Stellar winds and the complex evolution of globular clusters

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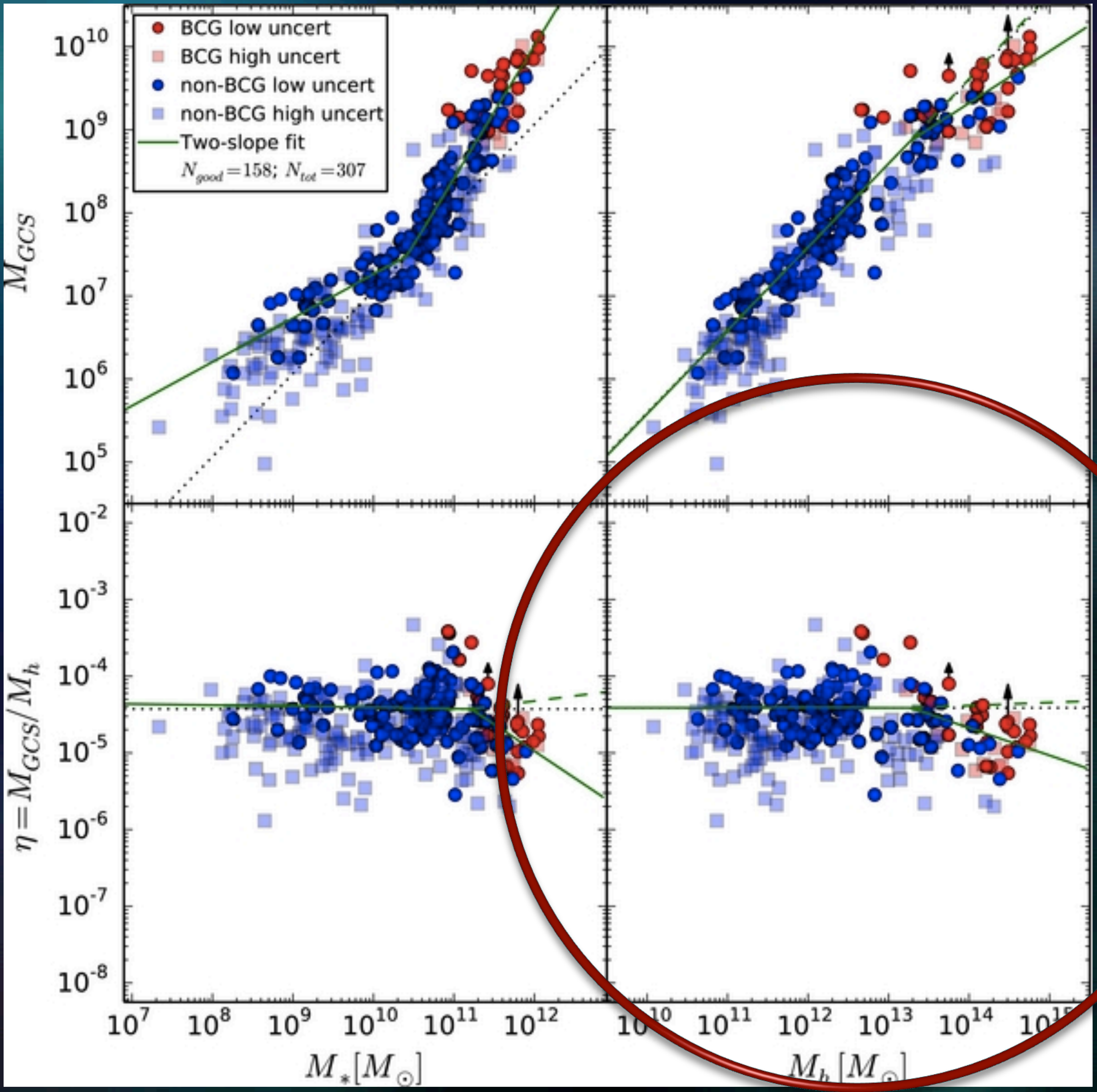
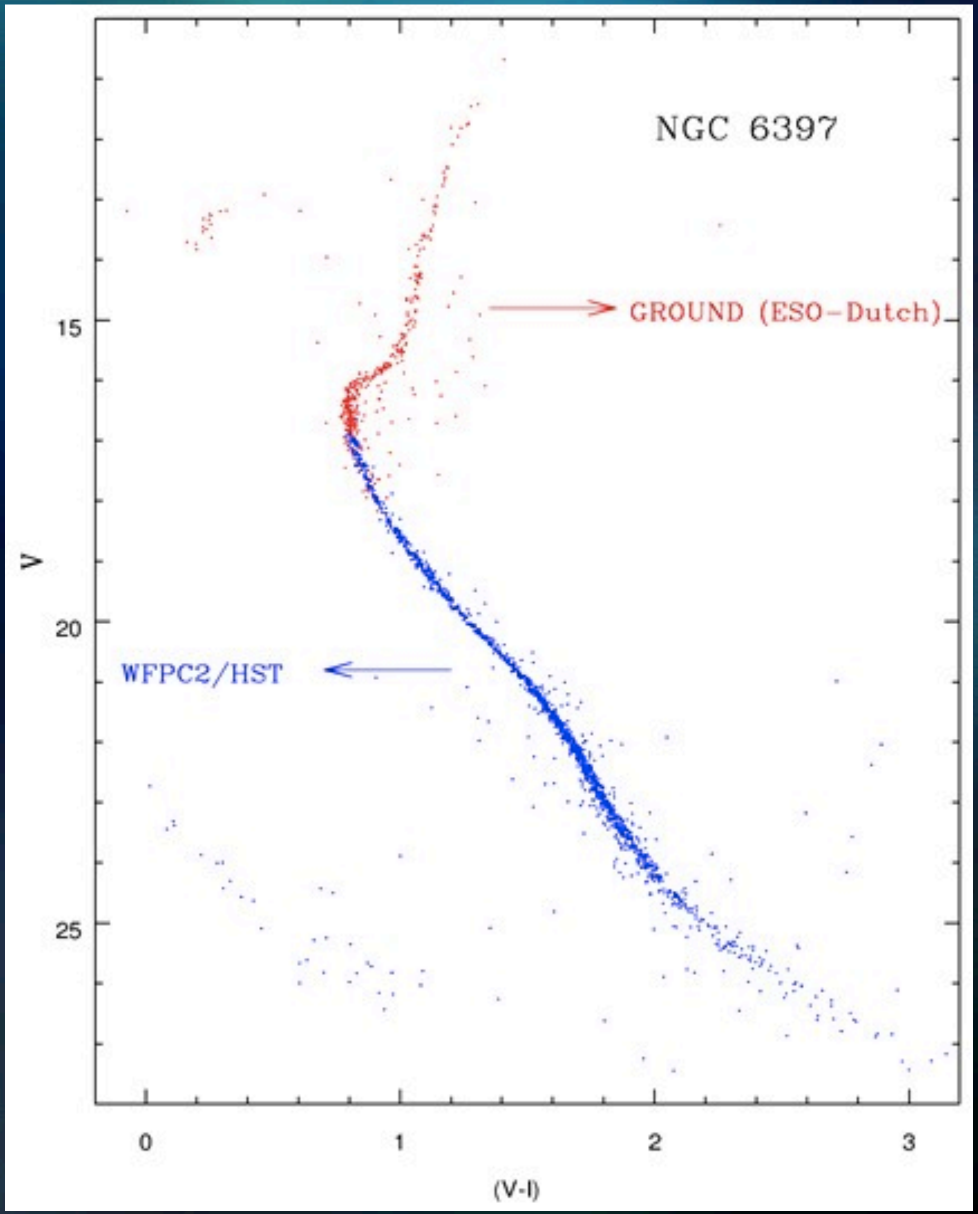
Hudson et al. (2014)



A 'classical' globular cluster CMD



Simple Stellar Population

Coeval stars, born with the same chemical composition

Carretta et al. (2009)

O-Na anticorrelation

Also

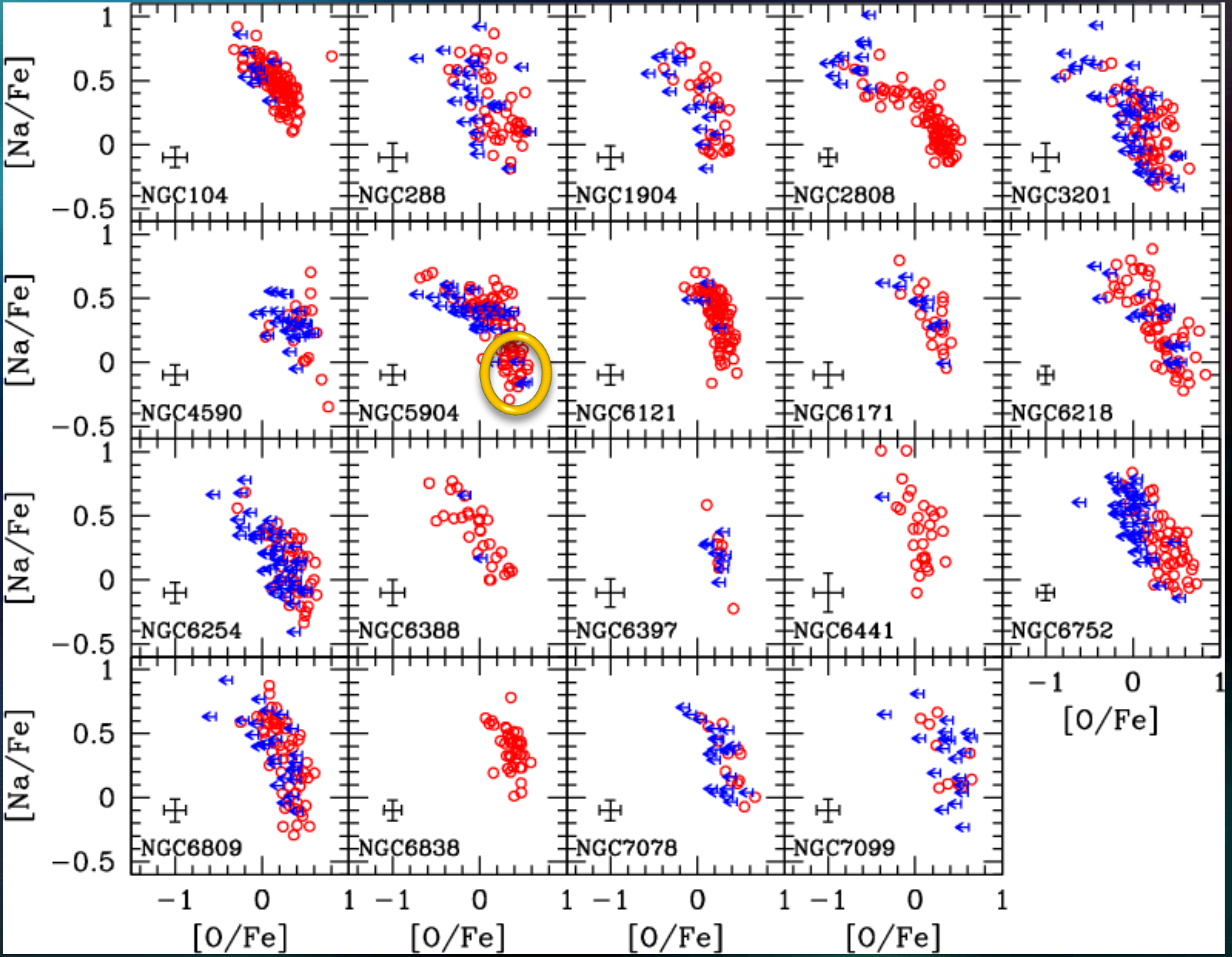
C-N

Not always

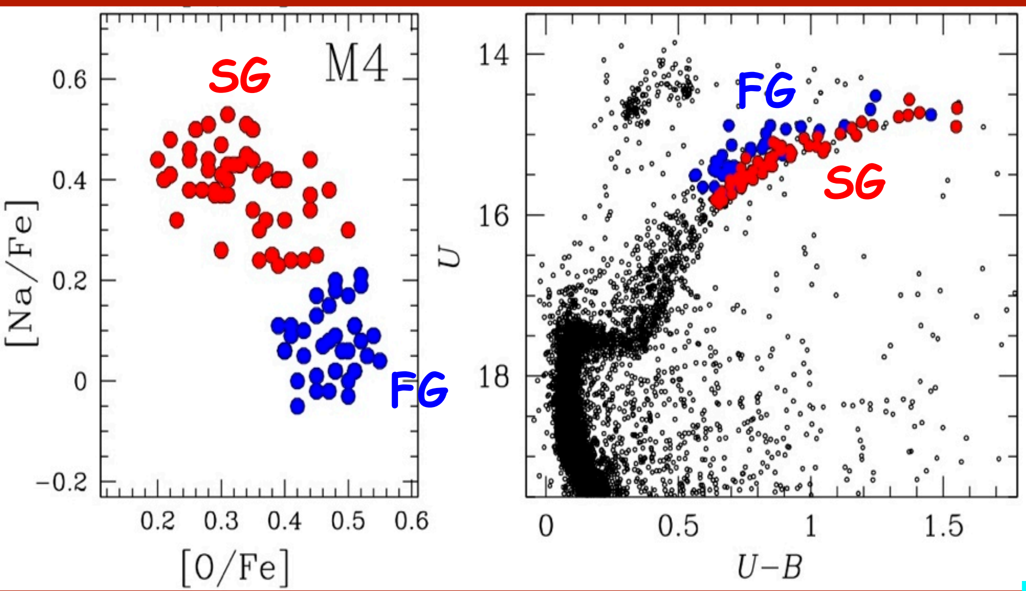
Mg-Al

Same extension
in
TO-SGB-RGB
stars

Primordial

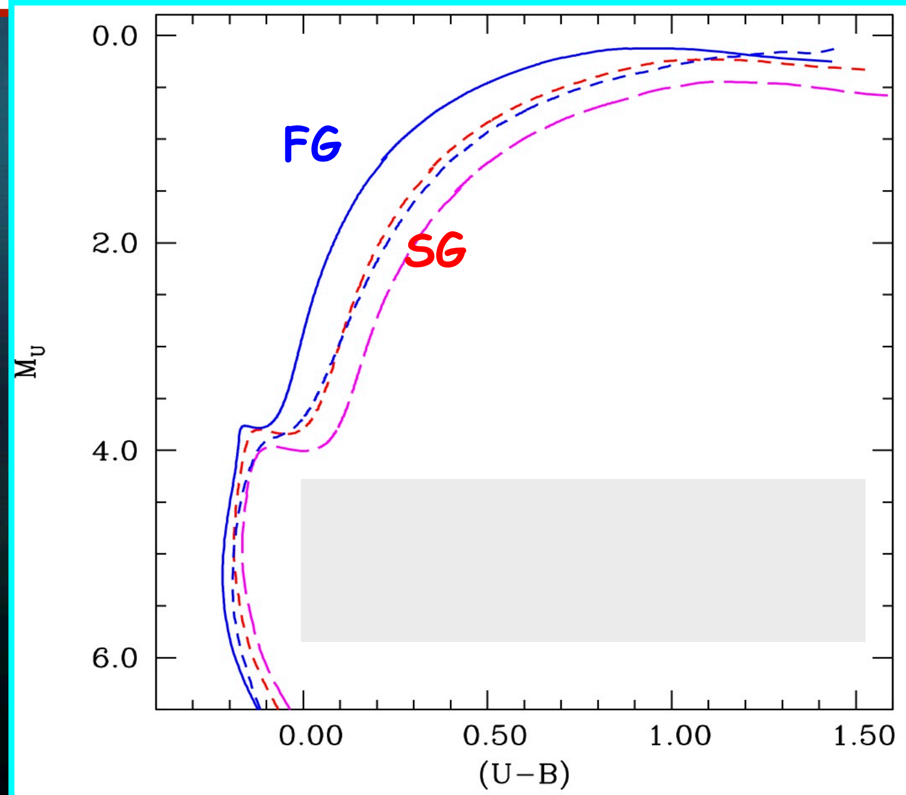


M4



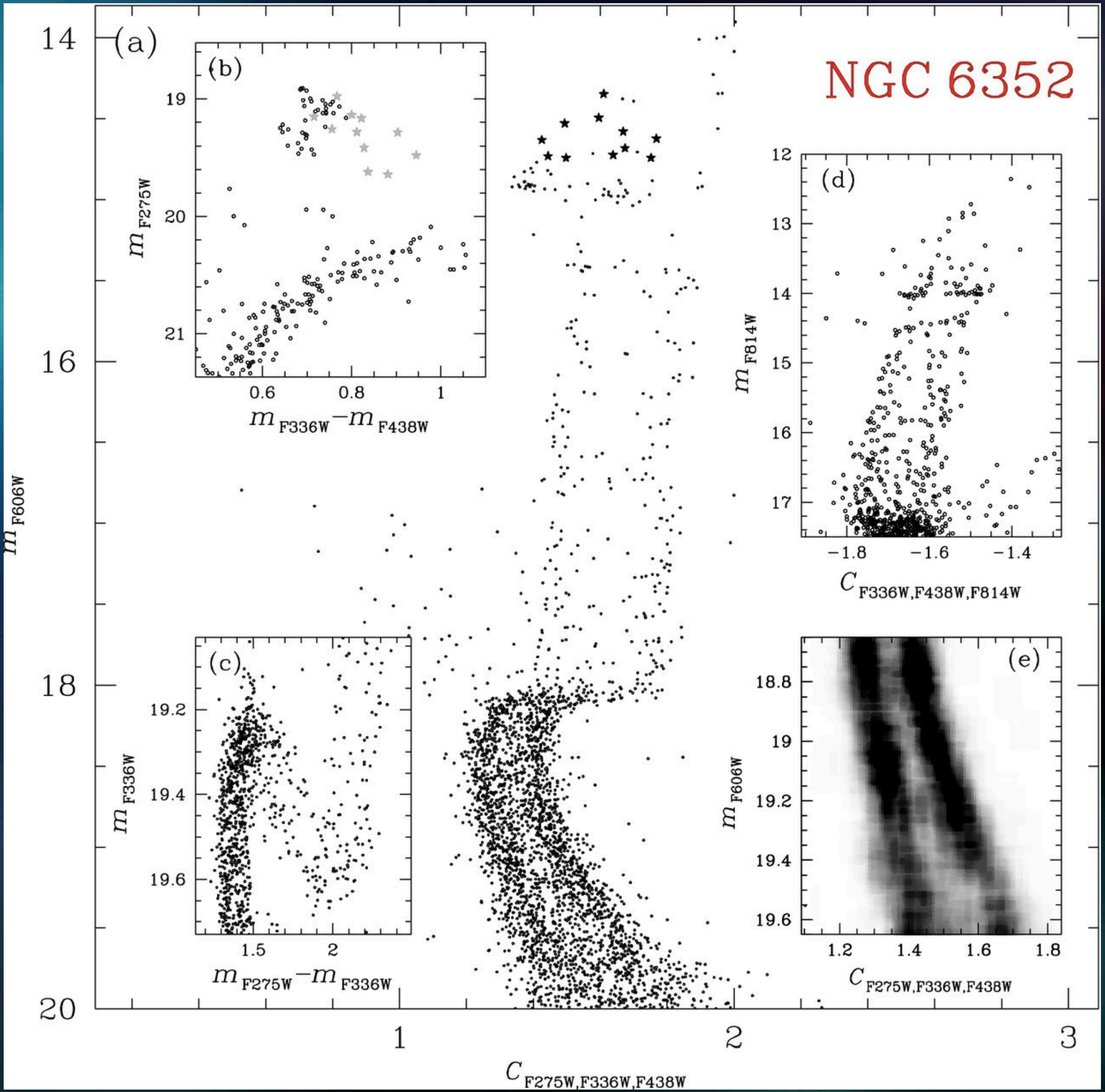
Marino et al. (2008)

Sbordone, Salaris et al. (2011)

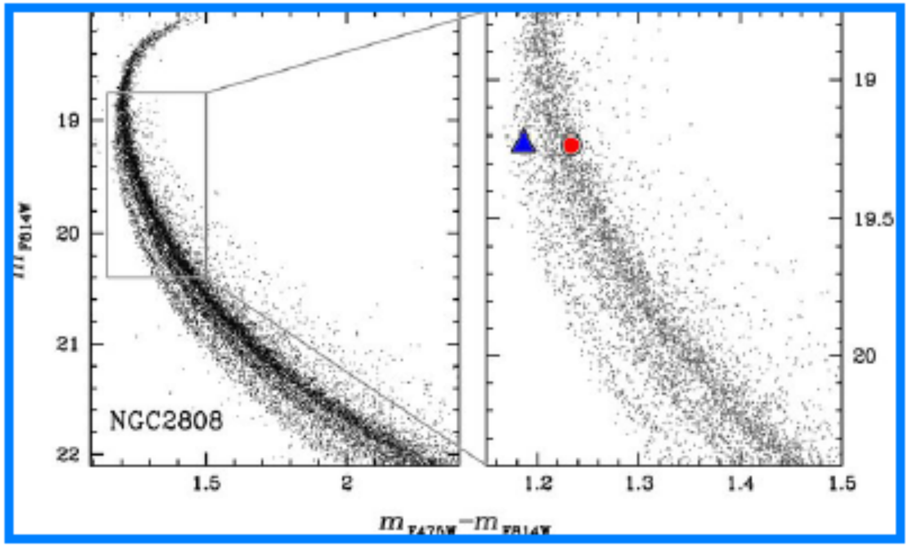


Nardiello et al. (2015)

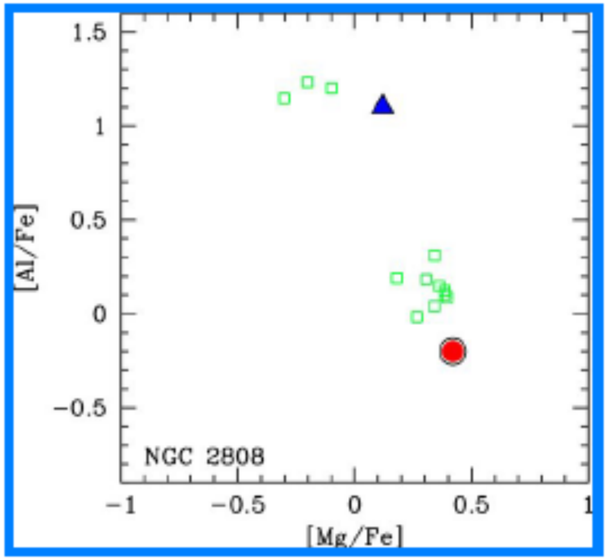
Hubble Space Telescope (HST) 'UV Legacy Survey of Galactic Globular Clusters: Shedding Light on Their Populations and Formation' (GO 13297)



He and Na along the main sequence of NGC2808



Bragaglia et al. (2010)



He-rich: Na-rich, Al-rich, Mg-poor

He-poor: Na-poor, Al-poor, Mg-rich

How do we explain the presence of other populations of stars in individual clusters, with these chemical abundance patterns?

C ↓ N ↑ O ↓ Na ↑ Mg ↓ Al ↑

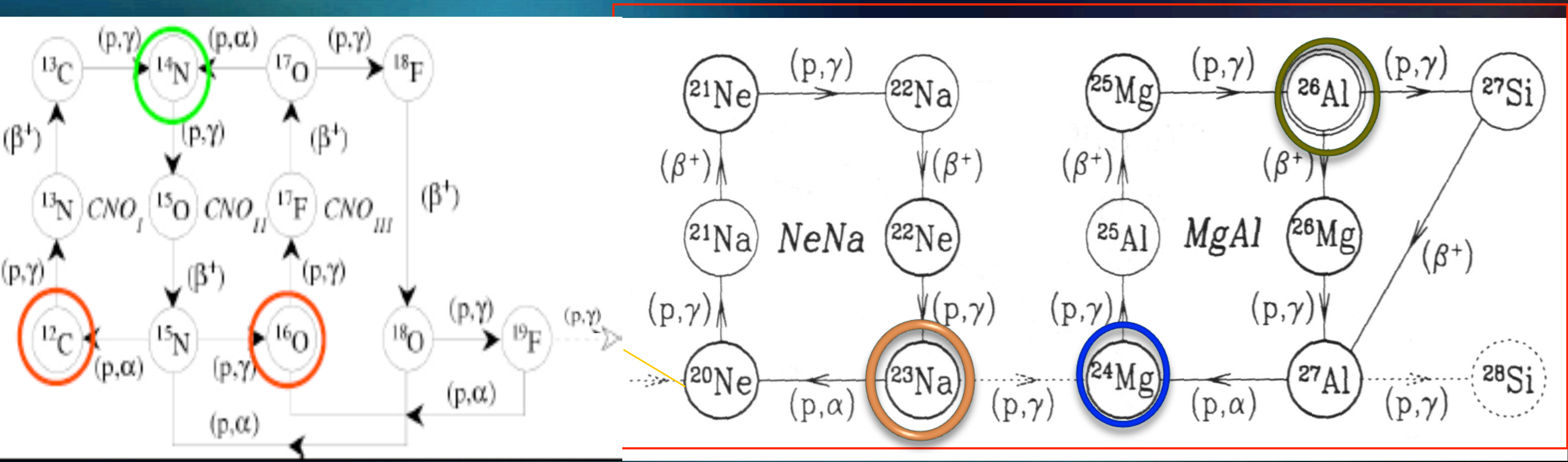
He ↑ Li ↑ ↓ ↔

C+N+O ↔

CNO cycle

NeNa cycle

MgAl cycle



T~20MK

T~35-50 MK

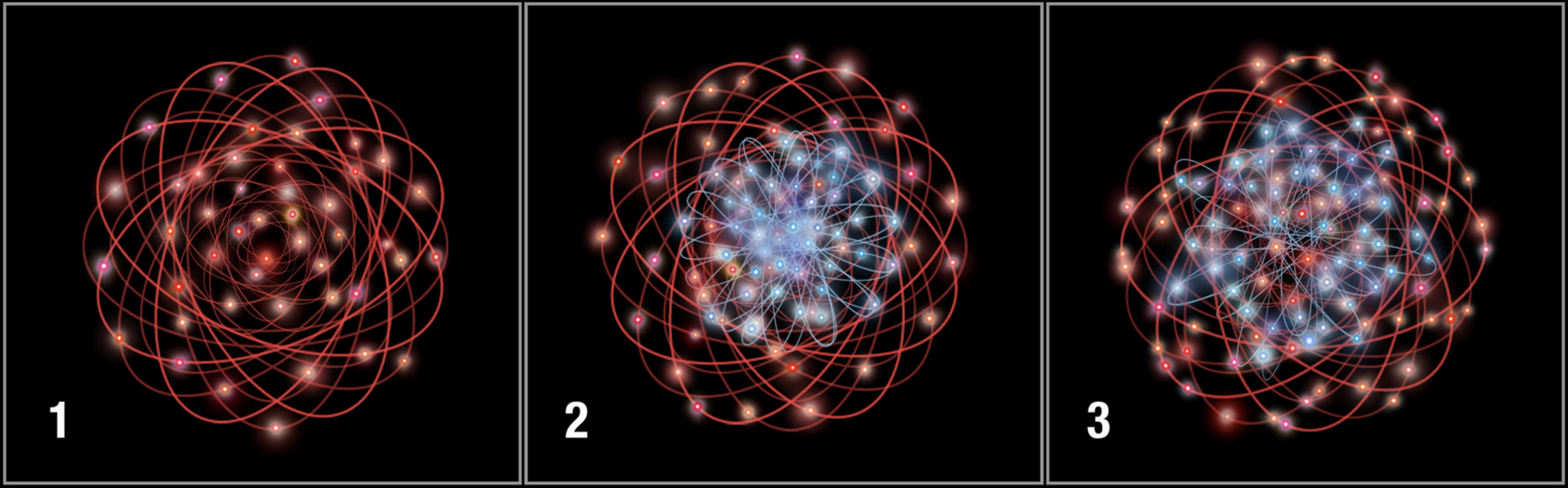
T>~50MK

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

In the same regions where CNO, NeNa, MgAl cycles are efficient,

Helium is also produced

A 'broad brush' scenario

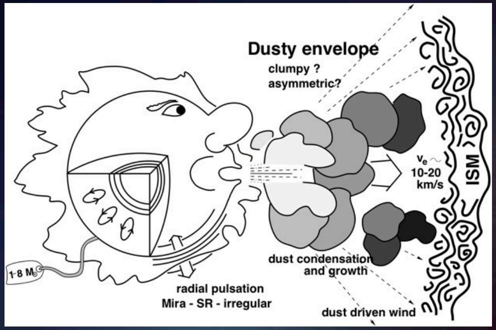


'First Generation' of stars form. Winds from some 'Polluters' belonging to the FG are injected into the intracluster medium

A 'second generation' of stars form out of this gas

FG and SG stars get dynamically mixed by the cluster dynamical evolution

Massive- and Super-AGB stars



(D'Ercole et al. 2008,2010, D'Antona et al. 2016)

They eject large amounts of mass at low velocity (~10–20 km s^{-1}) that can be retained in the potential well of the cluster

4-6(8) $M_{\odot}$ stars experience Hot Bottom Burning, that can potentially produce the observed CNONa (and MgAl) pattern within their convective envelope

They also experience the second dredge-up (2DU) shortly before reaching the AGB, leading to a sizable helium enrichment in the whole stellar envelope

Timescale of the polluters ≈ 10^7 – (not more than) 10^8 yr

Fast rotating massive stars (FRMS)

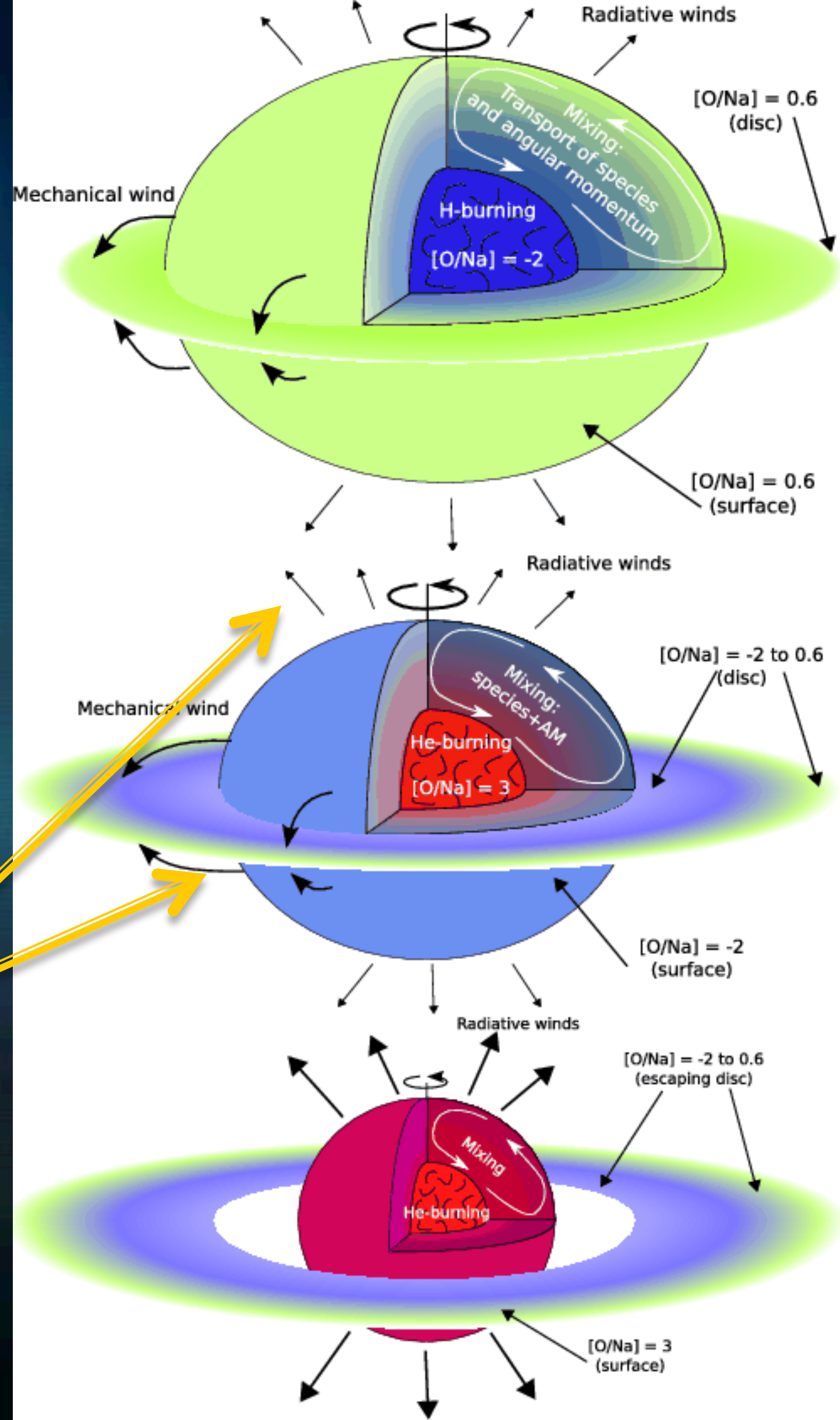
(Decressin et al. 2007a,b)

The formation of fast rotating stars is assumed to be favoured in dense stellar systems (surface rotational velocities of the order of a few 10^2 Km/s)

Meridional circulation and shear mixing in massive fast rotating stars bring to the surface products of hydrogen burning, while losing mass in two distinct and physically separated modes

SG stars are expected to form due to gravitational instabilities in the discs.

Timescale of the polluters ≈10^6 yr



i) NUCLEOSYNTHESIS

(super)AGB nucleosynthesis complicated by interplay of SDU, TDU, HBB

Interplay of several different processes:

SDU He ↑ Na ↑ N ↑ O ↓
TDU C ↑ Na ↑ O ↑ Mg ↑ (Al ↑)
HBB C ↓ N ↑ O ↓ Na ↑ (or ↓ as Mg, and Al ↑ if T at the base of conv. env. very high)

Predicted surface composition very author-dependent (for example CNO sum not always conserved)

FRMS

Nucleosynthesis more straightforward.

Need to modify the ^{24}Mg+p rate by a factor 1000 to reproduce amplitude Mg-Al anticorrelation in NGC6752. Not hot enough to deplete Mg appreciably

ii) Dilution

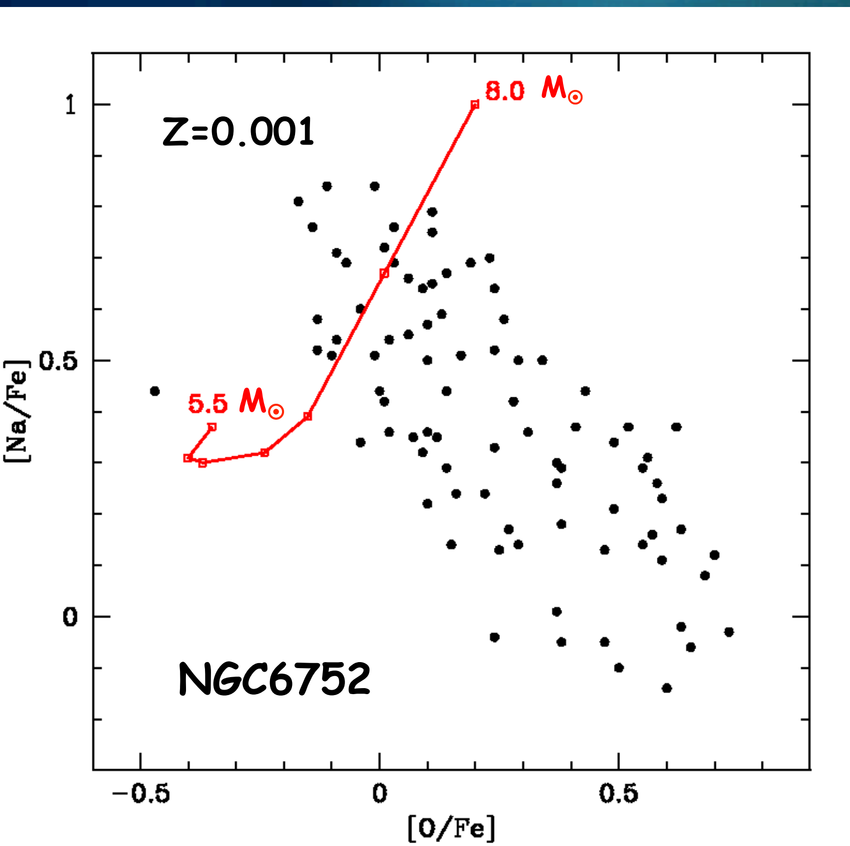
(super)AGB

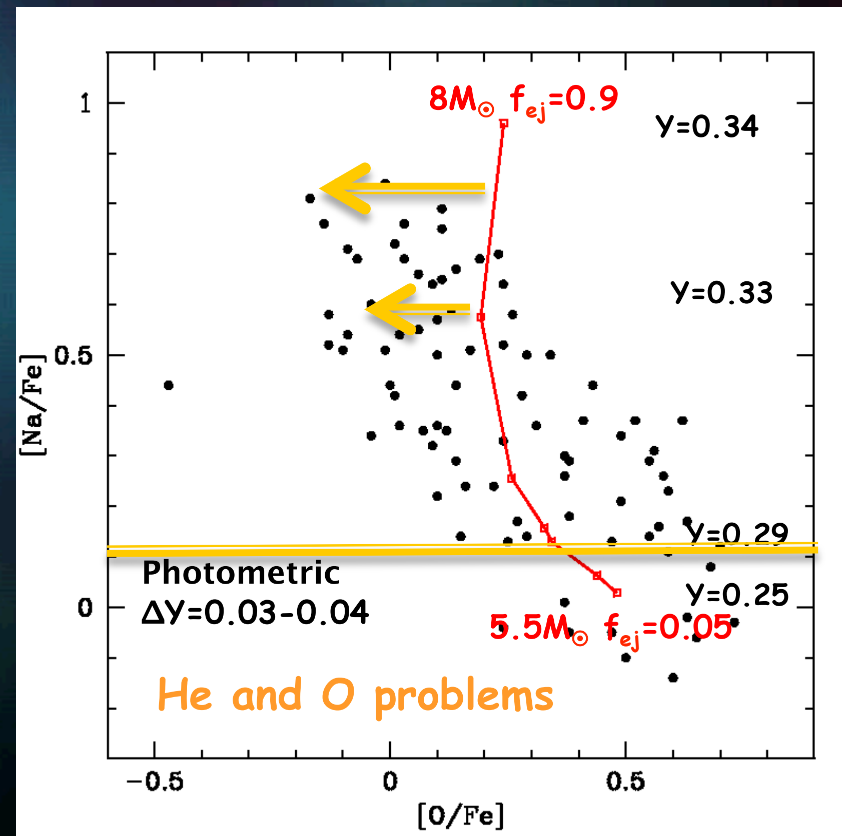
The mass of the FG diluting gas must be of the same order of the AGB star ejecta

Carretta et al. (2007) data

Ventura et al. (2013) models

f_{ej}=fraction of AGB ejecta

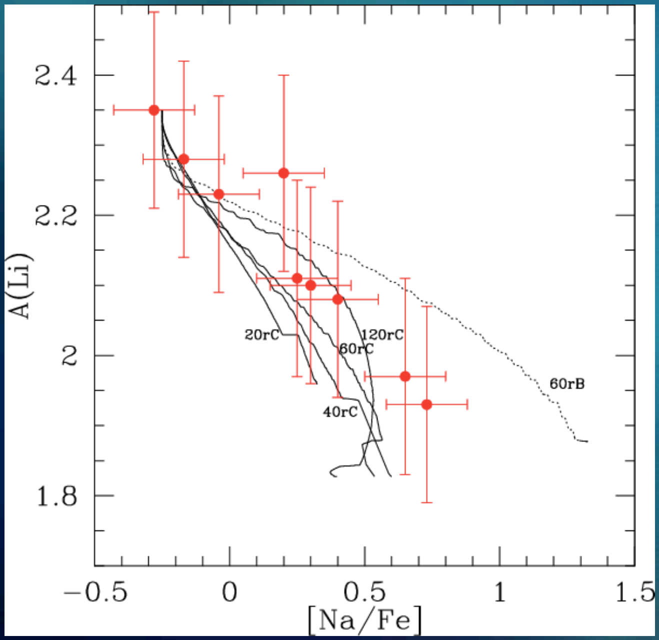




Decressin et al. (2007)

FRMS

NGC6752



SG matter FRMS ejecta FG matter

t=current time

t_{*}=lifetime slow winds

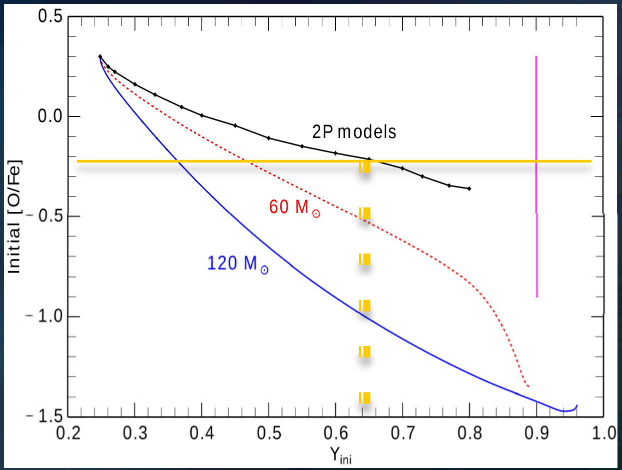
$$X_i^{2G}(a_t) = (1 - a_t) X_i^{SW}(t) + a_t X_i^{init}$$

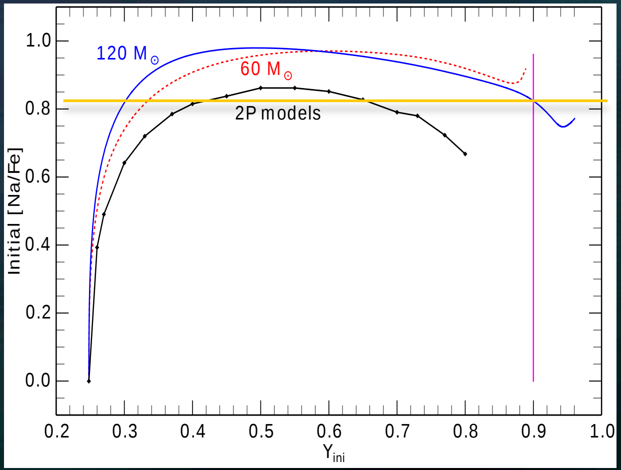
$$a_t = 1 - (1 - a_{min}) \frac{t}{t_*}$$

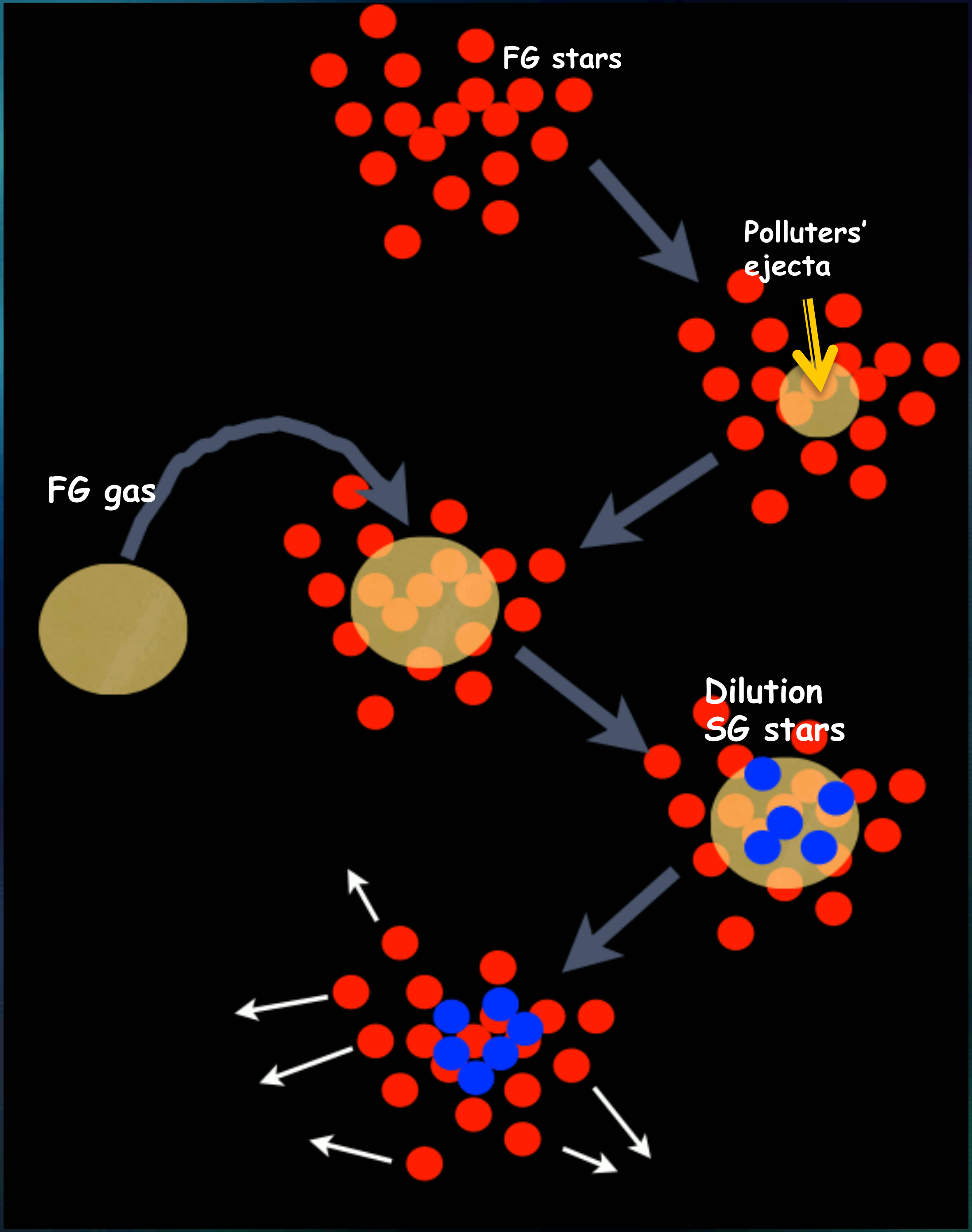
FRMS slow winds pollute only on a small scale around the progenitor and are diluted locally

He-problem as for AGB stars

To reproduce the Li-Na anticorrelation, matter ejected earlier by an individual FRMS encounters more pristine gas and is more diluted than mass ejected later

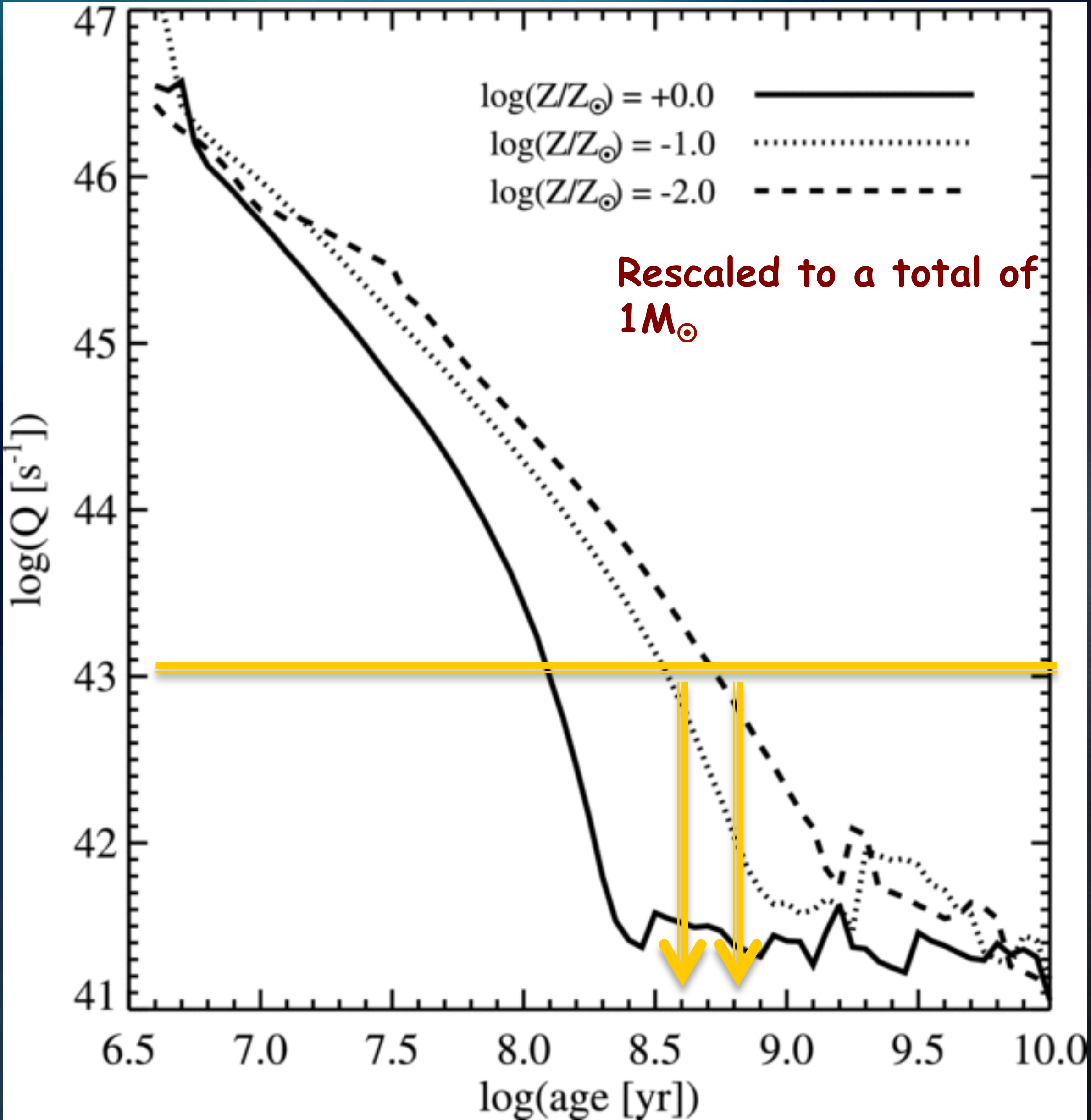





FG stars
Polluters' ejecta
FG gas
Dilution
SG stars

iii) Can the ejecta cool down ?

Conroy & Spergel (2011)



Lyman-Werner (912 < Å < 1100) photon density prevents gas cooling because photodissociation of H_2

Can self-shielding play
a role?

Evolution of the Lyman-Werner photon production rate for coeval stellar populations

iv) Mass budget, FG and SG IMF

$0.1 < M_{\odot} < 100$ Kroupa IMF

'reasonable' IFMR (WD, ns or BH)

$M_{gas}^{SG} \approx 0.10\ M^{FG}_{now}$

AGB polluters $5 < M_{\odot} < 8$

$M_{gas}^{SG} \approx 0.06\ M^{FG}_{now}$

FRMS polluters $20 < M_{\odot} < 100$

We observe nowadays $N_{FG} \approx N_{SG}$

Even assuming 100% SFE and IMF truncated at $1 M_{\odot}$ major mass budget problem for SG stars

Also, upper mass limit must be less than $\cong 10 M_{\odot}$ to avoid SG SNII to interfere with star formation

Either the FG IMF was flatter, or GCs were about 10-40 times more massive at birth and have lost most of the FG long lived stars

FG star loss mechanisms

Two-body relaxation
Too long timescales

External tidal shocks
Too long timescales

Stellar evolution induced (D'Ercole et al.2008)
(loss of SN ejecta → cluster expansion beyond its tidal radius → loss of stars)
It works with initial configurations very different with present globular clusters and young massive clusters

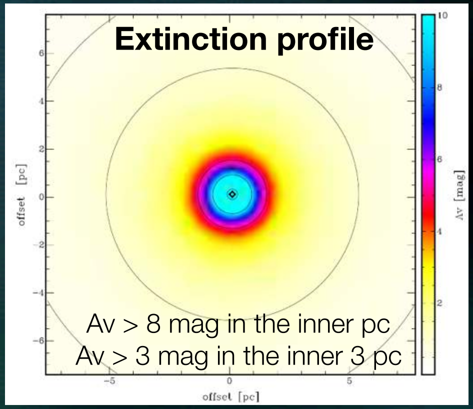
Primordial gas loss (Khalaj & Baumgardt 2015)
If enough gas is left after FG and SG formation (same mass of FG stars) , and this gas is expelled, it is accompanied by cluster expansion and loss of stars. It must happen in 10^5 yr. Not enough SN to achieve this

Predicts N_{SG}/N_{TOT} to decrease with present cluster mass… the opposite of what is observed

v) The lessons from young (YMC - and intermediate age) massive clusters (Longmore 2015, Bastian et al. 2014, Niederhofer et al. 2015, Bastian et al. 2013, Mucciarelli 2012)

Lack of ongoing star formation in YMCs with ages
Between 10-1000 Myr and mass 10^4-10^8 $M_\odot$
No sizable age spreads

YMCs are gas free after 3 Myr, no gas around the clusters

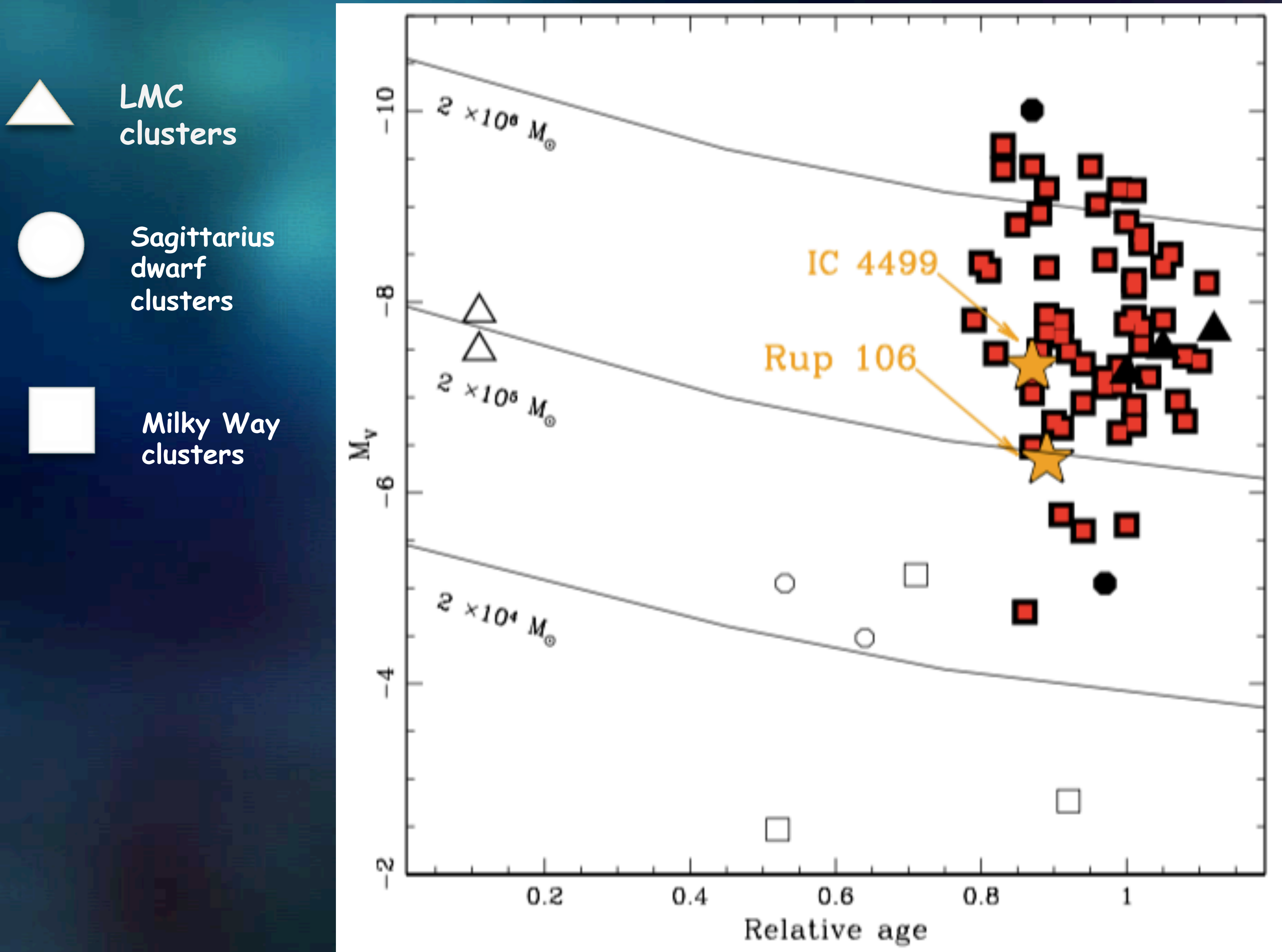


No large extinction (expected from accretion of FG gas to form SG) in the cores of YMCs

No abundance anticorrelations in a handful of LMC massive clusters with age 1-2 Gyr

vi) Dwarf galaxies field population (Larsen et al. 2012, 2014)

In a nutshell, if the globular clusters with [Fe/H]<−2 in Fornax, WLM and IKN were 10 times more massive at birth (hence lost their stars to the galaxy haloes), the mass of field halo stars in the same metallicity range would be higher than observed.


LMC clusters
Sagittarius dwarf clusters
Milky Way clusters
IC 4499
Rup 106
2 ×10⁶ M⊙
2 ×10⁵ M⊙
2 ×10⁴ M⊙
M_V
−10
−8
−6
−4
−2
0.2
0.4
0.6
0.8
1
Relative age

A SMALL SET OF MAJOR QUESTIONS

a) Yields

Na (or O)-He relationships predicted for the polluters do not match the observations.

Is it possible to demonstrate that within current known uncertainties the polluters' yields can eventually work?

b) Dilution, SF

Where was the FG gas?

Does dilution really happen?

Why SG high mass stars do not form?

Proper calculations of SG formation (H_2 formation and cooling) are needed

c) Mass budget, IMF

The mechanisms proposed to lose FG stars do not seem to work or do not seem to match (at least some) current observational constraints.

ARE THE PROPOSED SCENARIOS TOO FLEXIBLE? CAN THEY BE FALSIFIED?

DO WE NEED A NEW PARADIGM?