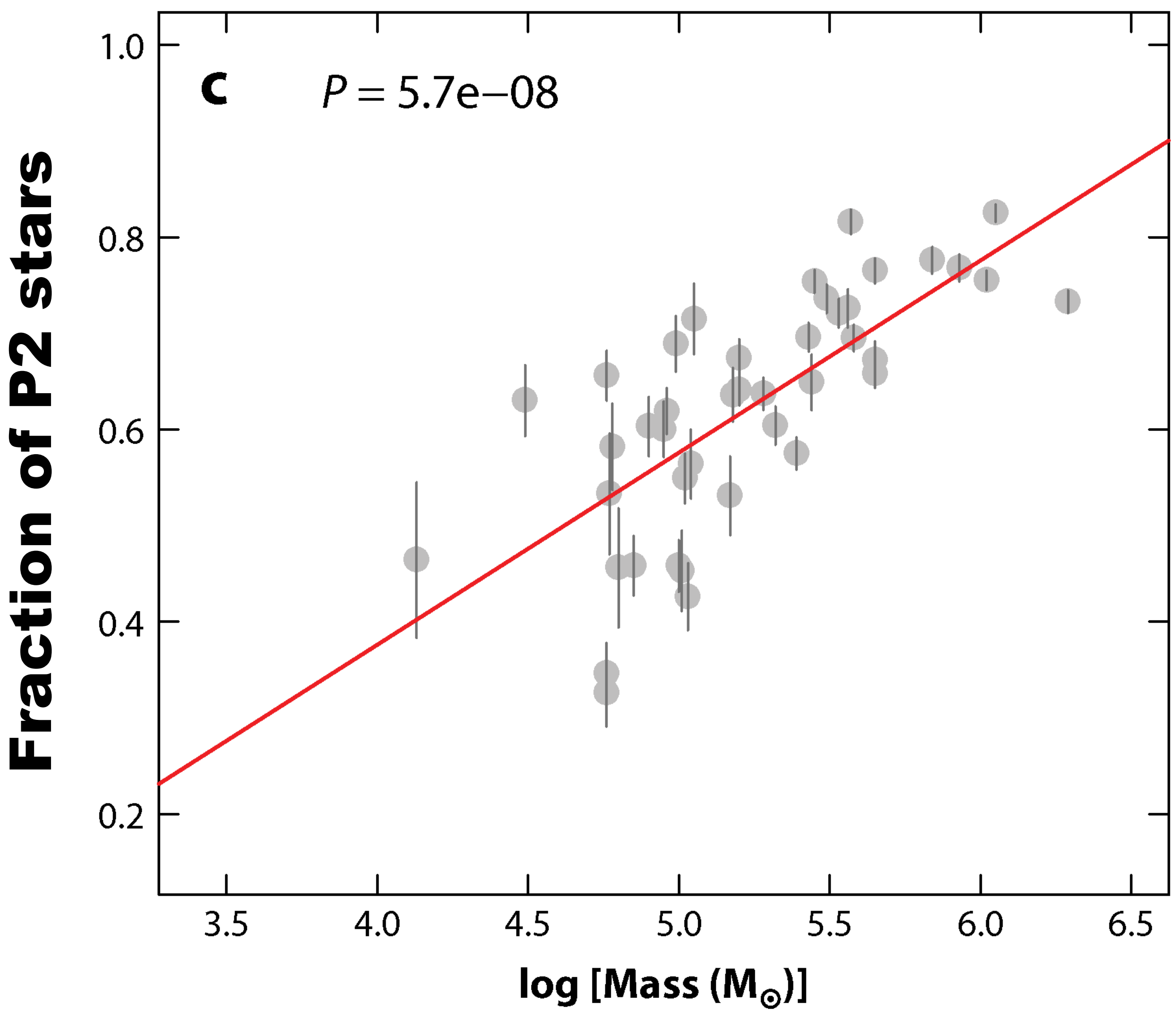
- The **level of enrichment increases with cluster mass**, with variations in N, Na, and He being larger in more massive clusters
- The mechanism responsible for the MPs should **depend on mass (or density)**



Adapted from Milone et al. 2017

P2 Fraction vs. Mass

- Similarly, **the fraction of P2 stars increases with cluster mass**, rising from about 50% in lower-mass clusters to over 80% in higher-mass clusters.

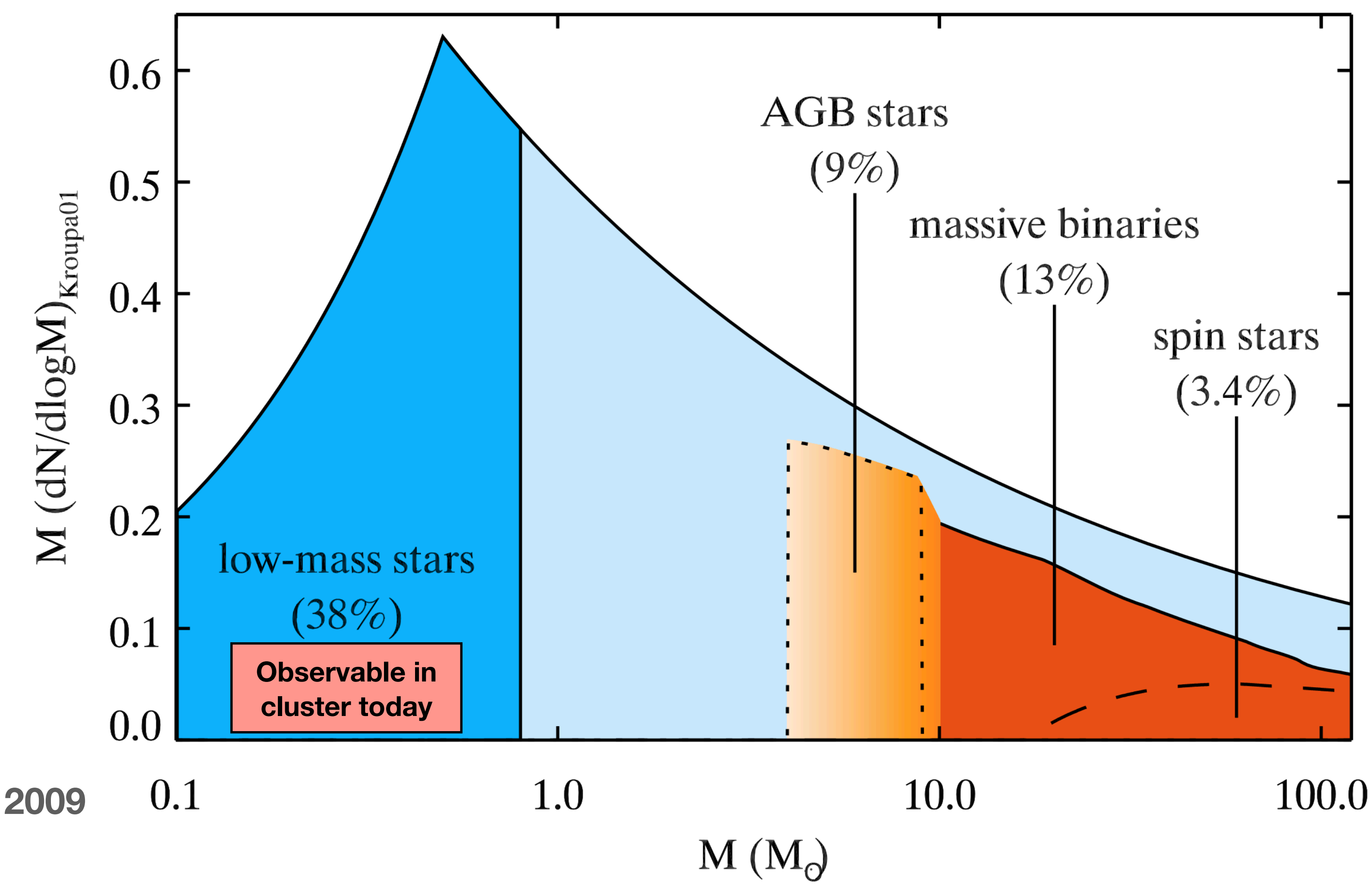


Adapted from Milone et al. 2017

Mass budget

Ejecta are **insufficient to produce a second generation of stars as numerous as the first,** even under the assumption of highly efficient star formation

De Mink et al. 2009

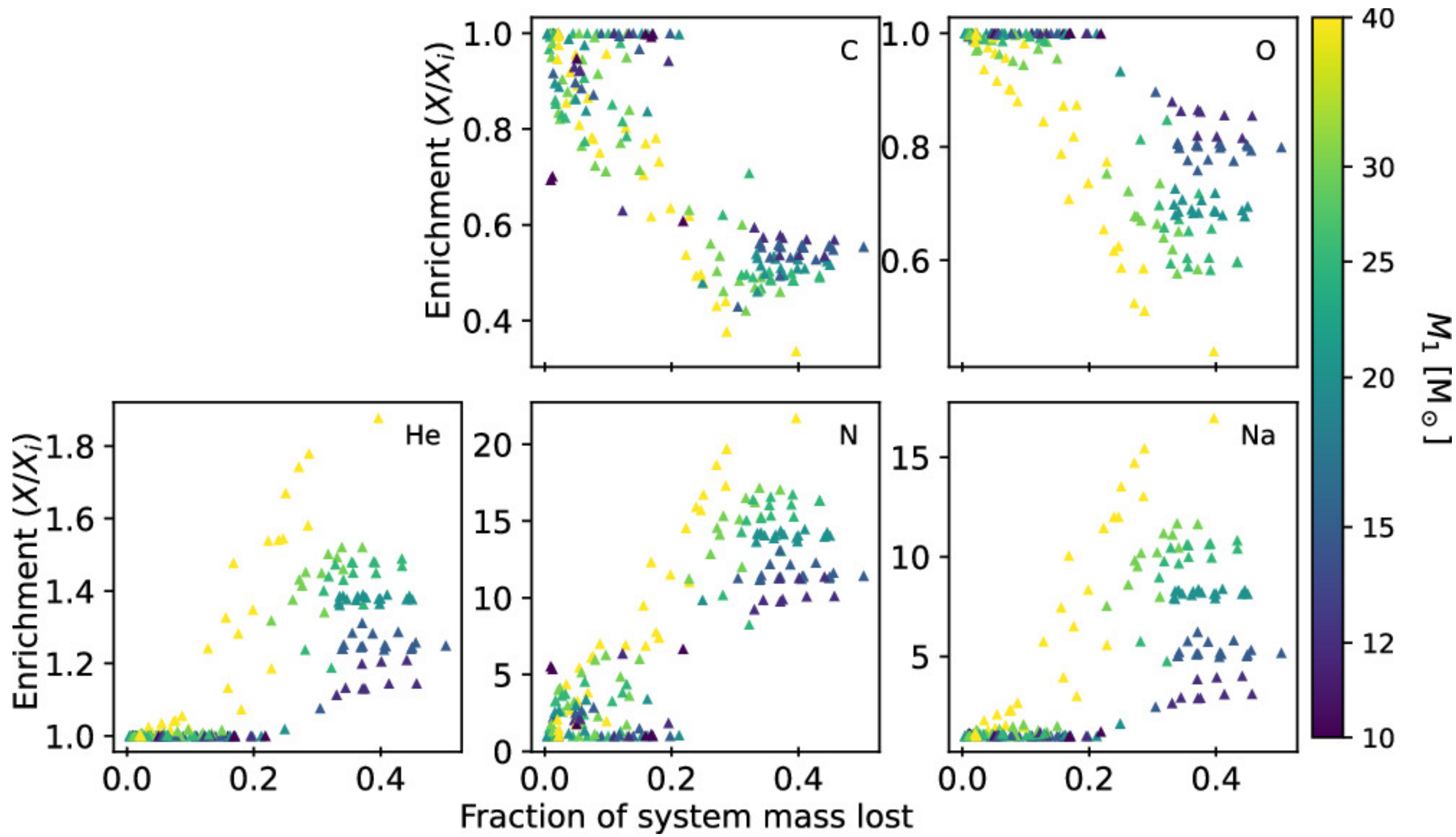


(*) This considered evolution of a 20 M⊙ star in a close binary

The dominance of P2 suggests that **the original P1** population, which processed material to form P2 stars, **must have had a substantially higher mass than the P1 stars that remain bound** to the clusters today

New binary models

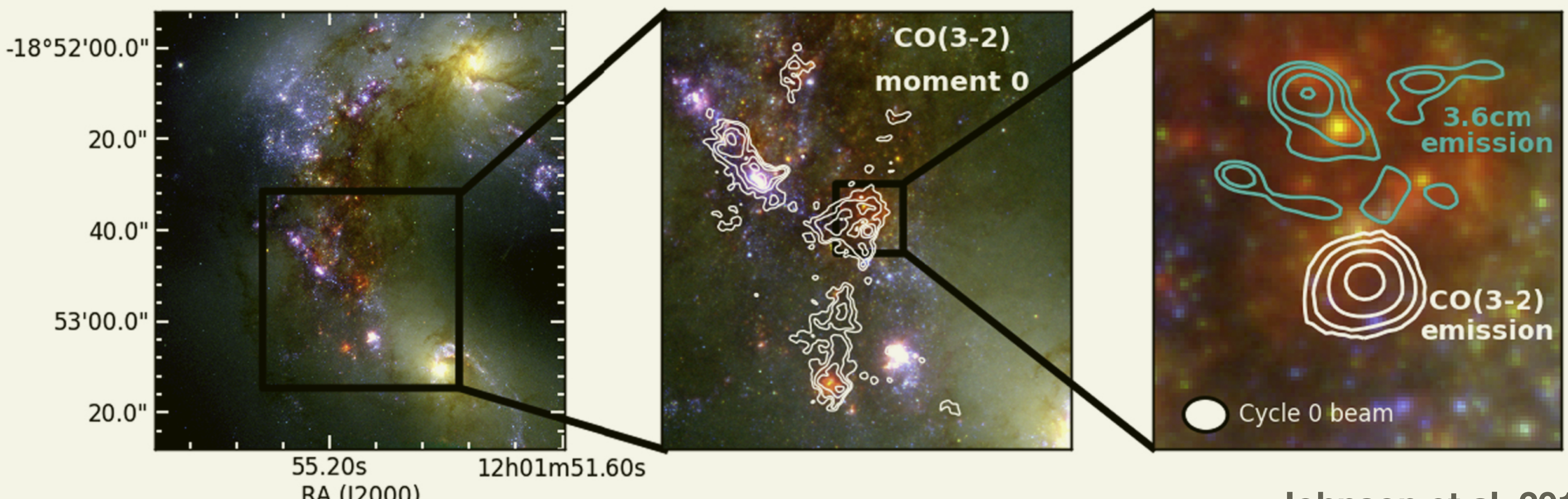
Nguyen and Sills 2024



- Binaries release **23% of their total mass** in ejecta with the *right* composition over 12 Myr (compared to 4% if all the stars were single; Nguyen & Sills 2024)
- Nearly all **massive stars form in binaries** or higher-order systems
- Binaries are **promising sources** to explain MPs (e.g., Renzini et al. 2022)

Cluster formation within GMCs

- Simulations show young massive clusters can chemically self-enrich within the first 5 Myr
- Clusters form in filamentary GMCs via **gas accretion** and **proto-cluster mergers**.
- First- and second-population stars can form **almost simultaneously** during this process.
- The **"mass budget"** problem is mitigated by GMCs, which provide **a gas reservoir for continuous accretion**

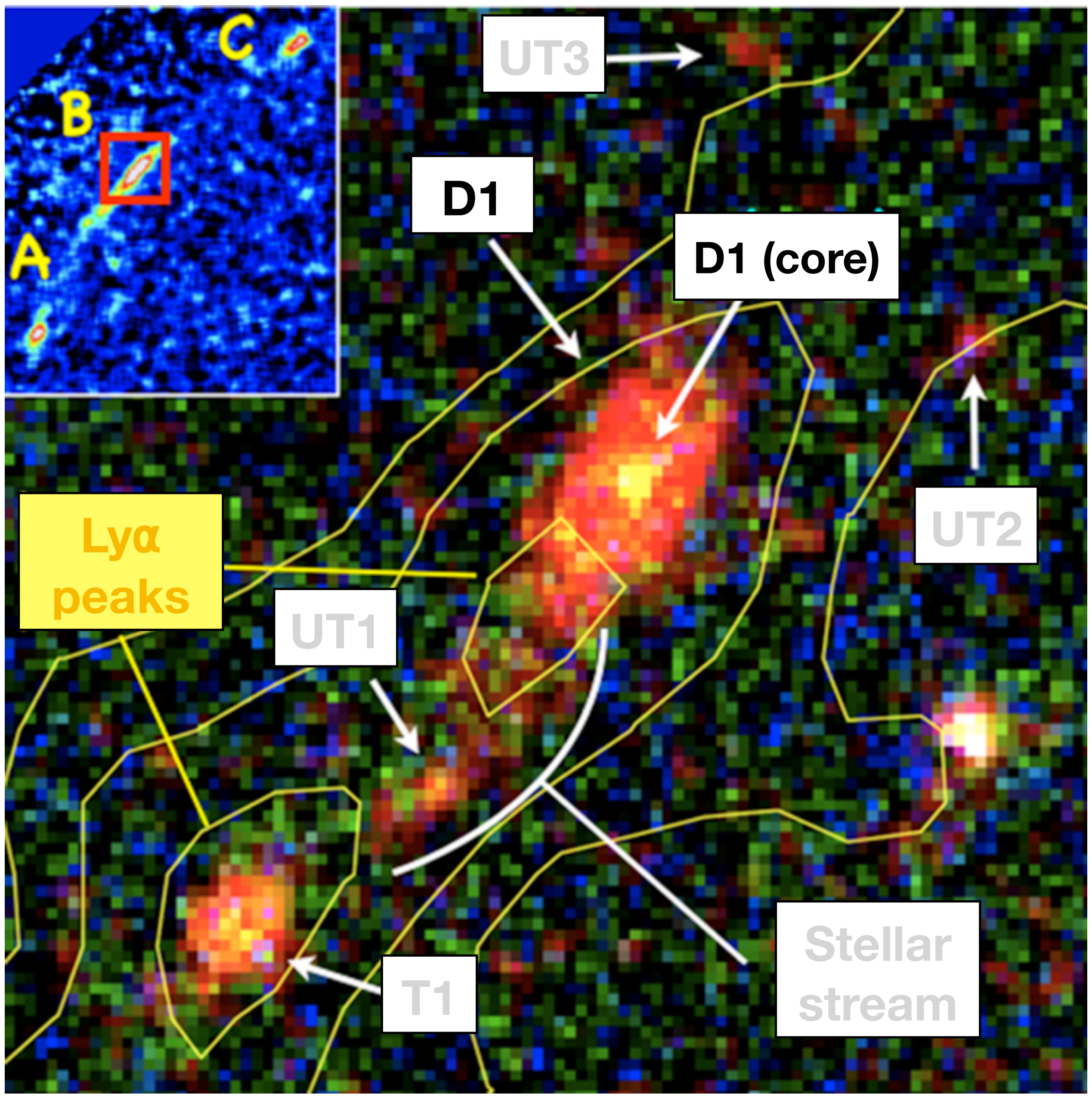


Johnson et al. 2015

A clump within a massive GMC in the Antennae (~5 × 10⁶ M⊙) is in the right range to form a young GC

Clues from high-z protoclusters

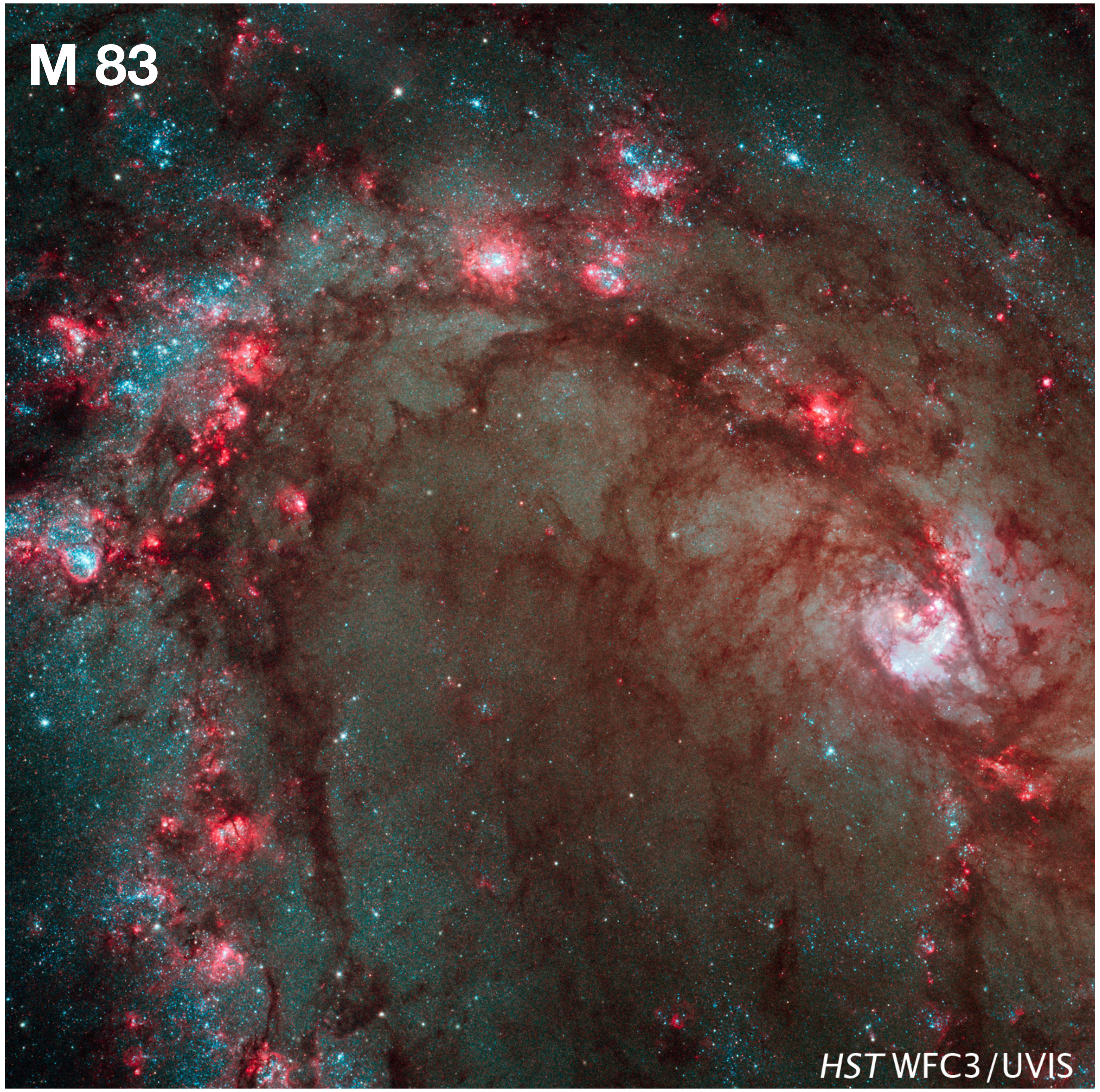
Vanzella et al. 2019

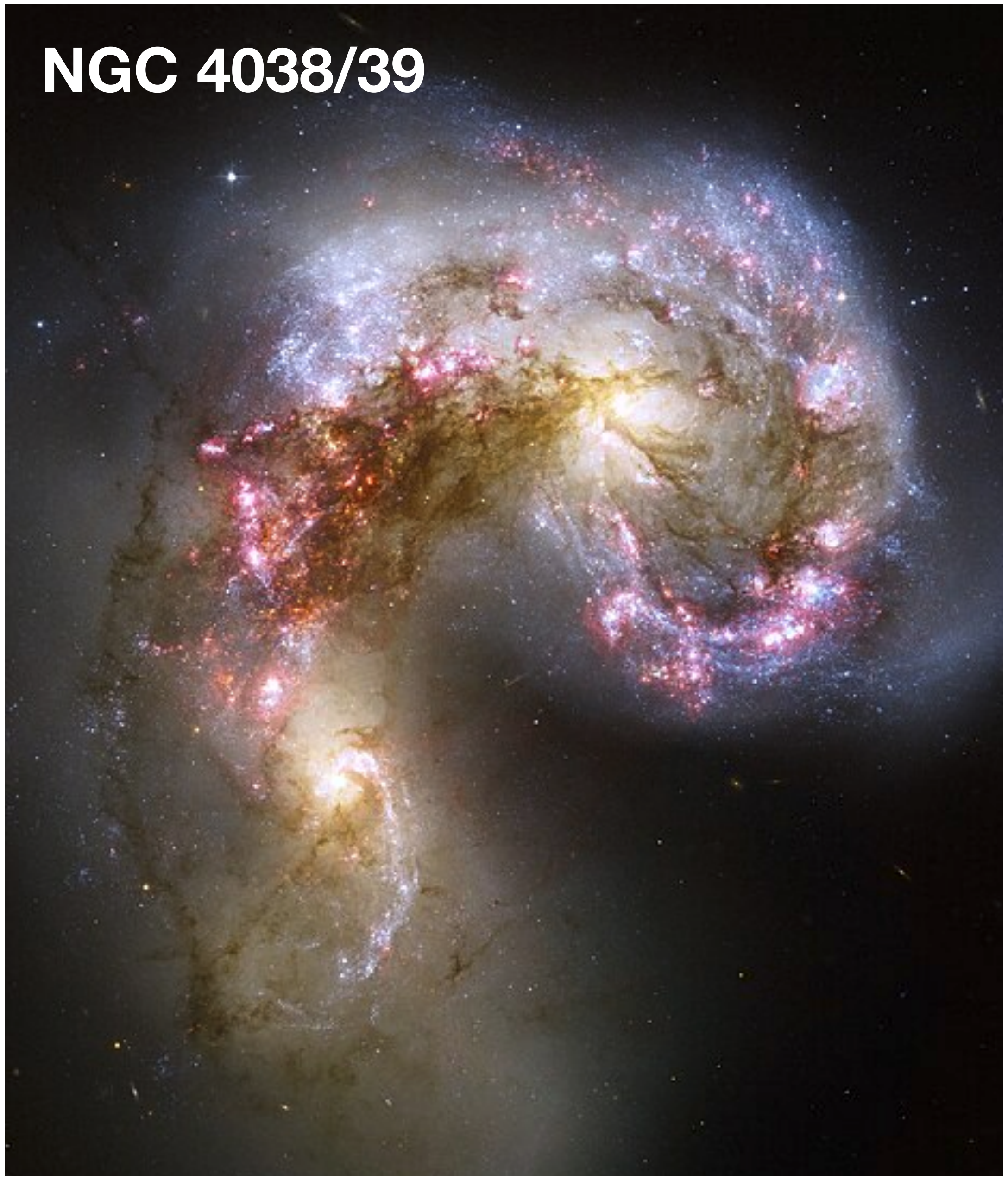


- Evidence for a GC **(D1 core)** forming inside a dwarf **(D1)** at $z \sim 6$ from a highly lensed HST image
- **Compact unresolved nucleus** with $R_e < 13$ pc and mass of $\sim 10^6 M_\odot$ (similar to some local SSCs)

Dwarf galaxies may contribute processed material for MP formation. This could help solve the **"mass budget"** problem

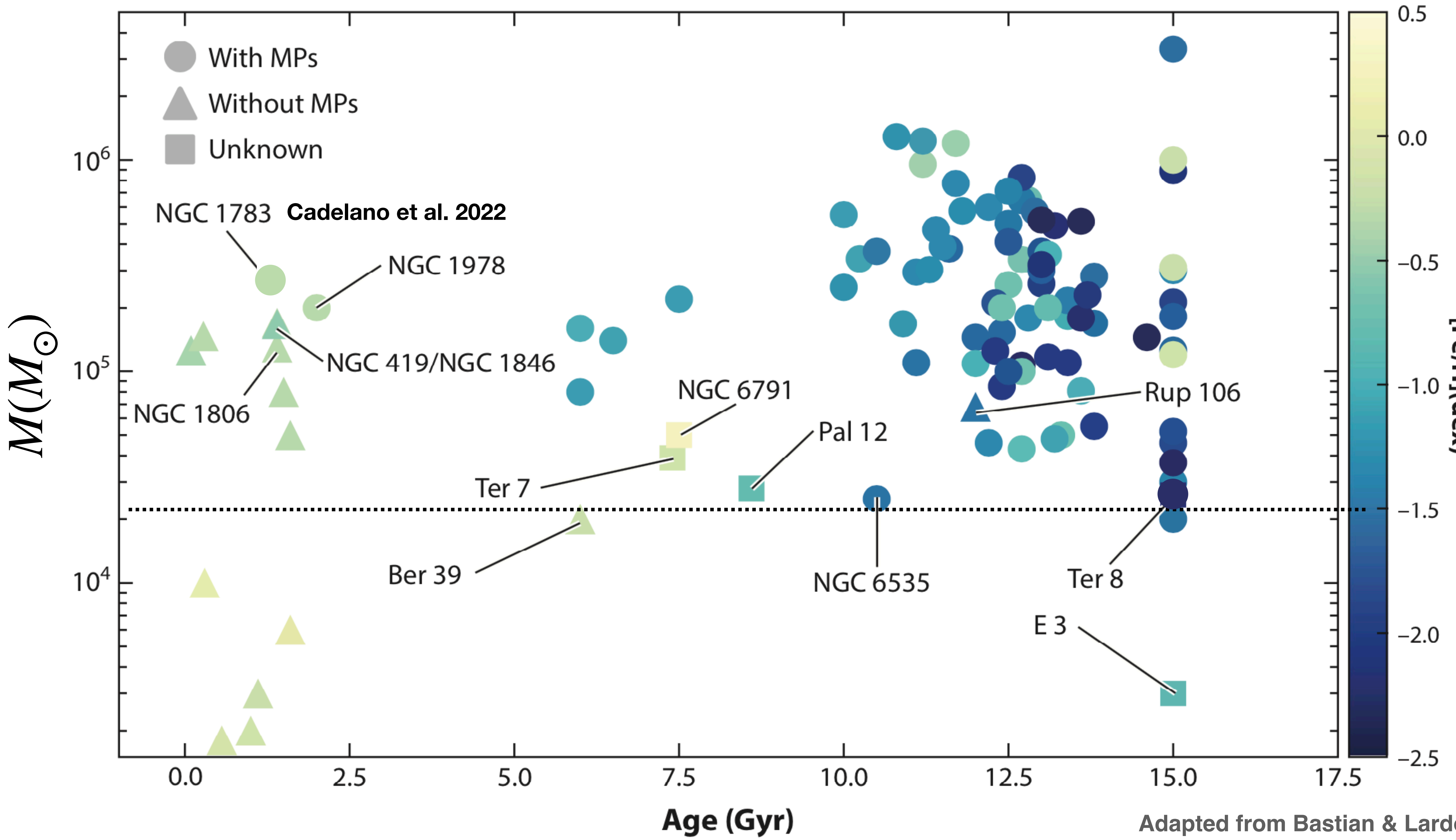
Using YMCs to constrain MPs





(e.g. Portegies Zwart, McMillan & Gieles (ESO) 2010, Adamo et al. 2020).

MPs at Different Ages

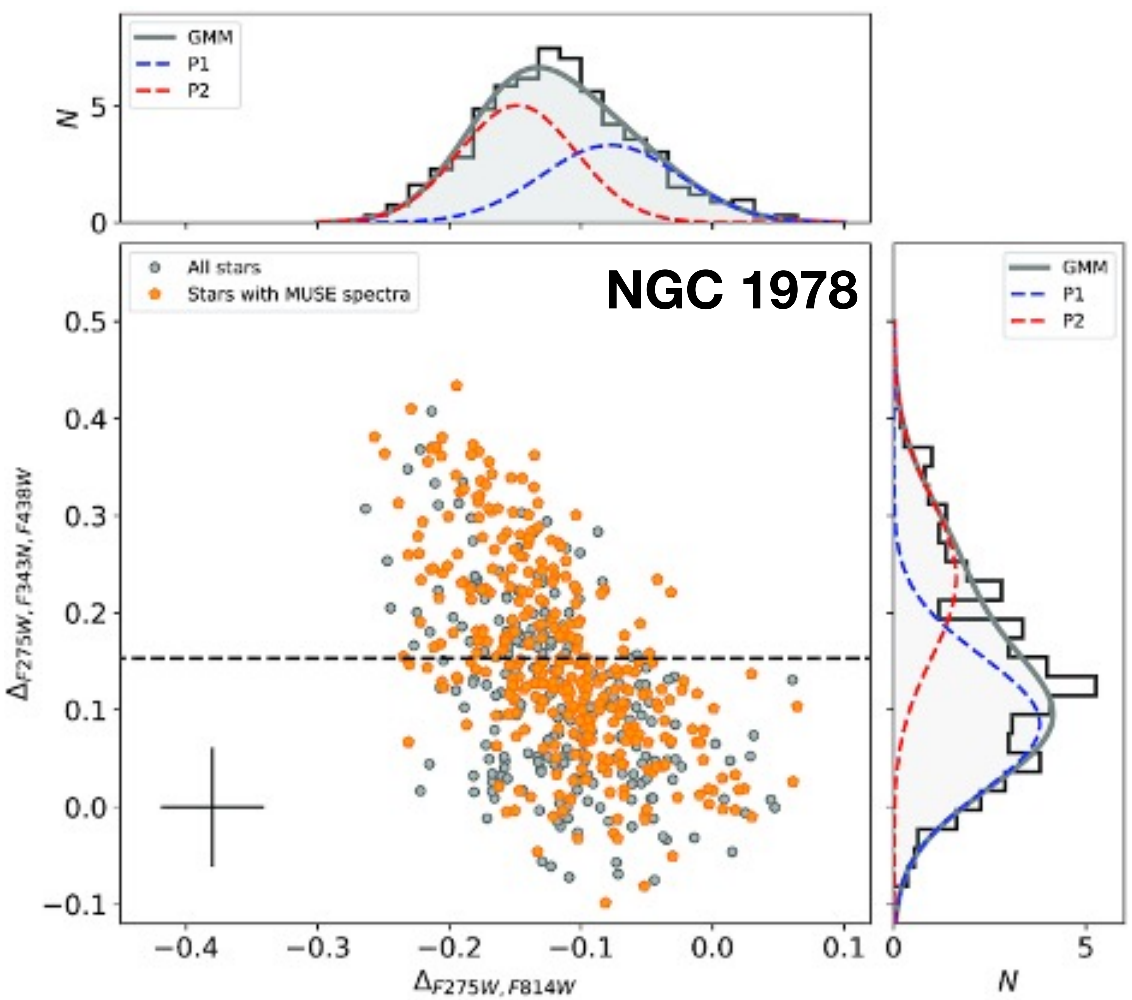


Adapted from Bastian & Lardo 2018

(e.g. Mucciarelli et al. 2009, Colucci et al. 2009, 2014; Schiavon et al. 2013, Larsen et al. 2012; Dalessandro et al. 2016, Niederhofer et al. 2016; de Silva et al. 2009; Bragaglia et al. 2014; MacLean et al. 2015; Lardo et al. 2015, Bastian et al. 2020).

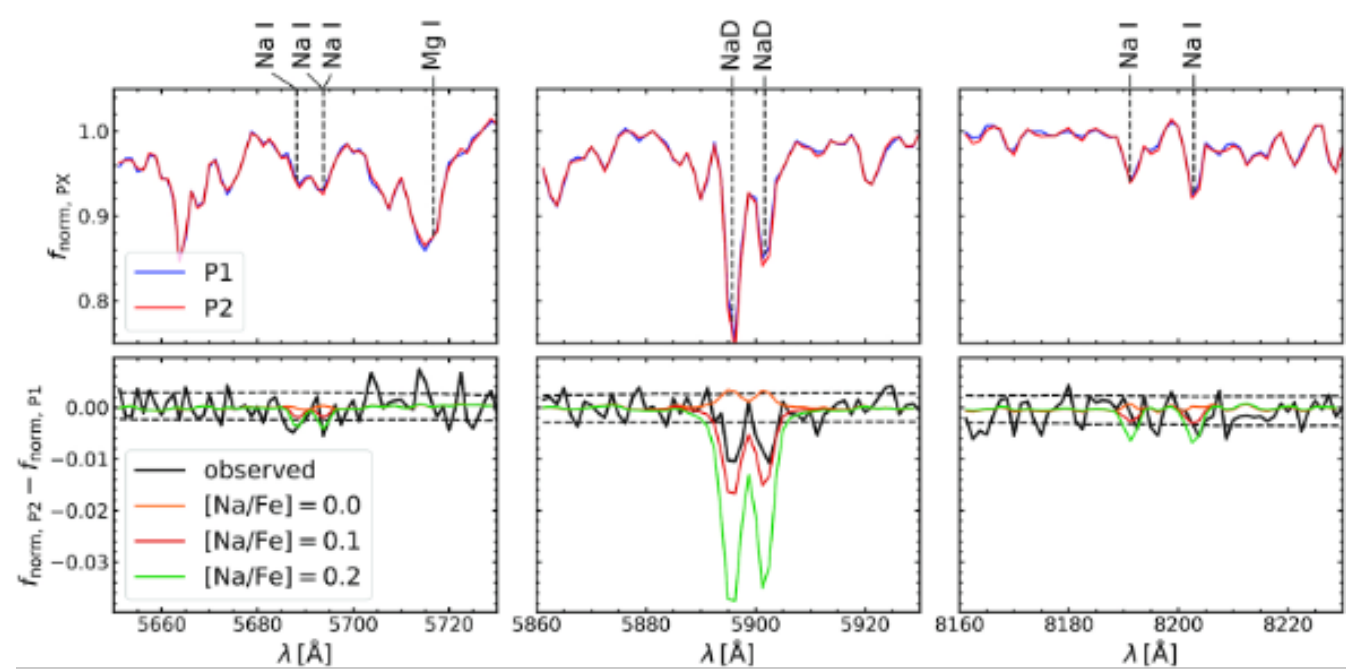
Do we observe a ΔNa?

- Variations in N and Na in young and intermediate-age clusters suggest the MP phenomenon **is similar to that in older GCs.**
- This supports the idea that **young** and **old** massive **star clusters are the same objects at different life stages**



$[Fe/H] = -0.38$; $\log(M/M_{\odot}) = 5.33$; Age = 2 Gyr

$\Delta[Na/Fe] = 0.07 \pm 0.01$



Saracino et al. 2020

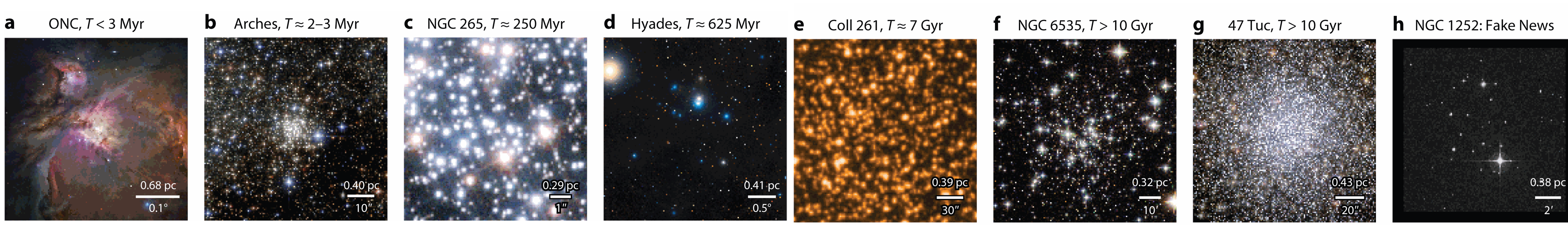
Insights from Younger Clusters

MPs have not a cosmological origin

- NGC 1978's age corresponds to a formation redshift of $z \sim 0.17$.
- Massive clusters may form under **normal star formation conditions**, not requiring special **early Universe conditions**.

Young clusters to constrain MP scenarios

- Young clusters offer the opportunity to **place limits on the age difference between successive star formation events** in self-enrichment models.
- Analysis of SGB stars in NGC 1978 shows two populations with different N have **virtually the same age (**Martocchia et al. 2018b)



Krumholz et al. 2019

Conclusions

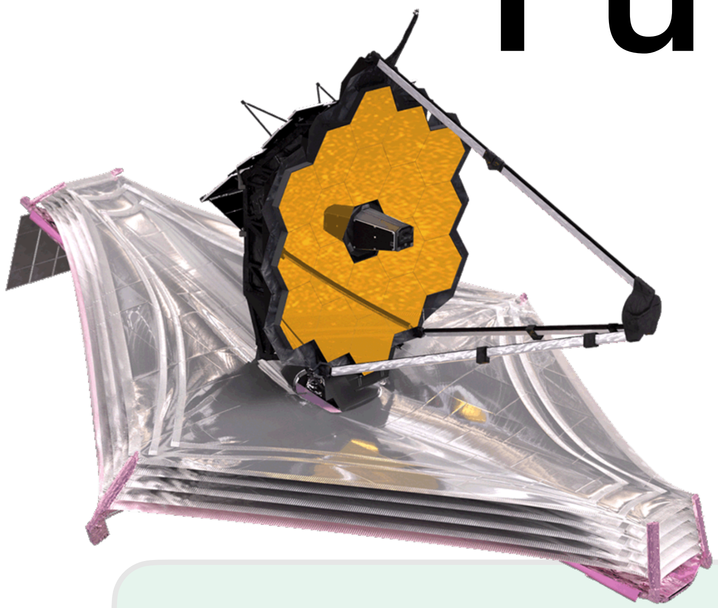
MPs are observed in nearly every massive cluster, suggesting that their formation is a **typical outcome of star formation**

The exact origin of these populations **remains unclear** (Renzini et al. 2015; Bastian & Lardo 2018; Gratton et al. 2019; Milone & Marino 2022)

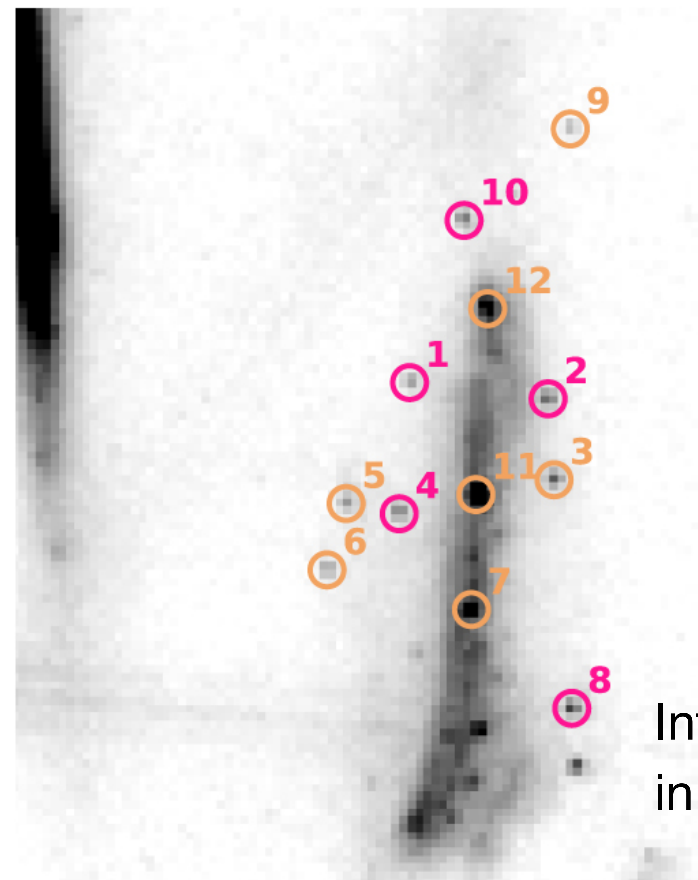
A complete model must:

- Identify a nucleosynthetic site capable of processing H-rich material at 70 MK to deplete Mg
- Ensure that this material is available to form new stars (or be added to the surfaces of pre-existing stars)
- Provide enough material so that half or more of the current stars in the cluster have *modified* abundances
- Focus primarily on clusters, as only a small fraction of field stars exhibit these chemical patterns
- Act on a short timescale, as there is no detectable age difference between populations.

Future Perspectives

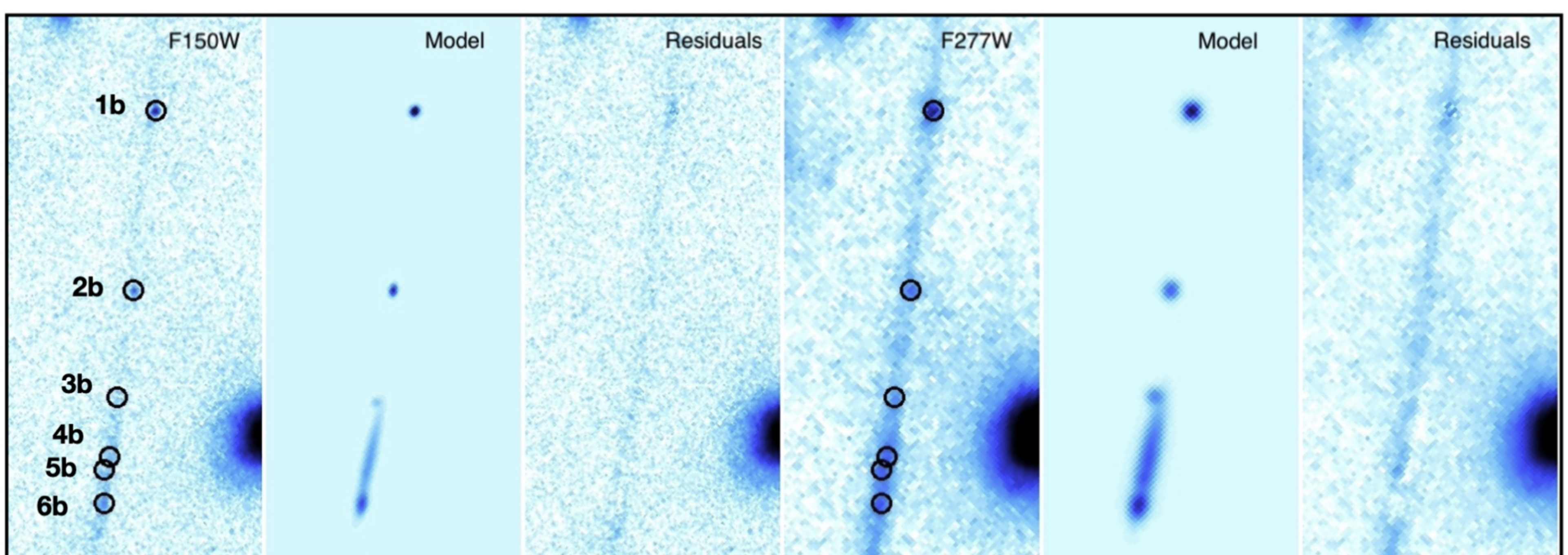


Important clues can be obtained from the observations of young and intermediate-age **massive clusters** forming **in the high-redshift universe** with **JWST**



Intermediate age star clusters in the Sparkler at $z \sim 1.4$

Mowla et al. 2022



Massive young star clusters in the Sunrise arc at $z \sim 6$

Vanzella et al. 2023