Multiple Populations in Star Clusters

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Star Clusters are quintessential Simple Stellar Populations (SSPs)

Obey The 3 Commandments of SSPs:

all stars have the same

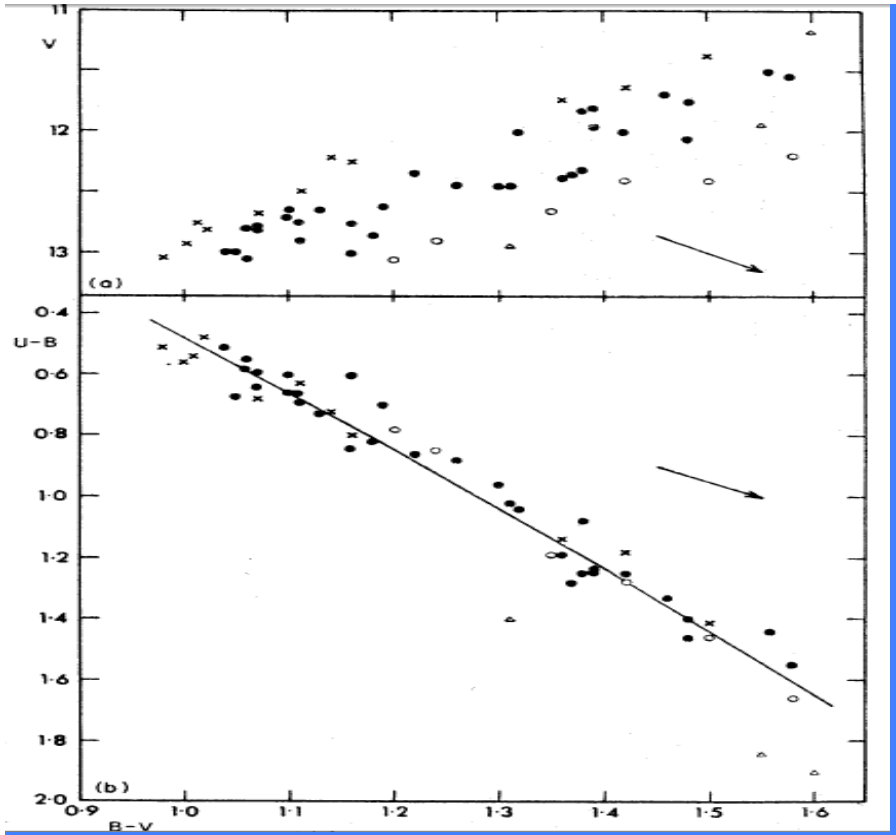
1 age (only one star formation burst)

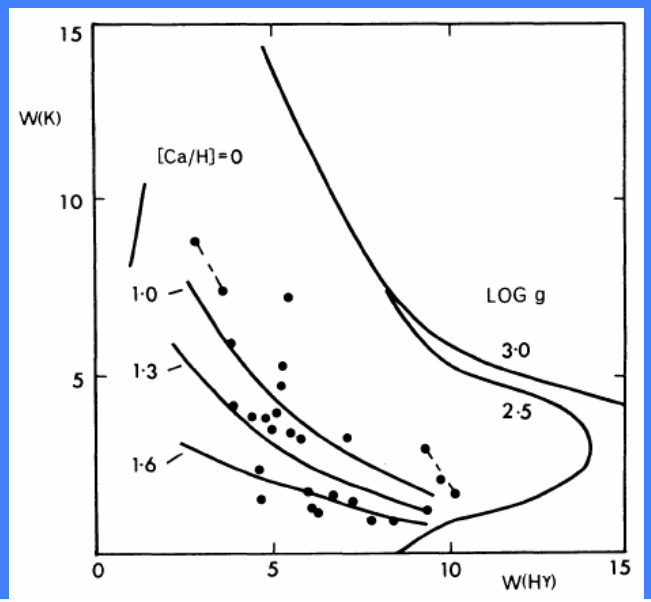
2 initial chemical composition

3 distance

Clusters are great tools to study:

- Stellar evolution
- Formation and chemical enrichment history of parent galaxy
- Unresolved stellar populations
- Stellar dynamics
- Distance scale
- ...





Globular Clusters (GCs) host ~~Simple Stellar Populations (SSPs)~~

Multiple Populations (MPs)

ϖ Cen: Invented MPs >40 yr ago!

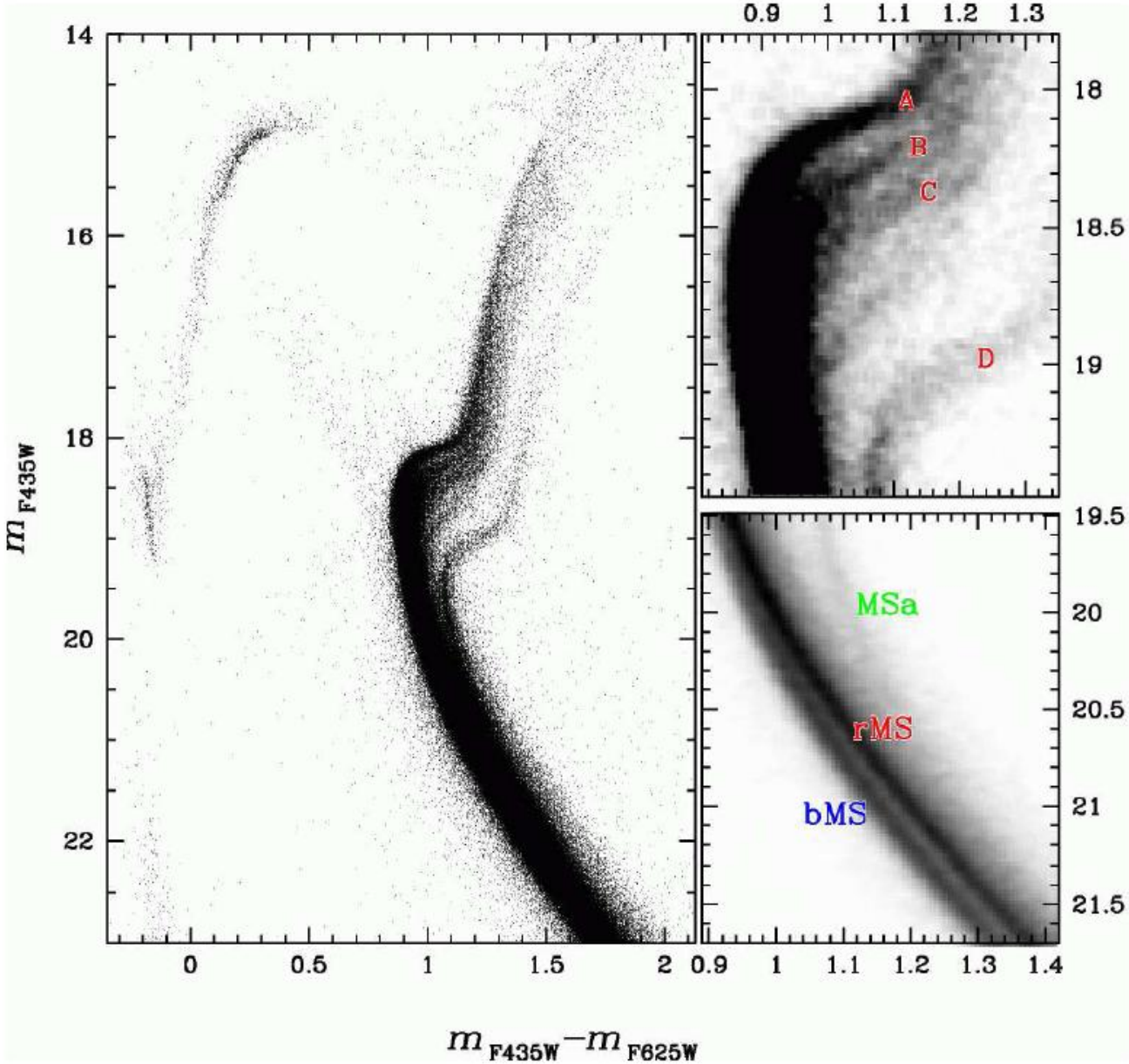
Cannon & Stobie 1973: RGB is WIDE!
NOT due to photo errors (2CD narrow) or differential reddening (reddest RGB * should lie above bluest in 2CD).

WHY??

Freeman & Rodgers 1975:
spectra of 25 RR Lyrae ➔
metallicity varies over 1 OOM!

MPs were born!

Now we know ϖ Cen is really complex!



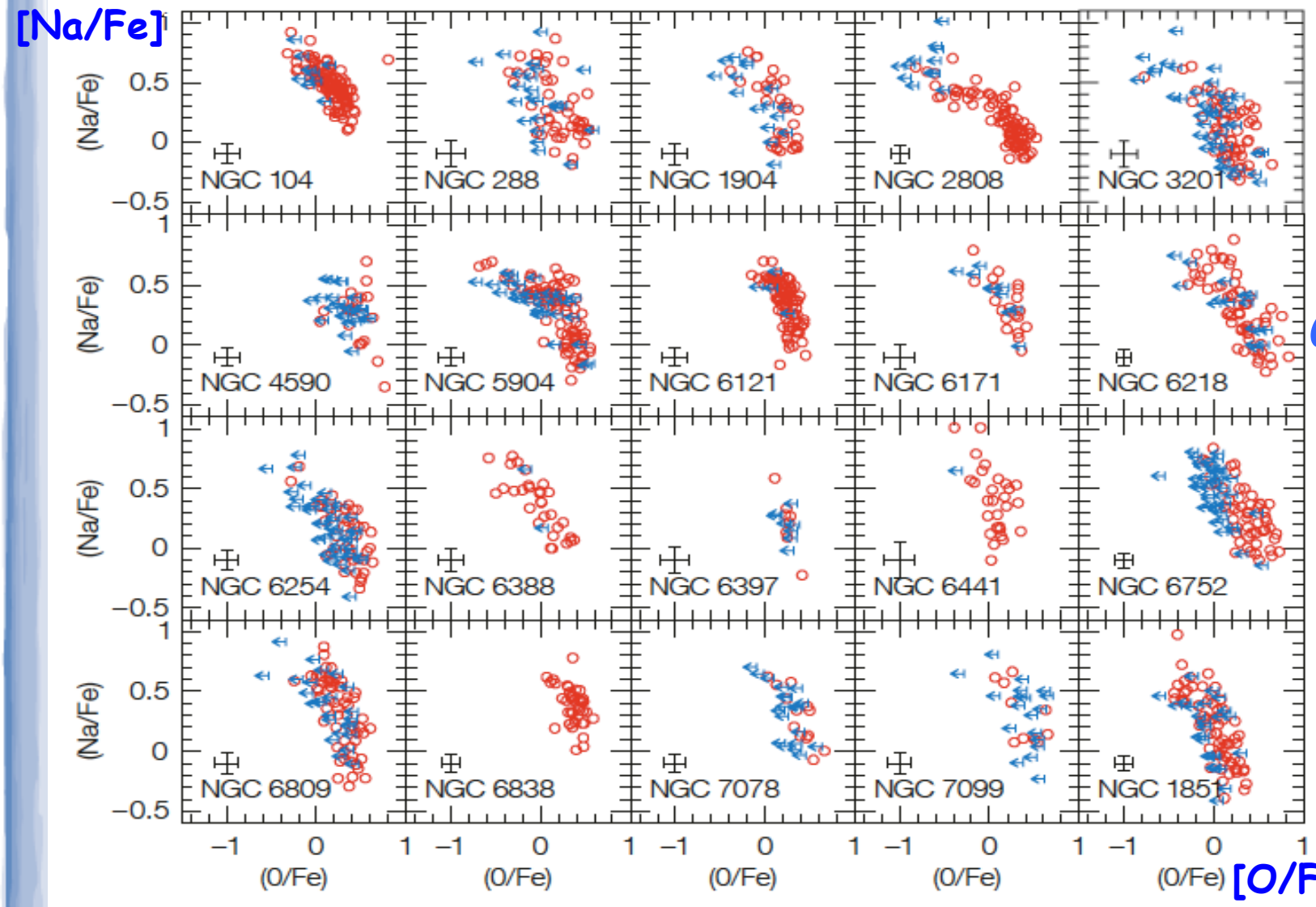
Bedin et al. '04

But ϖ Cen is weird!

UNIQUE!?

Na-O anticorrelation

Carretta et al. '09



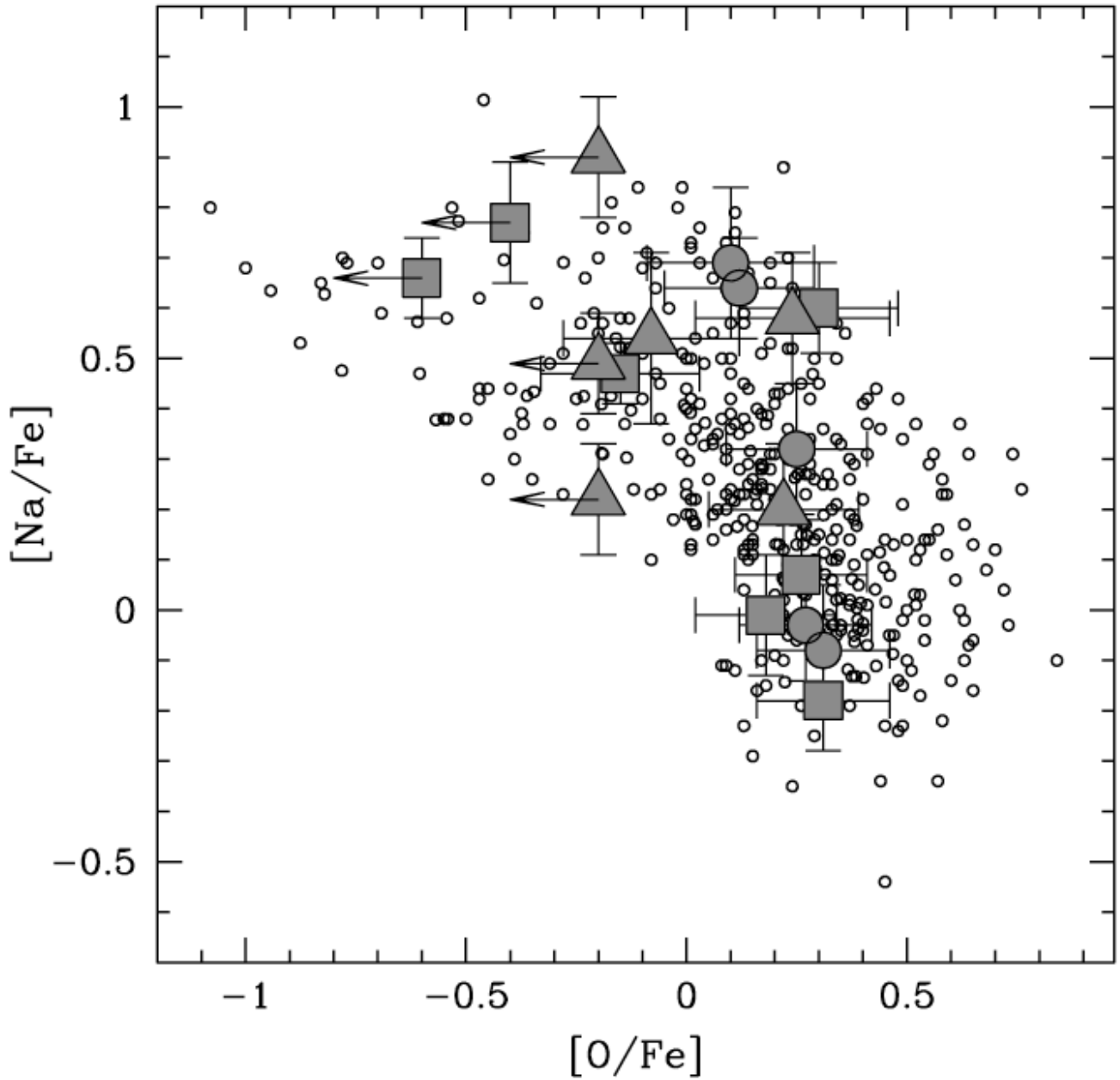
>200 ★ UVES

>2000 ★ GIRAFFE

FLAMES@VLT, 24 GCs

High Resolution Spectroscopy shows MPs (at least Na:O anticorrelation) are NORMAL in Galactic GCs

Maybe MPs are universal in GC?



Mucciarelli et al. '09:
3 old, massive
LMC GCs show same Na:O anticorrelation as in Galactic GCs!

Is there a difference between GCs and OCs (open clusters)?

Carretta et al. 2010:

Properties of stellar generations in globular clusters and relations with global parameters⋆,⋆⋆

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ABSTRACT

We revise the scenario of the formation of Galactic globular clusters (GCs) by adding the observed detailed chemical composition of their different stellar generations to the set of their global parameters. We exploit the unprecedented set of homogeneous abundances of more than 1200 red giants in 19 clusters, as well as additional data from literature, to give a new definition of *bona fide* GCs, as the stellar aggregates showing the Na-O anticorrelation. We propose a classification of GCs according to their kinematics and

New CHEMICAL definition!

GCs ≡ MPs (antithesis of old definition!)

OCs = SSPs(?)

What about other elements?

Observed to vary in all GCs

Observed to vary in some GCs

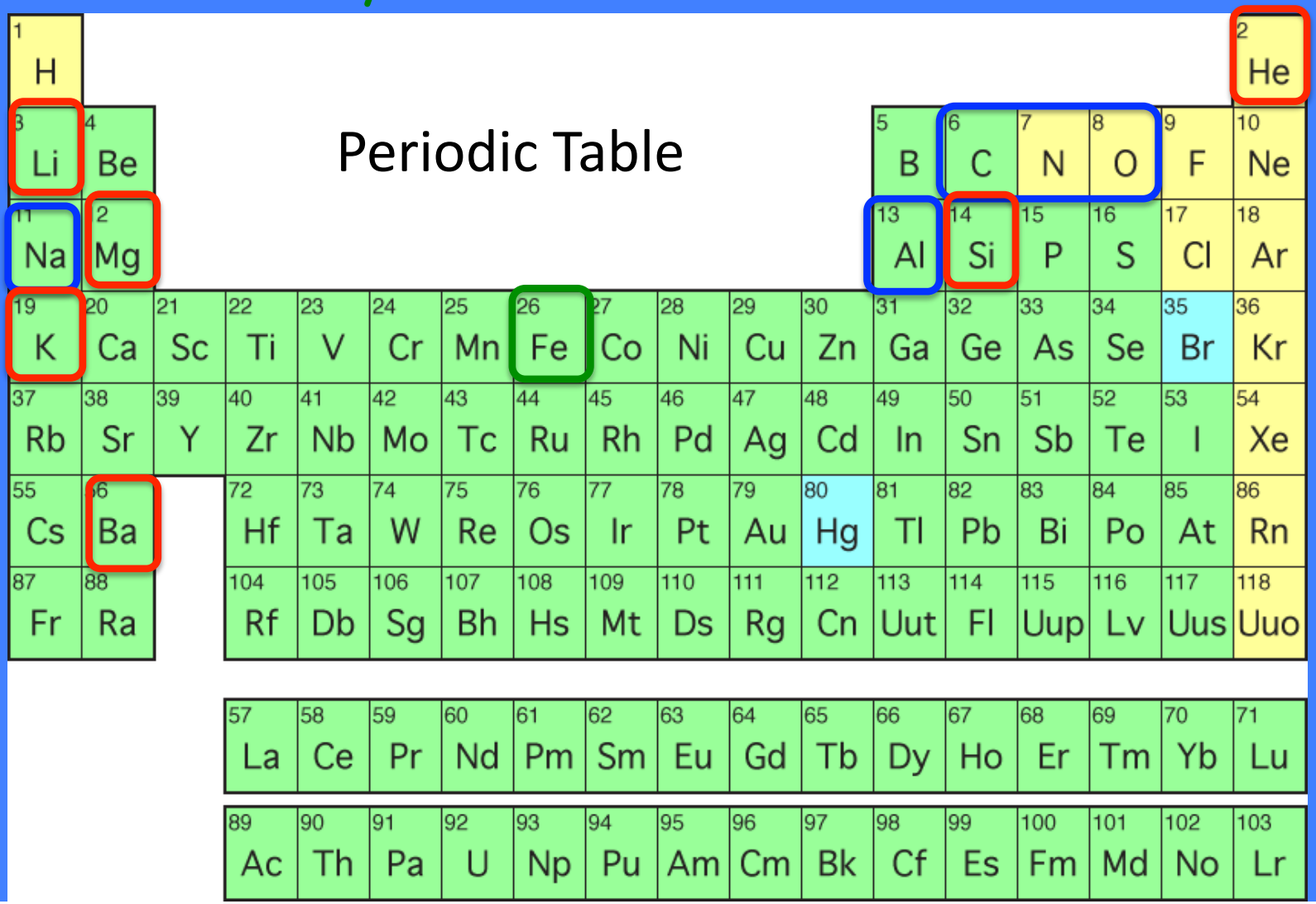
Observed to vary in a few GCs

Na:O anticorrelation:

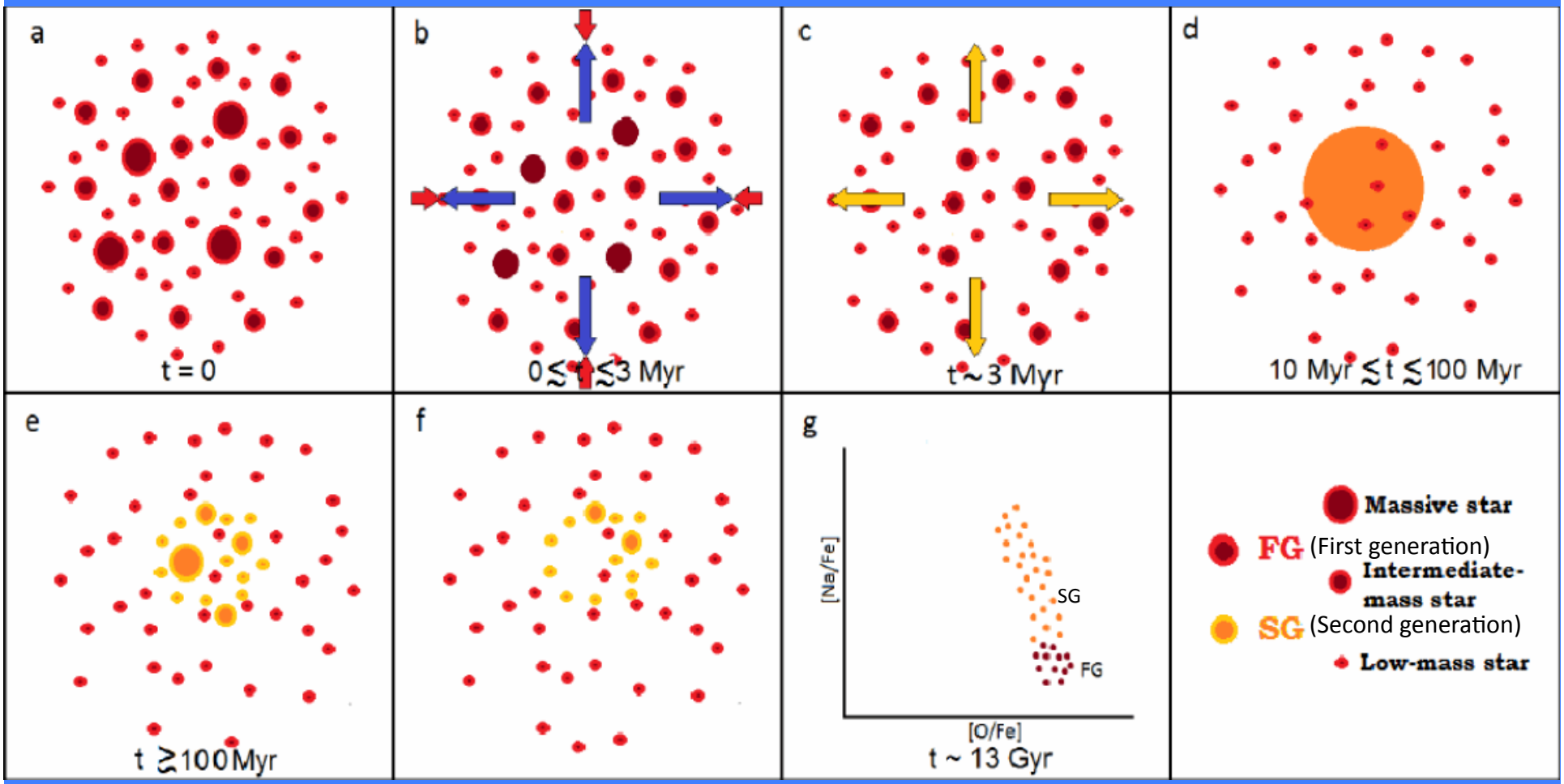
→ high temp. H-burning

→ high mass stars - pollute

→ polluted gas now in stars

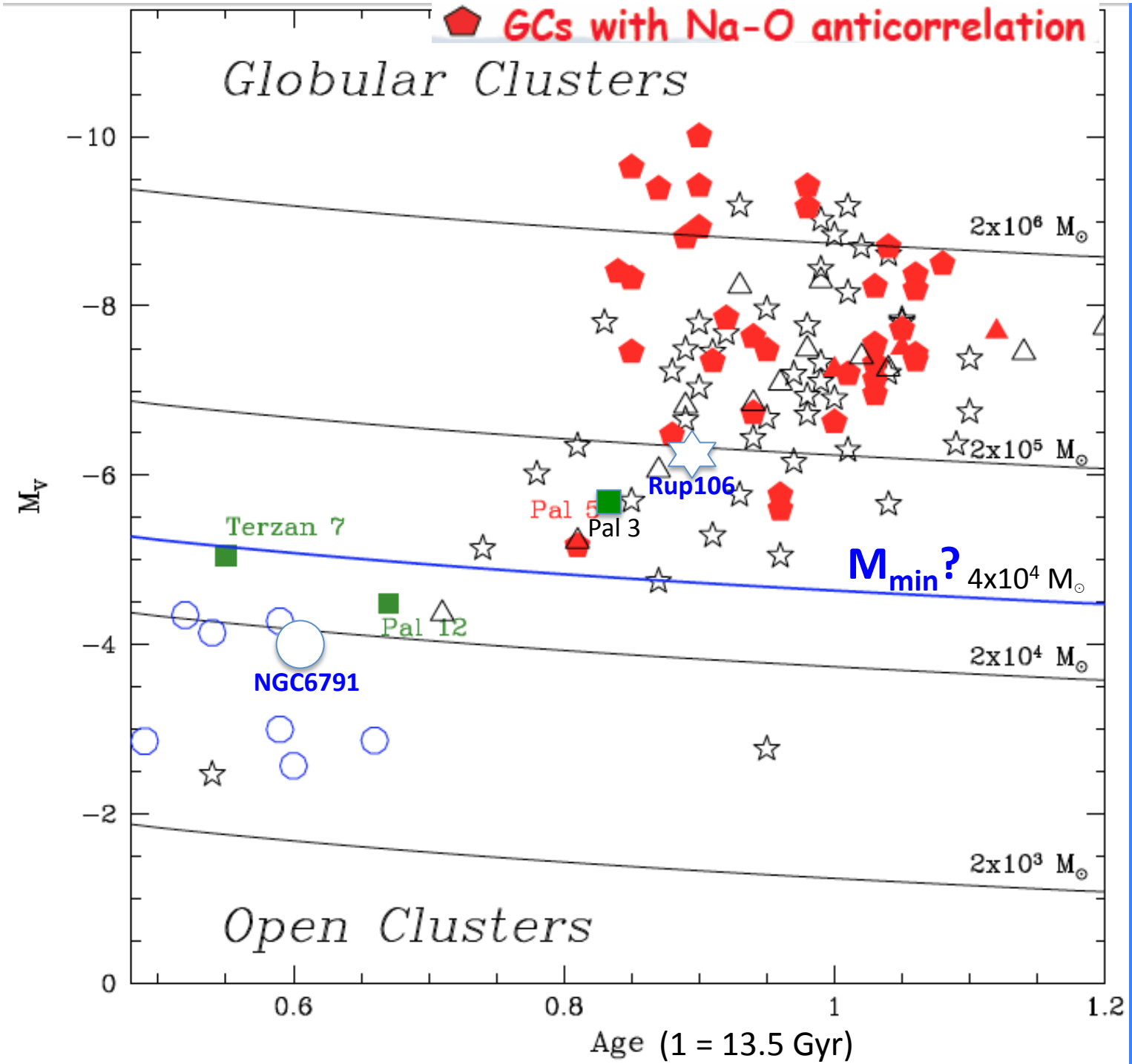


MPs = multiple(?) formation epoch(s) + chemical pollution



Valcarce & Catelan '11: FG forms from raw ISM – SNeII: gas & * expelled – stellar winds (fast rotating MS* Decressin '07, or AGB* Ventura et al. '01) collect polluted material (Na rich, O poor) in center in ~10^7 (or ~10^8) yr – SG forms – gas lost. INITIAL MASS critical – need to retain gas + ejecta.

D'Ercole et al. '08: 90+% original cluster mass lost! Mass budget problem!



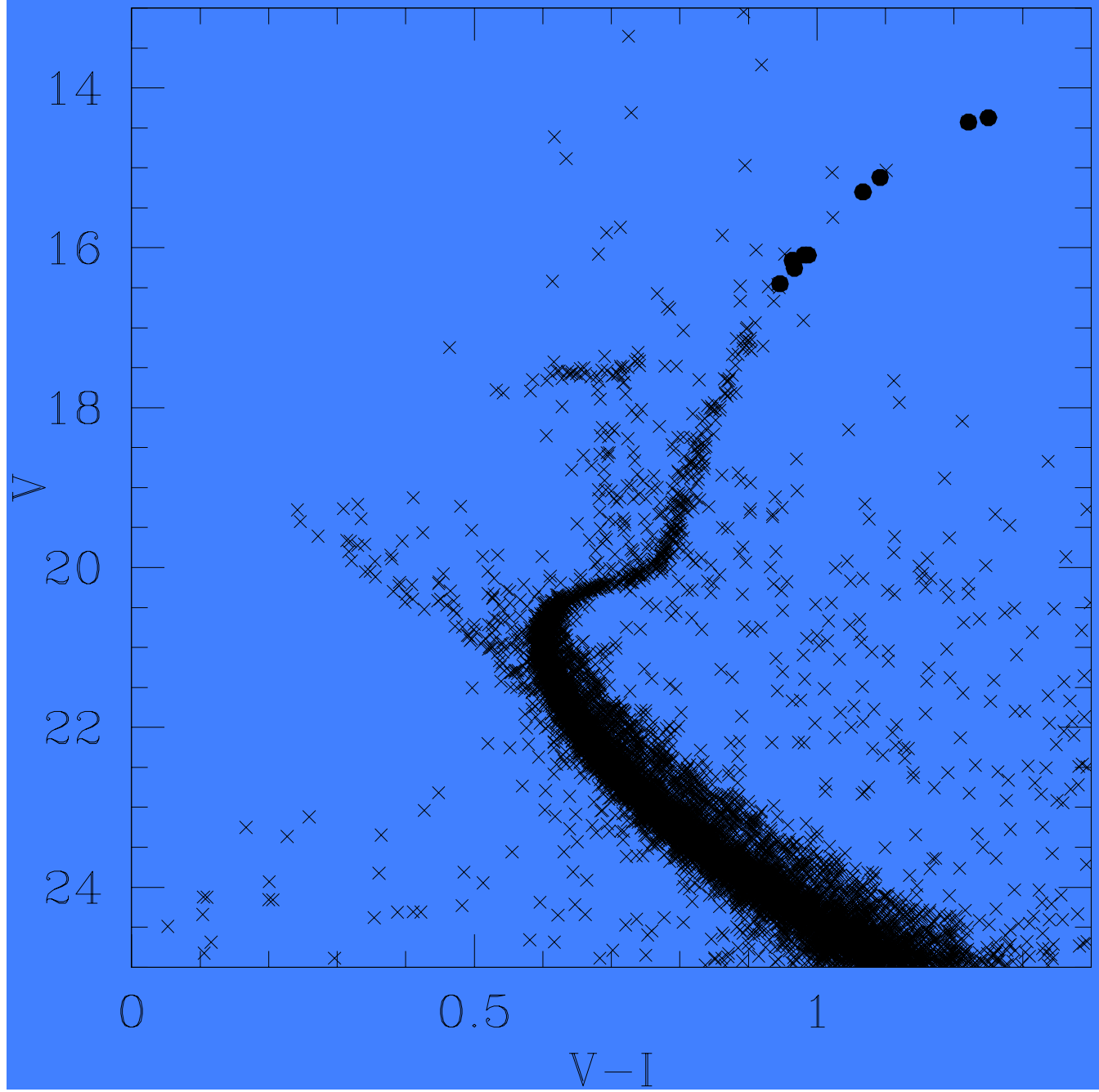
Carretta et al. '10: search for M_{min} limit between MPs (GCs?) & SSPs (OCs?)

So far, OCs DON'T show MPs...

Both theory and observations so far suggest M_{min} ~few 10^4-$10^5 M_\odot$.

Study low M GCs, high M OCs and look for MPs...

Study MPs spectroscopically



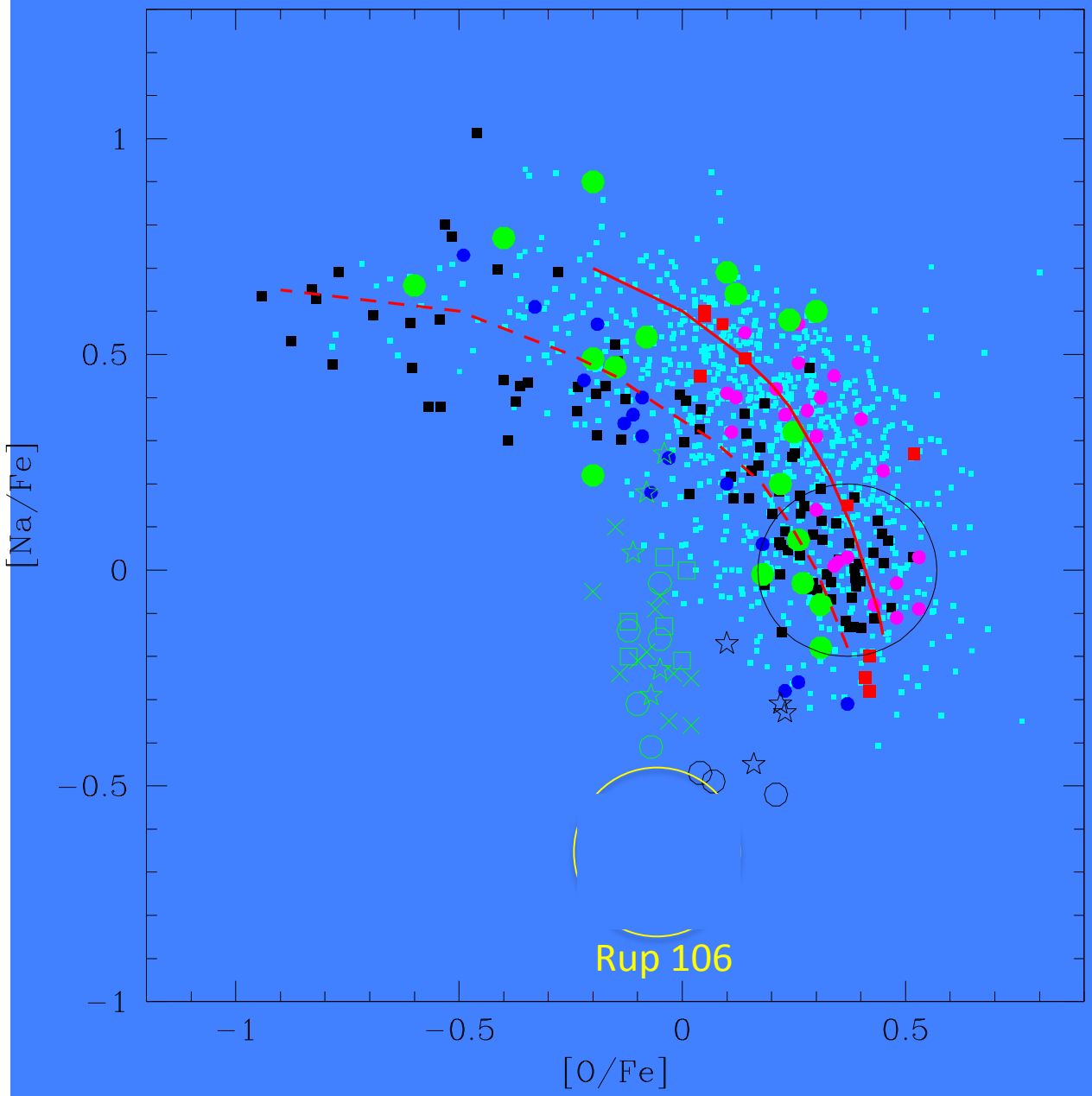
Caloi & D'Antona '11-
Best SSP candidates:
"GCs" with log M<4.8
+ stubby HB for [Fe/H]

Villanova et al. 2013:
Ruprecht 106: low M
GC with stubby RHB
- does it have MP?

Observations:

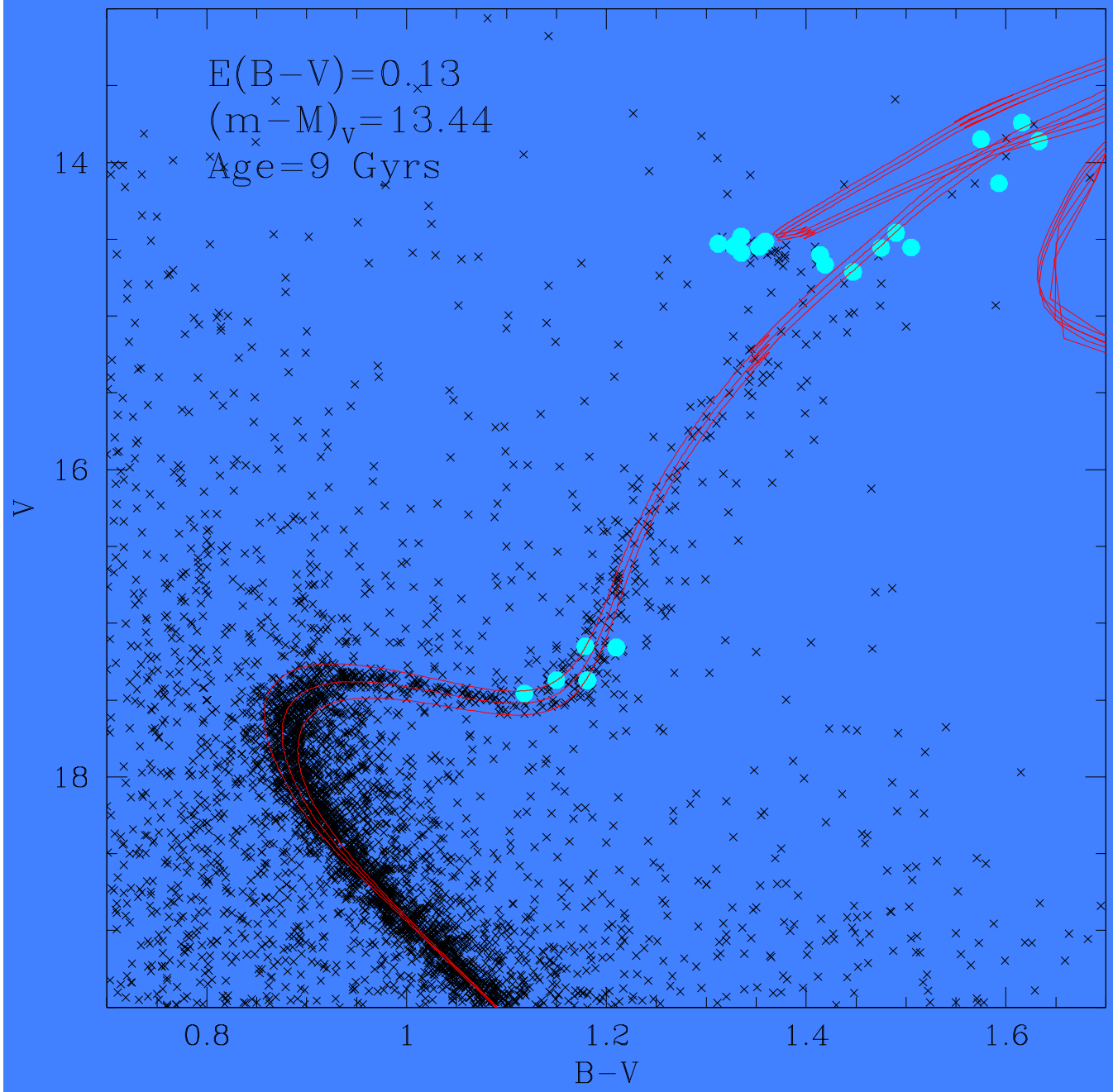
- VLT+UVES
- 10 upper RGB stars
- R=47000
- S/N=50-70

Rup 106: first GC without MPs!?



- No O or Na spread (or in any other element)
- P(missed SG)=.008% but need larger sample...

How about OCs?



Geisler et al. 2012:

NGC6791: classical OC

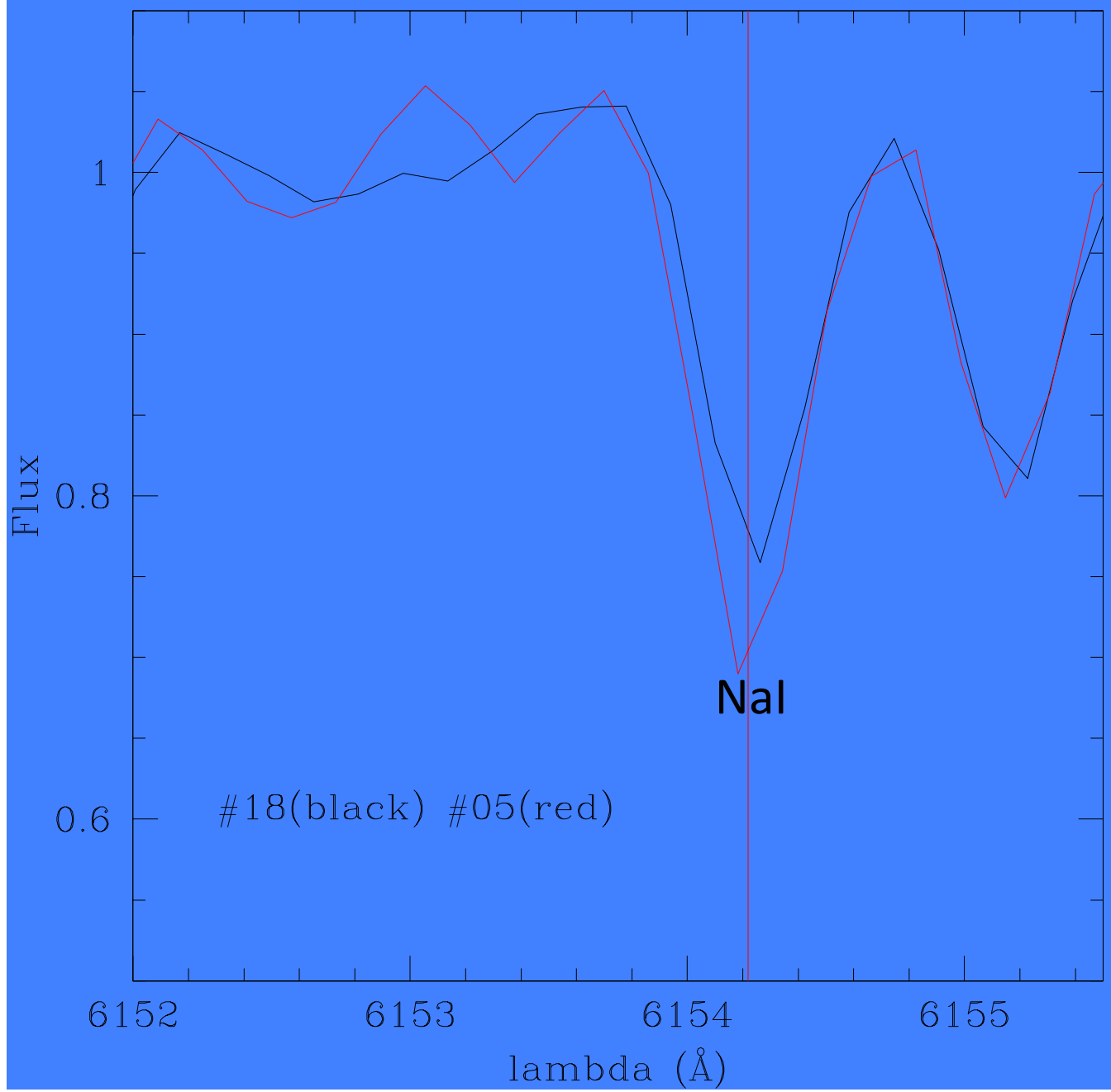
- does it have MP?

Observations:

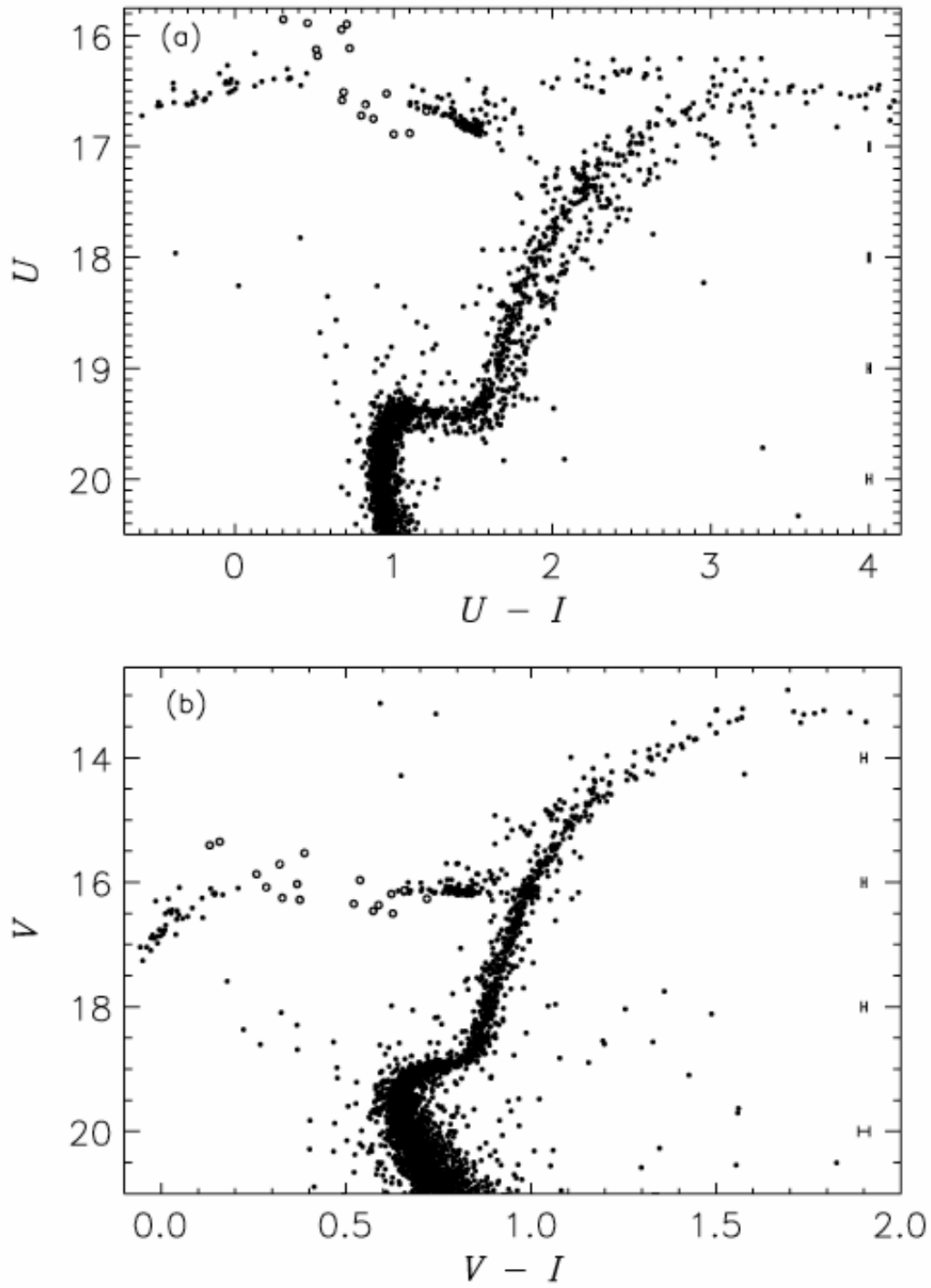
- Keck I + HIRES
- 5 lower RGB stars
- R=45000
- S/N=50

- WIYN + Hydra
- 19 upper RGB, RC *
- R=15000
- S/N=70

NGC 6791: First OC with MPs!???



Compare 2 RC *s with identical parameters:
absorption spread
≡ abundance spread!
BUT
several other studies (Bragaglia et al. '14, Cunha et al. '15) find NO Na/O spread but did not analyze any Na-poor stars...

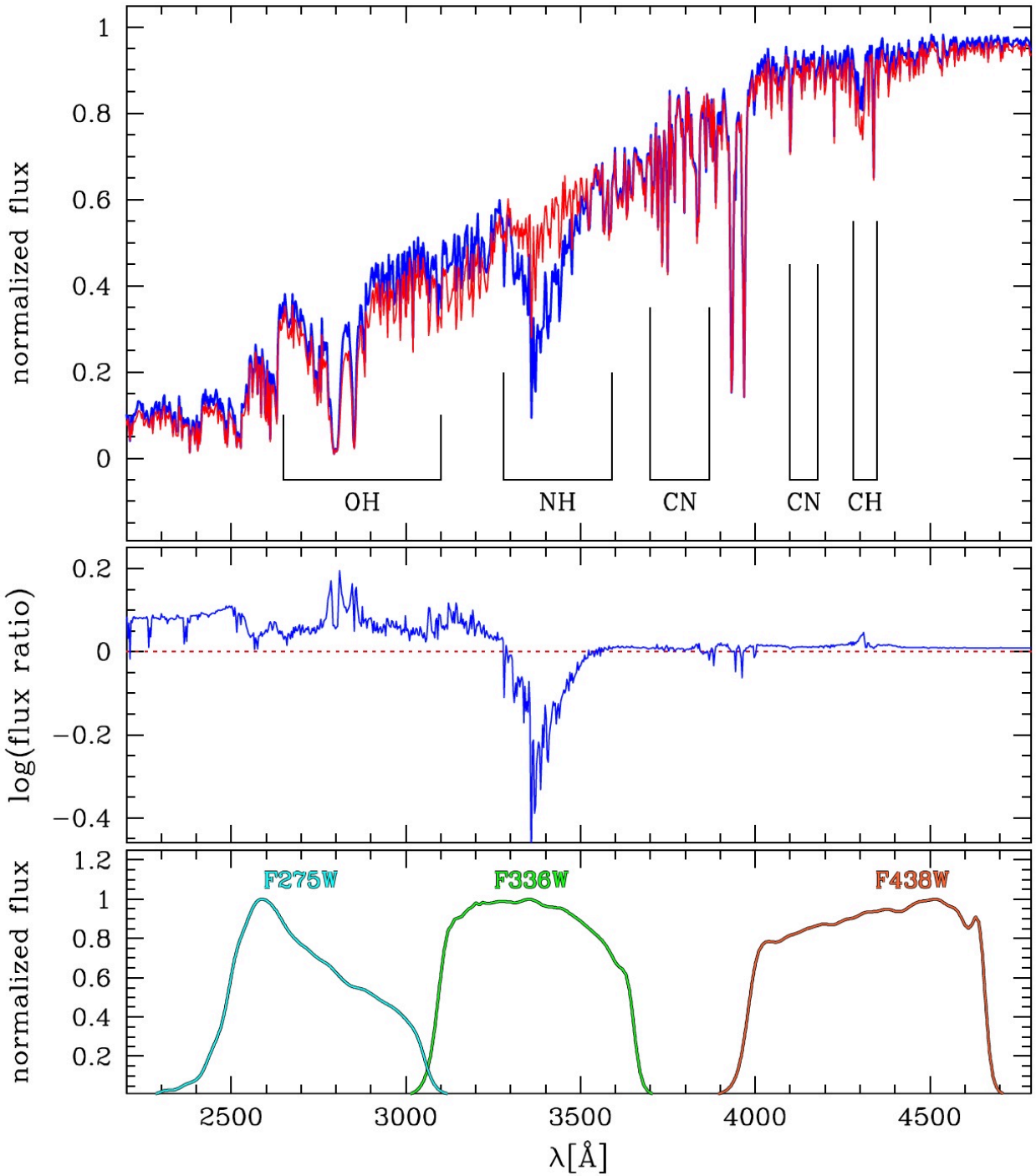


Study MPs photometrically:

Han et al. 2009:
UVI observations of NGC 1851
Some filters can pick up MPs...

some can't.
If sequences look simple,
you're using wrong filters...

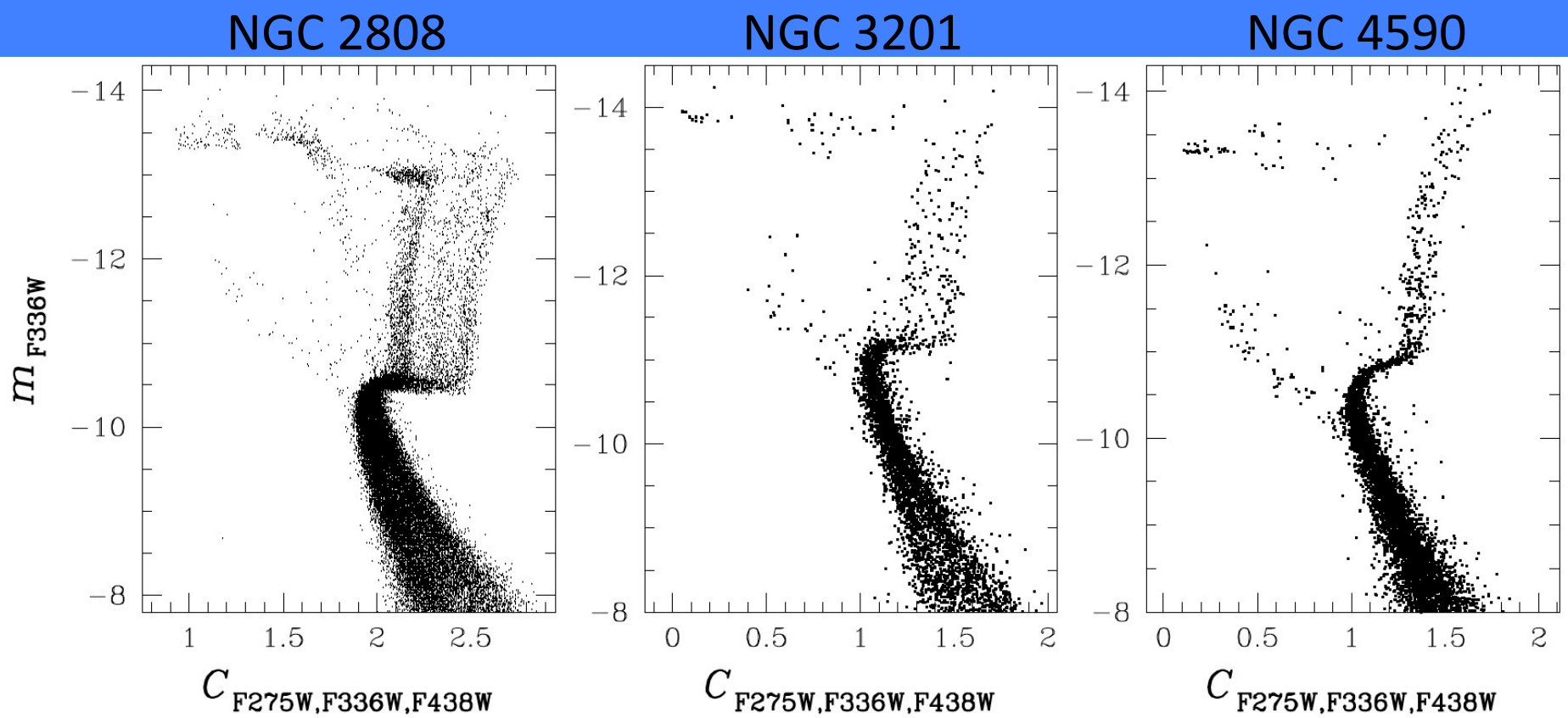
Requires UV filter!



Piotto et al. '14:
"magic trio" of HST UV WFC3 filters:
F275W
F336W
F438W

Very effective at uncovering MPs – RGB CNO variations in molecular bands: "DNA mapping". Conducting UV legacy survey of Galactic GCs

Bewildering variety of MP behavior

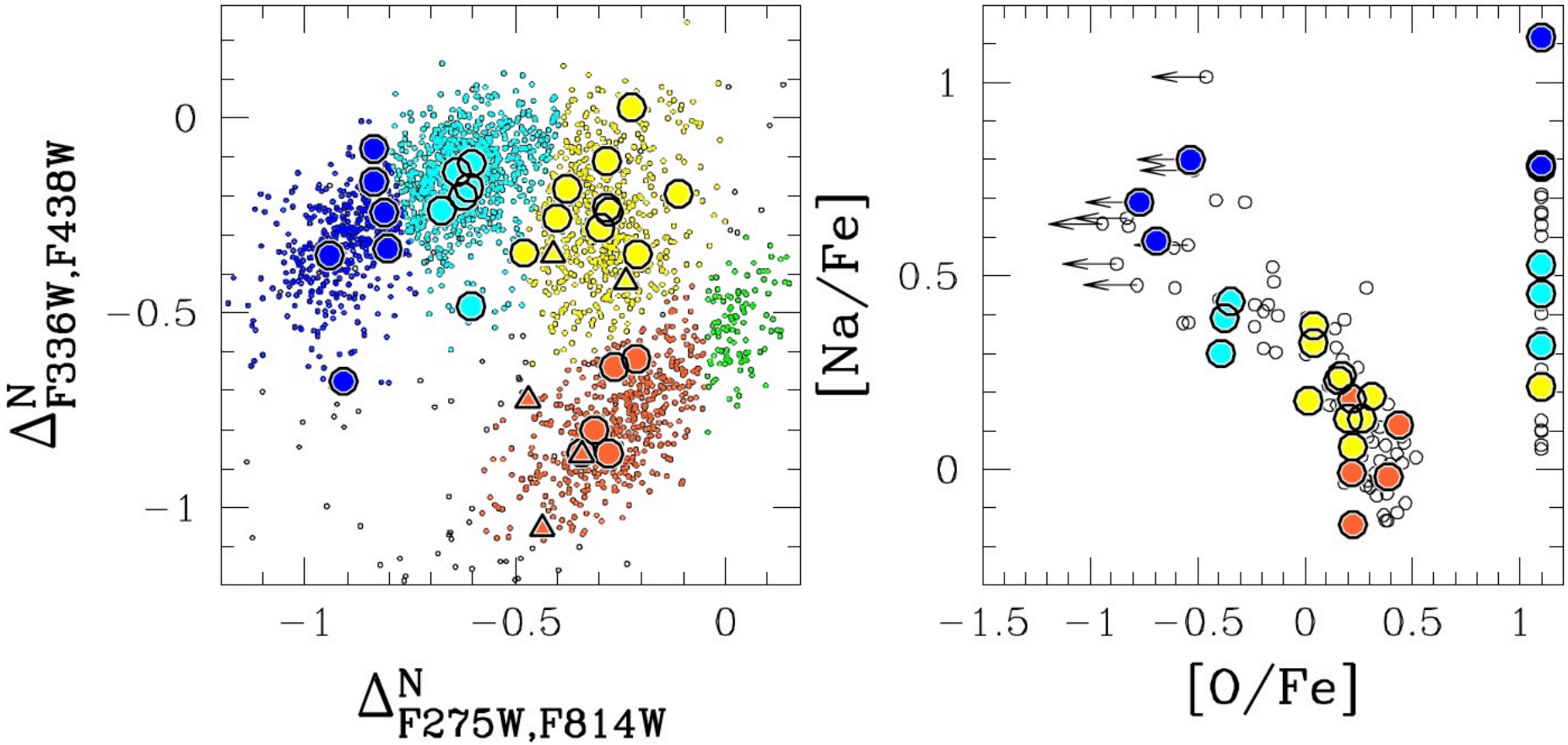


57 GCs – 57 different color distributions! All show MPs (but don't include Ruprecht 106...)

GC formation theory to explain full range of observations will need to be complex!

Put photometry and spectroscopy together

Milone et al. 15: NGC 2808

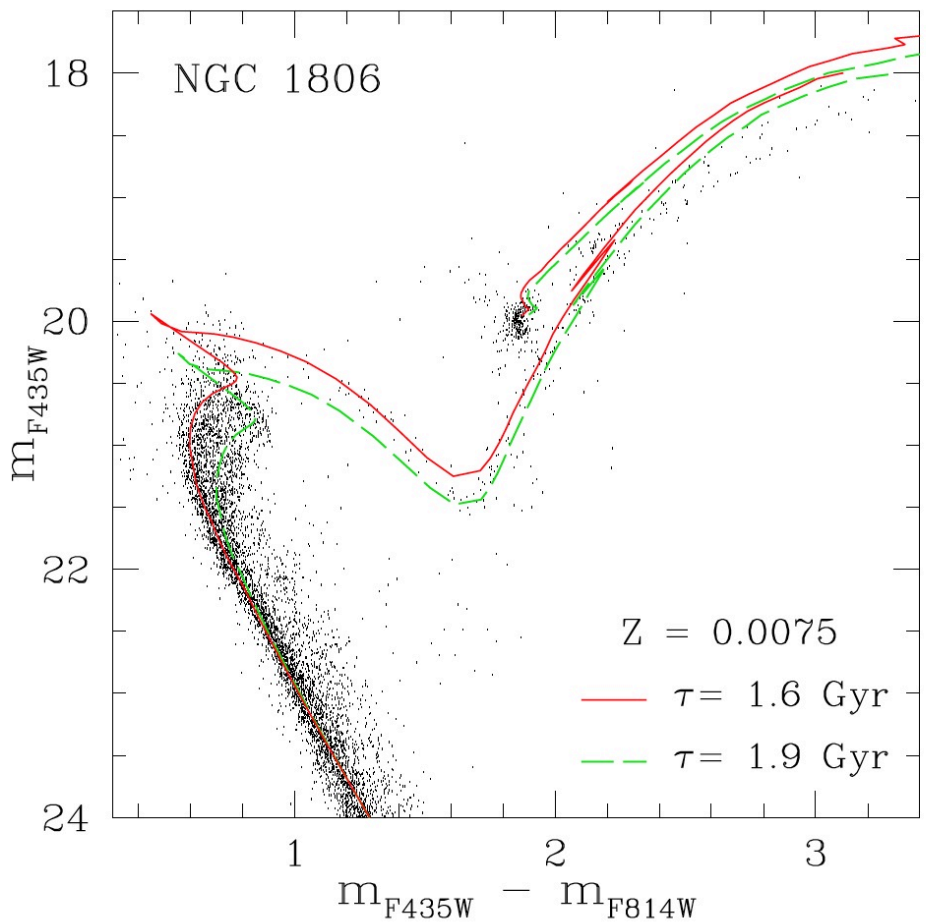


Has at least 5 pops photometrically which map cleanly into Na:O anticorr.

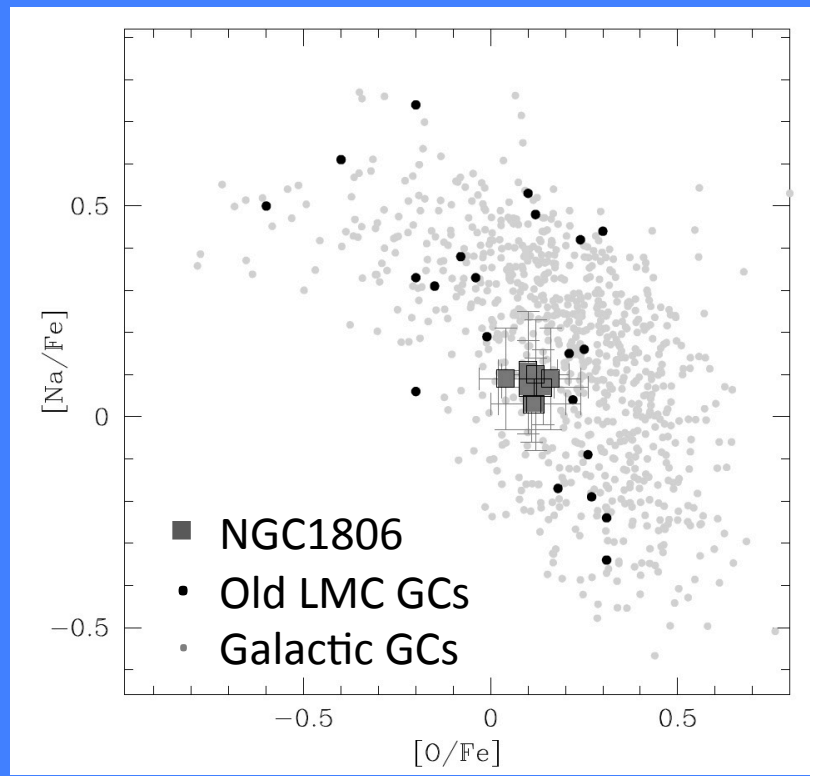
Extended MS Turnoffs (eMSTO) in Intermediate-Age Magellanic Cloud Clusters (IACs)

Milone et al. '09 – 70% of sample of LMC IACs show eMSTO

Mackey et al. '08 – NGC1806 $10^5 M_\odot$
1.7Gyr - Age spread of ~300Myr?

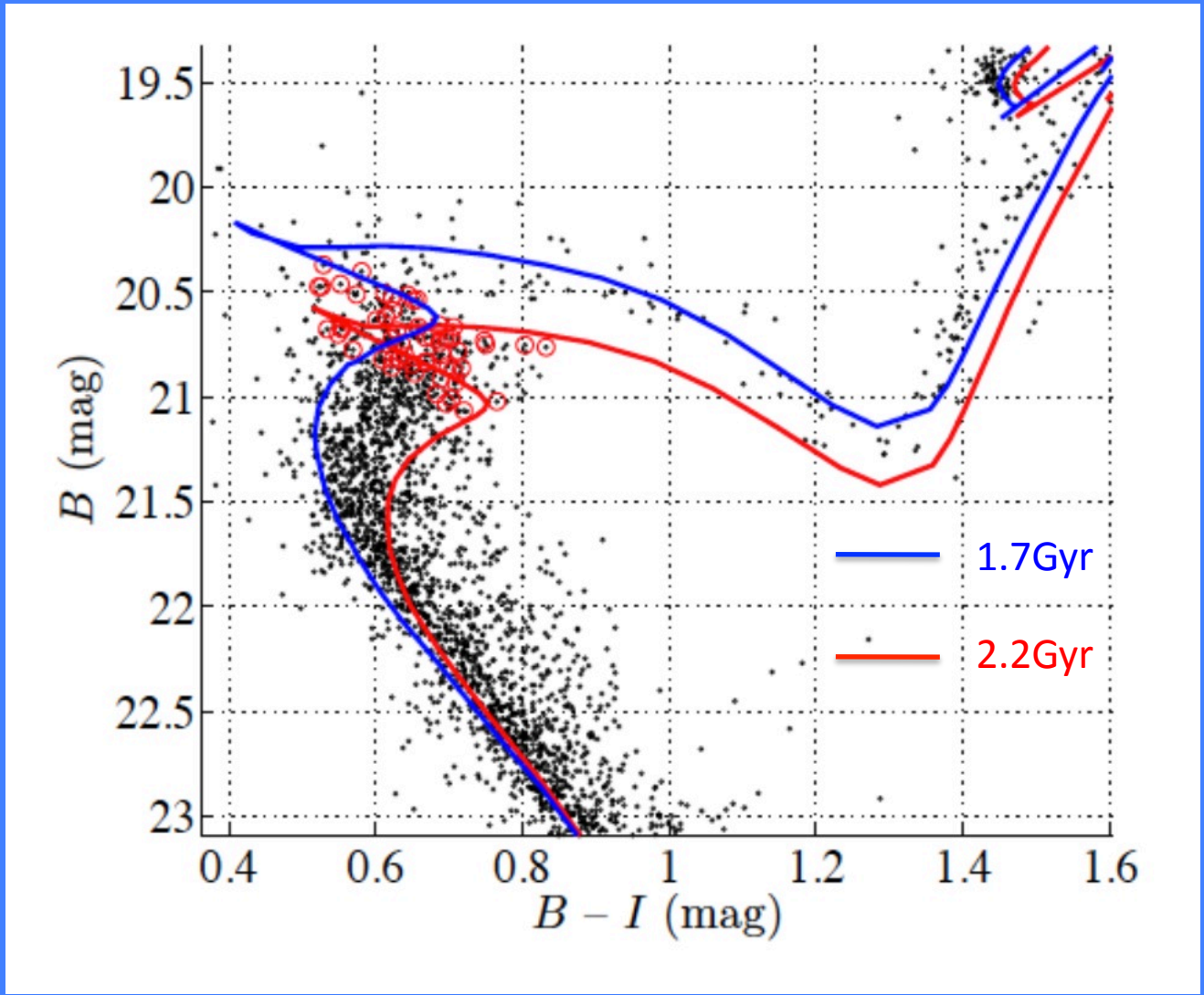


Mucciarelli et al. 2014:



No Na:O anticor in IACs with eMSTO: can't explain eMSTO with abundance differences

Li et al. 2014:

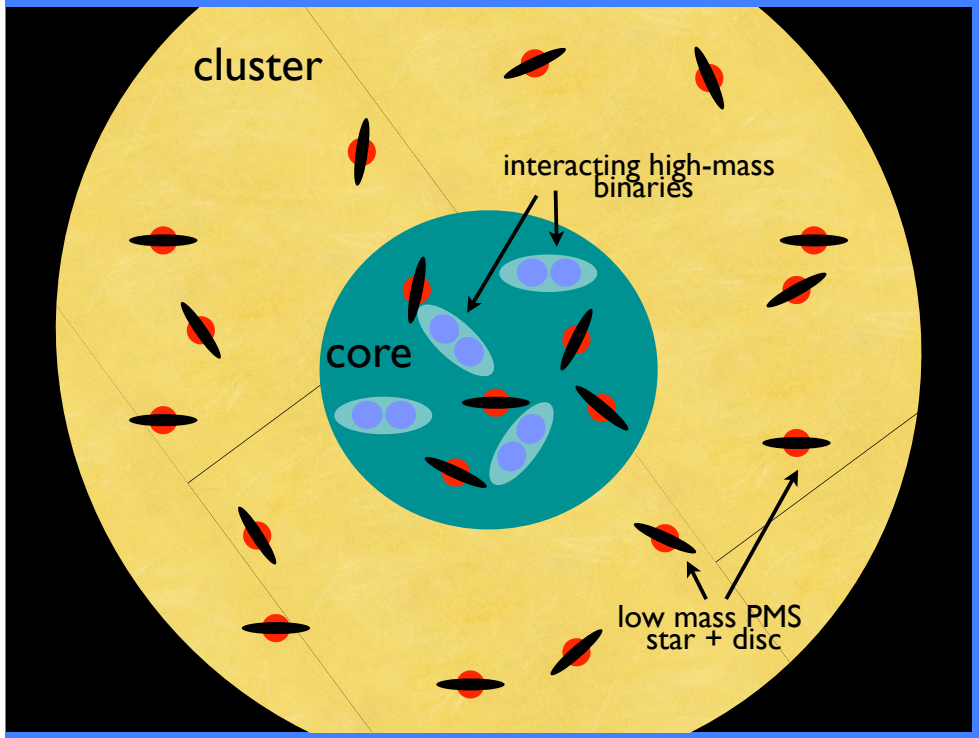


NGC 1651: eMSTO $2x10^5 M_\odot$ has single-age SGB – NO large age spread!

Bastian and de Mink 09: eMSTO caused by spread in rotation...

A word re: theory: Early disc accretion model

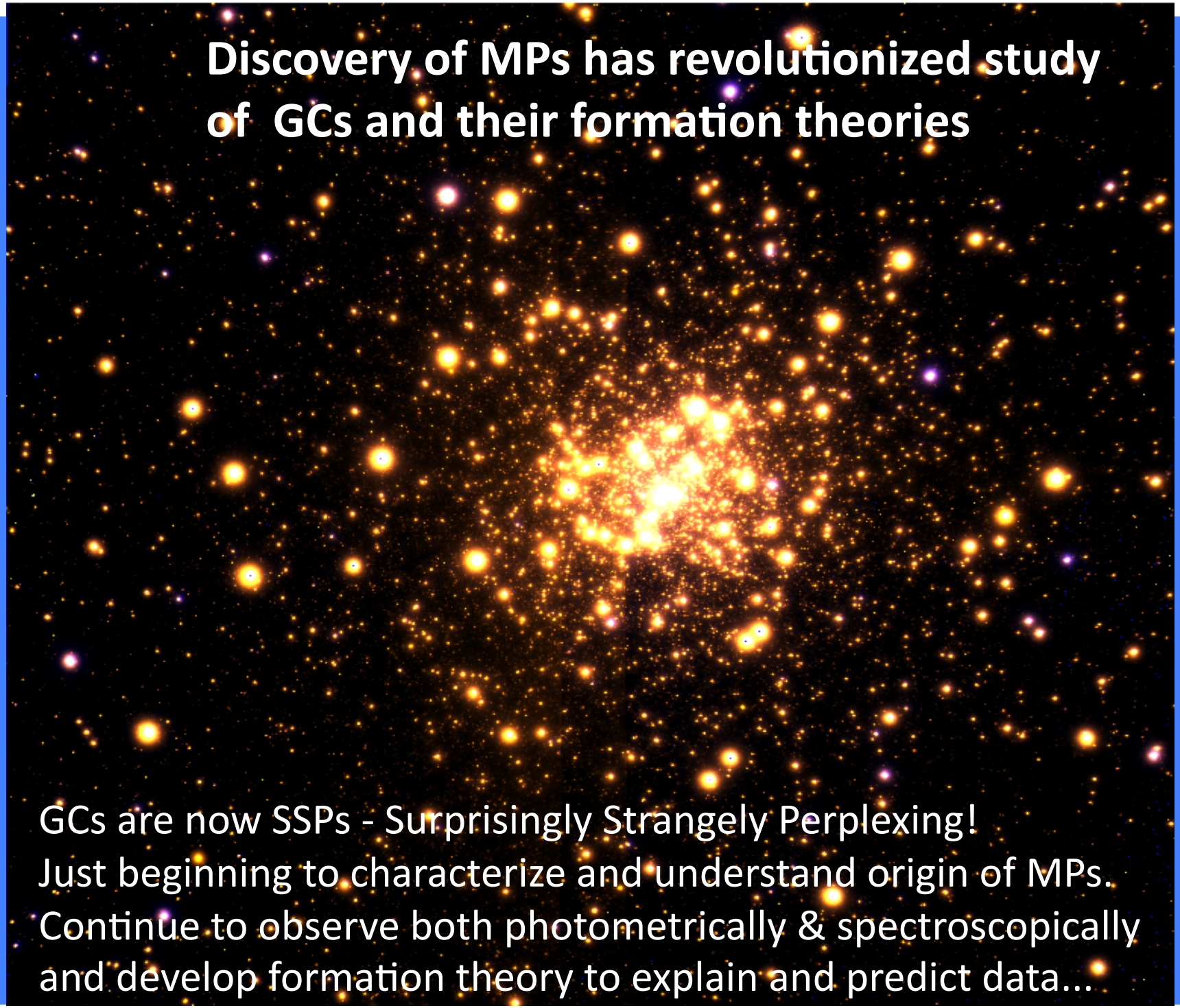
Bastian et al. 2013



- No multiple SF epochs
- No mass budget problem
- Explains why young massive clusters are gas free after ~2 Myr and don't show extended SFHs
- Can disks survive long enough?
- Are abundances correct?

No theory can account for all obs.

- single burst of star formation (i.e. SSP) – "FG"
- high mass stars (binaries) mass segregated to center
- interacting binaries and massive spin-stars eject (low velocity) processed material into center
- low mass pre-MS stars keep discs for ~10Myr, entrain processed material moving thru center
- material eventually accretes onto young star (<< stellar mass) – "SG"



Discovery of MPs has revolutionized study of GCs and their formation theories

GCs are now SSPs - Surprisingly Strangely Perplexing!
Just beginning to characterize and understand origin of MPs.
Continue to observe both photometrically & spectroscopically and develop formation theory to explain and predict data...