
# Multiple populations: spectroscopic evidence (history and prehistory)

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# Multiple in many ways

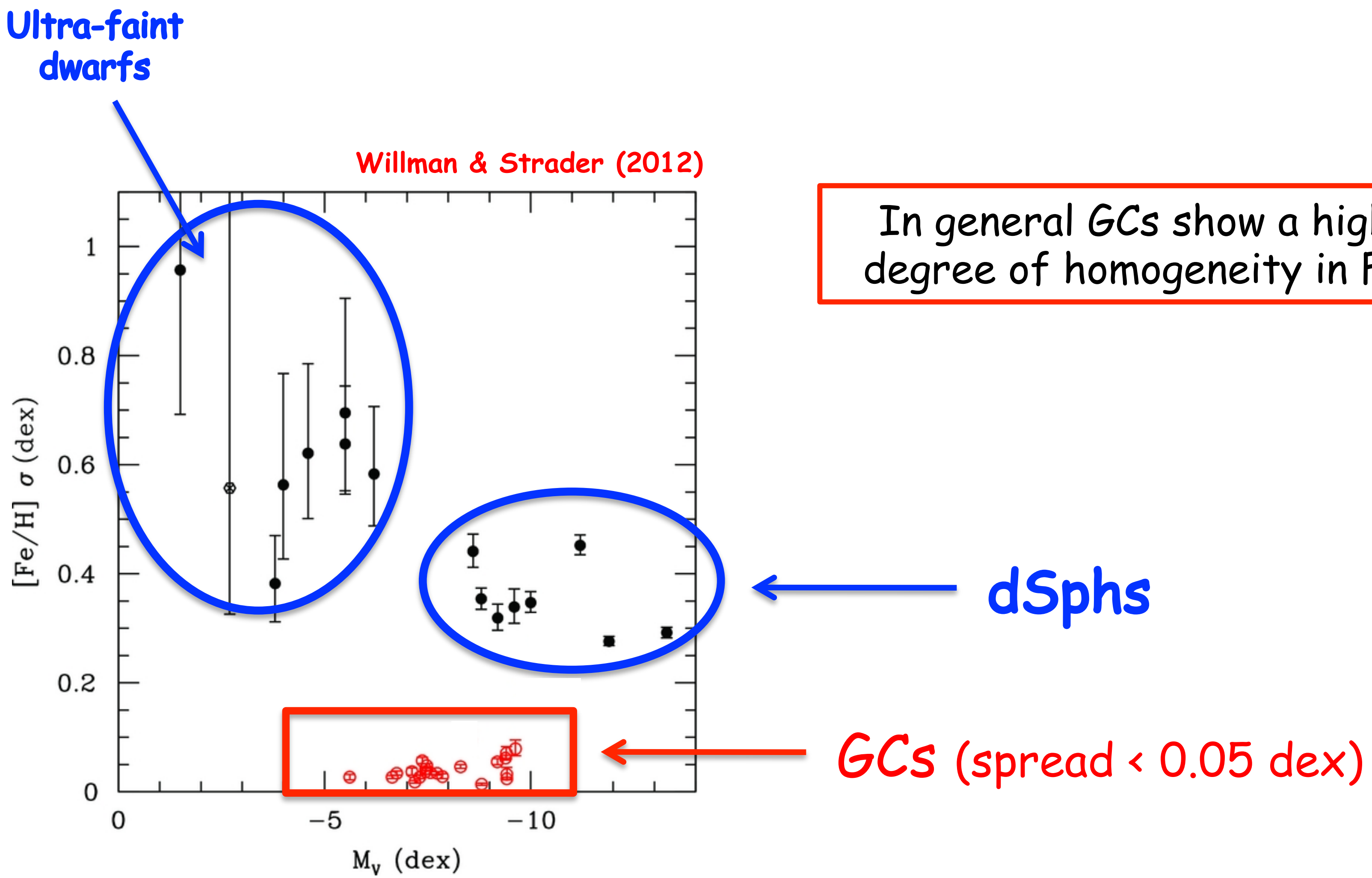
**GCs with homogenous Fe but spreads in light elements (C,N,O,Na,Al…)**

These systems did not retain SN ejecta but only those of AGB stars, fast-rotating massive stars, massive interactive binaries…

**GCs with spreads in Fe**

These systems were able to retain SN ejecta

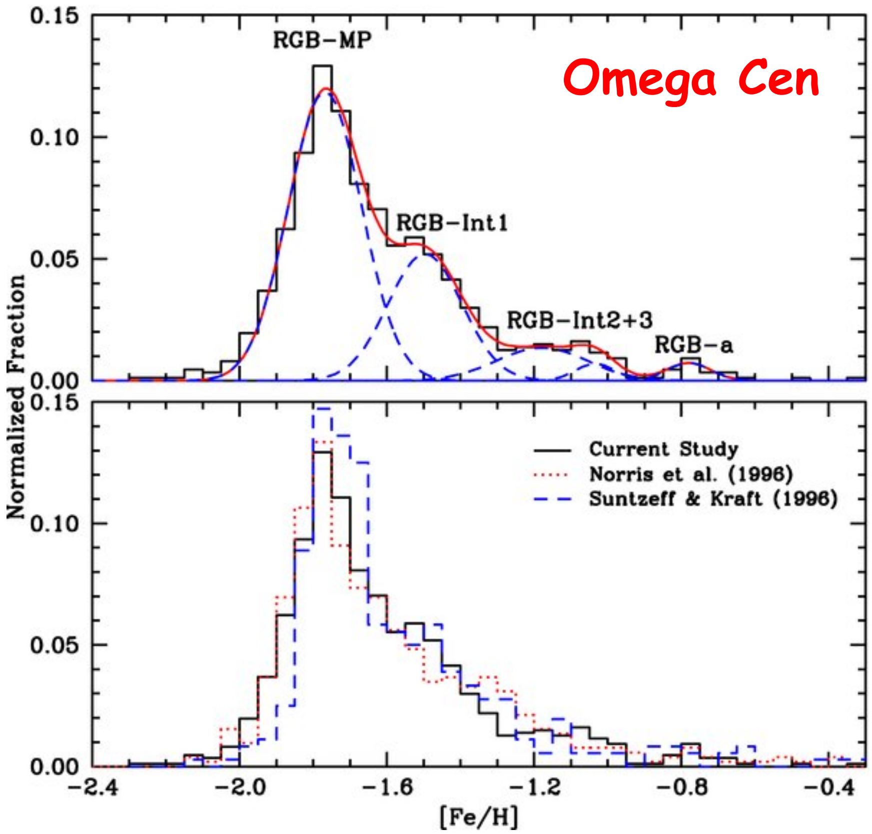
# Most of the GCs are homogeneous in Fe



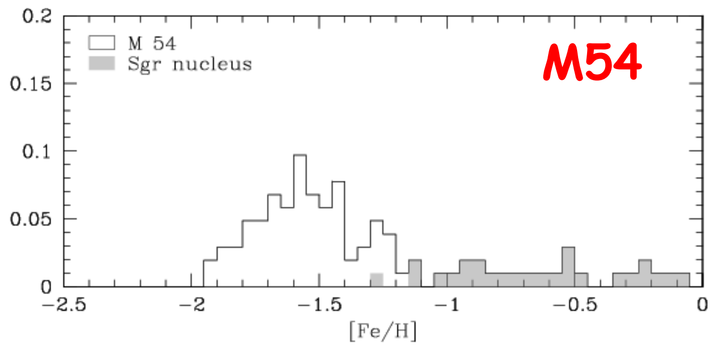

In general GCs show a high degree of homogeneity in Fe

# But some strange beasts have Fe spread

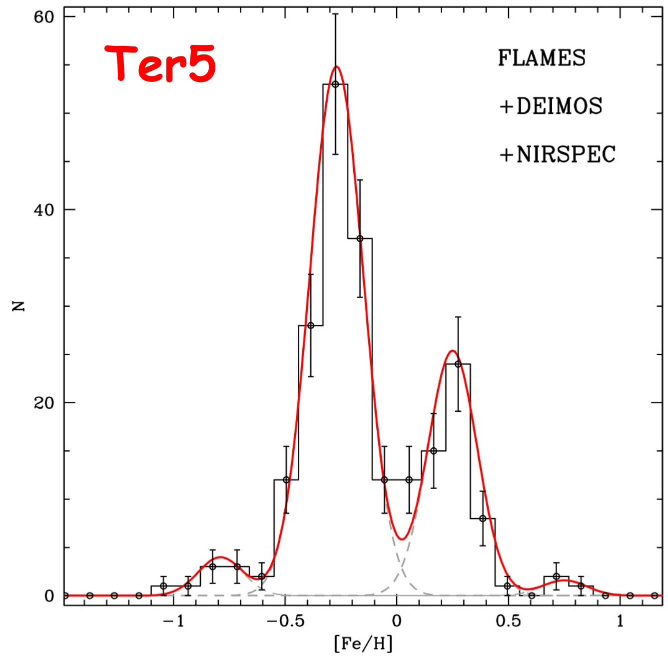
Johnson & Pilachowski+10




Carretta+10

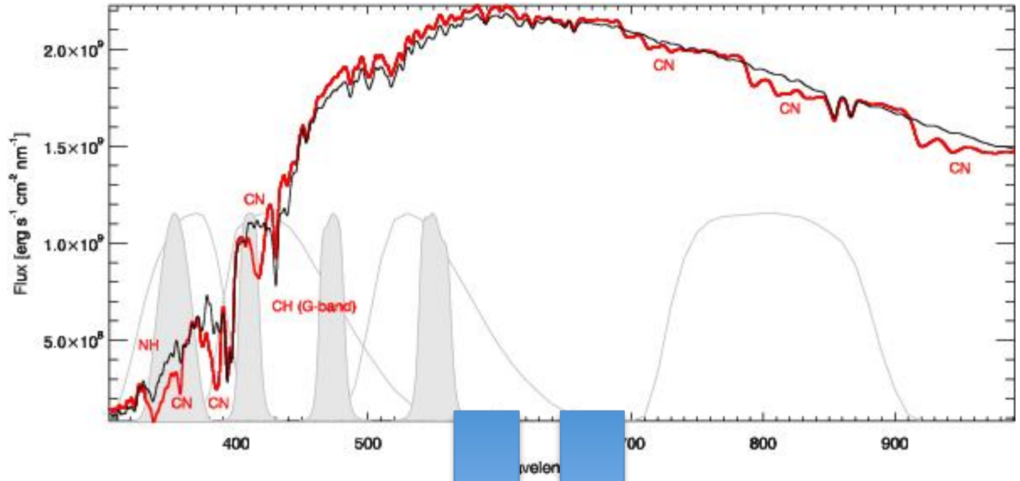



Massari+14




But other GCs have been proposed to have smaller Fe spread (controversial evidence):
M22 (Marino+09, Mucciarelli+15, Lee+17),
M2 (Yong+14, Lardo+16) …

Sbordone+12



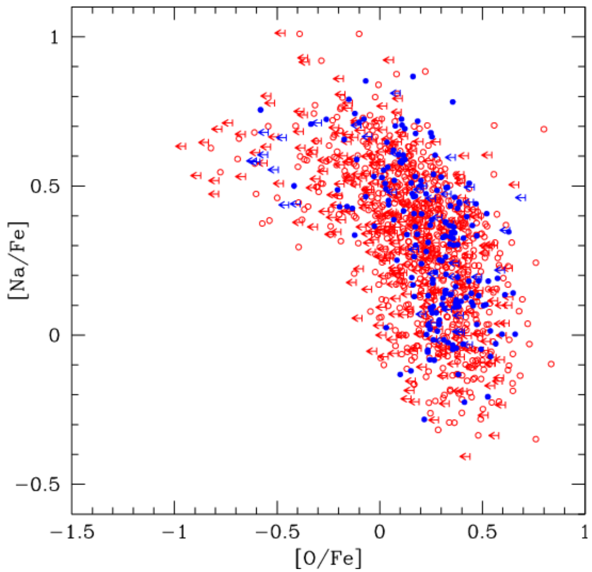

## Spectroscopy

Star-to-star variations
in some light elements

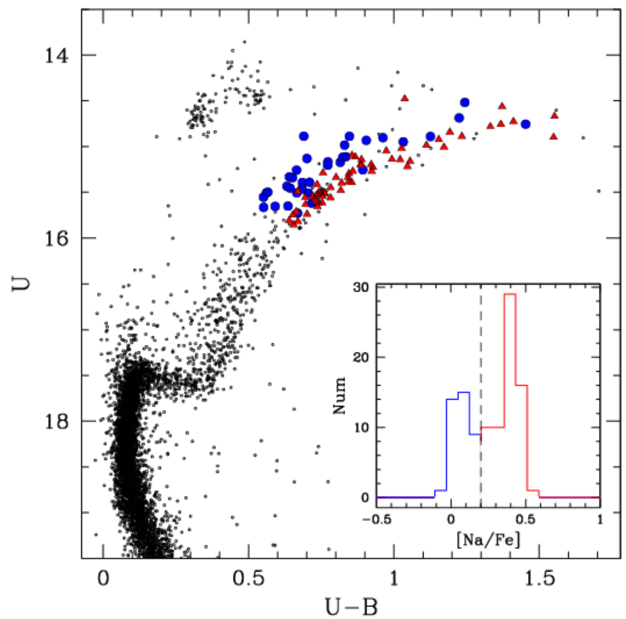
## Photometry

Splitting of the sequences
with suitable filter combinations

Carretta+09




Marino+08



# The history of MPs started by accident …

**Ph.D. Thesis of Wayne Osborn (Osborn 1973)**
Determination of temperatures, gravities and metallicities of stars in 5 GCs using suitable intermediate-band photometric colors

**By-product of this work (Osborn 1971):**

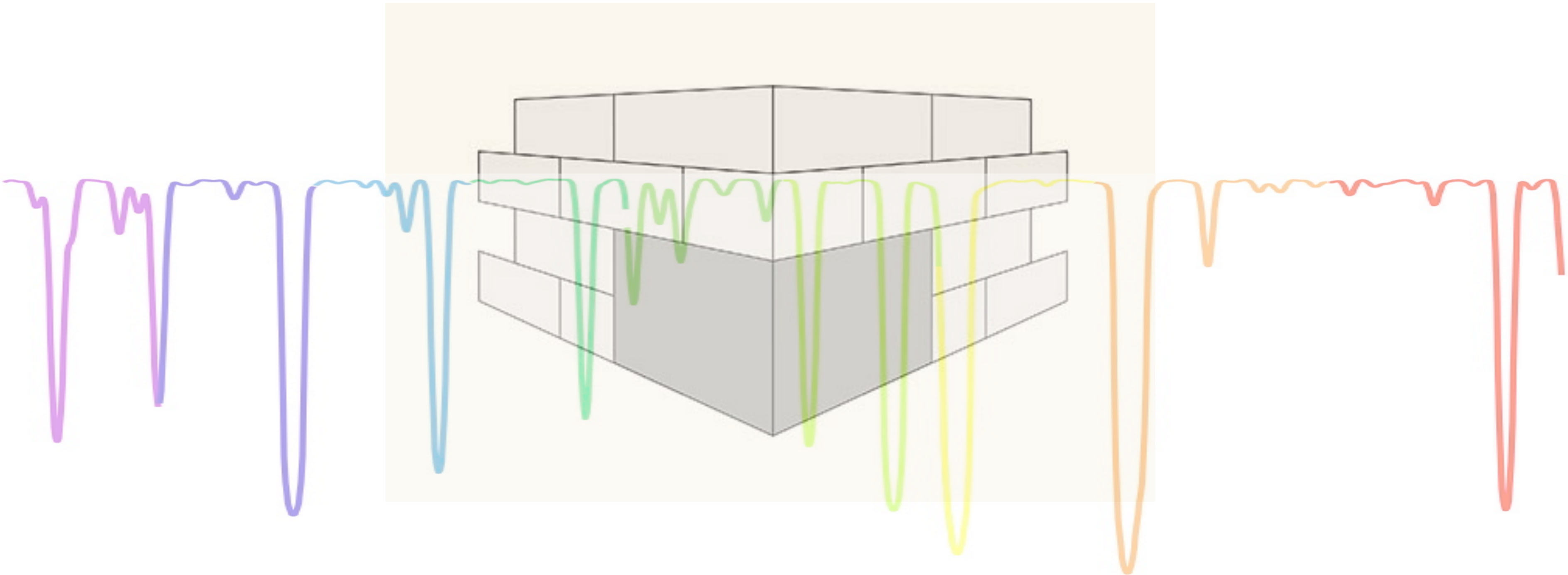
Two CN-strong RGB stars
(one in M10 and one in M5)

## Three main spectroscopic *cornerstones*

(1) CN-CH anomalies

(2) Na-O anticorrelation

(3) Down to turnoff



# The first cornerstone: CN-CH anomalies

**CN anomalies** in other in GC giant stars (with photometry or low-res spec)
(Strom & Strom 1971, Zinn 1973a,b, Freeman & Rodgers 1975, Hesser+76, +77)

**Hesser+77:**
Photometric survey of 145 RGB in 17 GCs.

**CN variations:**
- *in all the GCs*
- *regardless of the GC metallicity*
- *larger than those observed in field stars*

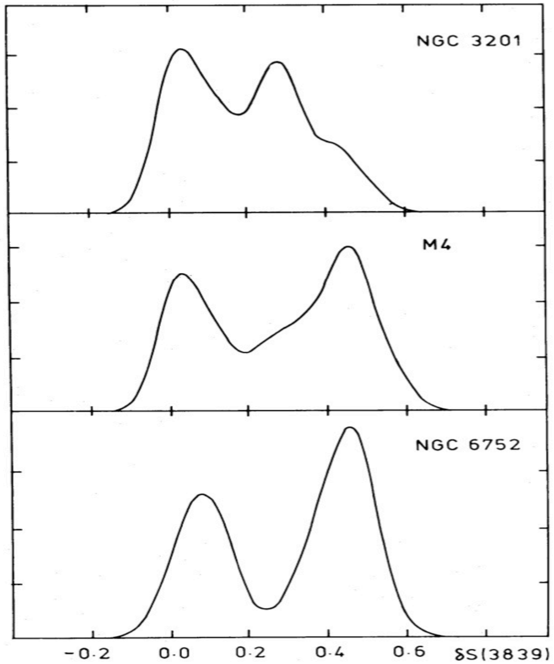
**CN-strong stars only in GCs and not in the field**

# The first cornerstone: CN-CH anomalies

## CN-bimodality

CN-strong + CN-weak stars

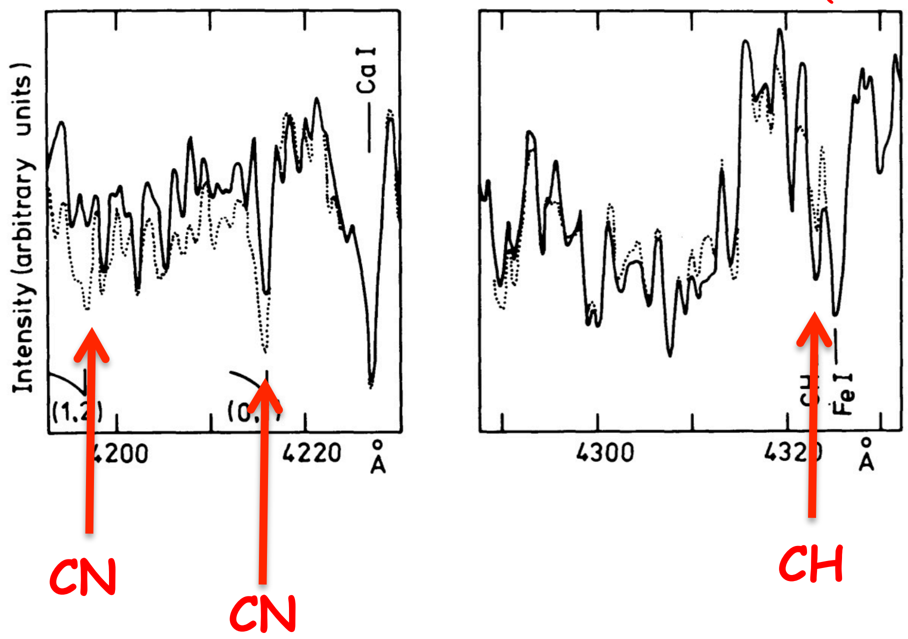
Smith & Norris (1982)




## CN-CH anticorrelations

CN-strong stars have weak CH bands and vice-versa

Norris & Cottrell(1979)




CN-strong stars are enhanced in N and depleted in C

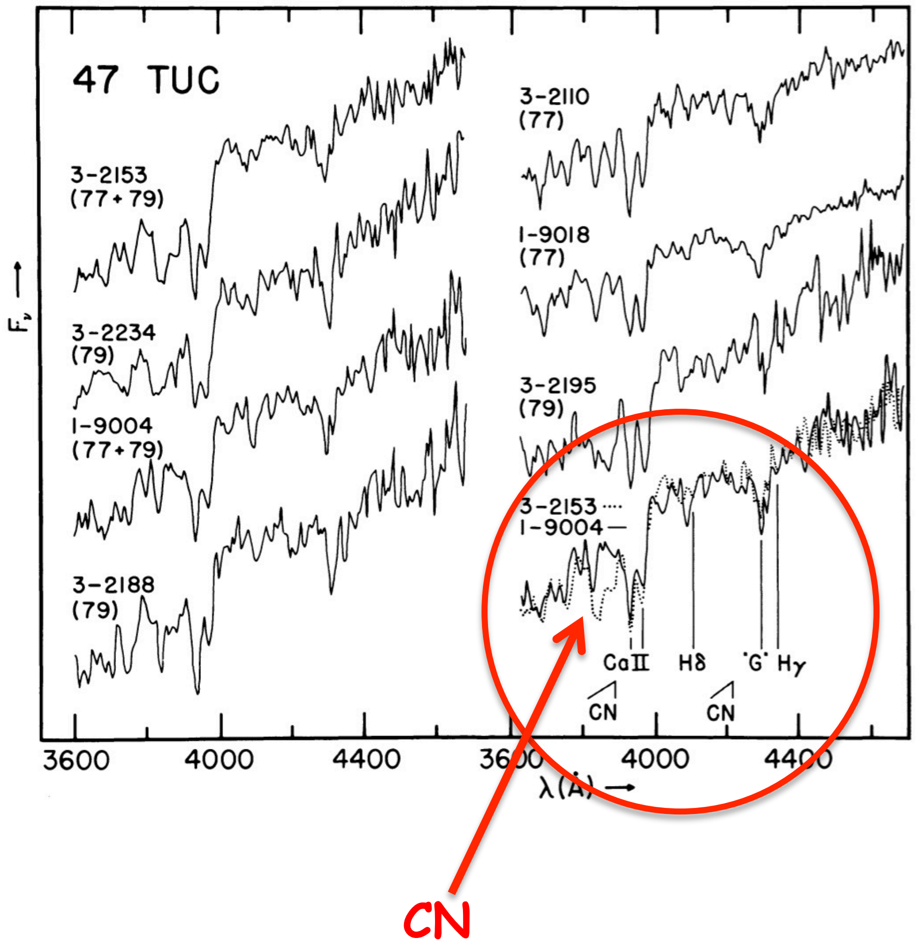
→ CNO-cycle plays an important role (mixing?) ←

# The first cornerstone: CN-CH anomalies

**Hesser (1978) + Hesser & Bell (1980)**

Variations of the CN band strengths
among 11 Main Sequences stars of 47Tuc

Hesser & Bell (1980)



Hesser (1978)

Interpretations of these observations center on two classes of ideas, although other explanations cannot be ruled out: (1) stars from more than one generation of star formation are being observed; or (2) newly created chemical elements have been mixed from the stellar core into the observable layers of the atmosphere,

Hesser & Bell (1980)

already be known; and that the bimodality of CN strengths claimed by Norris and Freeman (1979) in 47 Tuc may be weakly present in younger galactic populations. This possibility implies that the CN anomalies seen within globular clusters are a normal result of stellar evolution. However, the existence of a large N abundance range and readily observable C spectral features appears to be incompatible with alterations of the cosmic C/N ratio by mixing processes at such early stages of stellar evolution (Kraft, private communication). In the absence of alternate physical mechanisms, including a main-sequence mixing mechanism operative in such stars, our observations appear to imply a primordial origin for at least some of the observed CN anomalies in 47 Tuc.

**Here there are already some answers to the MPs problem: but we need to wait 15-20 years to have a complete confirmation of MPs in dwarf stars….**

# What we know about MPs ?

- CN and CH vary in RGB stars of GCs
- ... but also in dwarf stars
- CN-CH anticorrelations
- No CN-CH variations in field stars

→

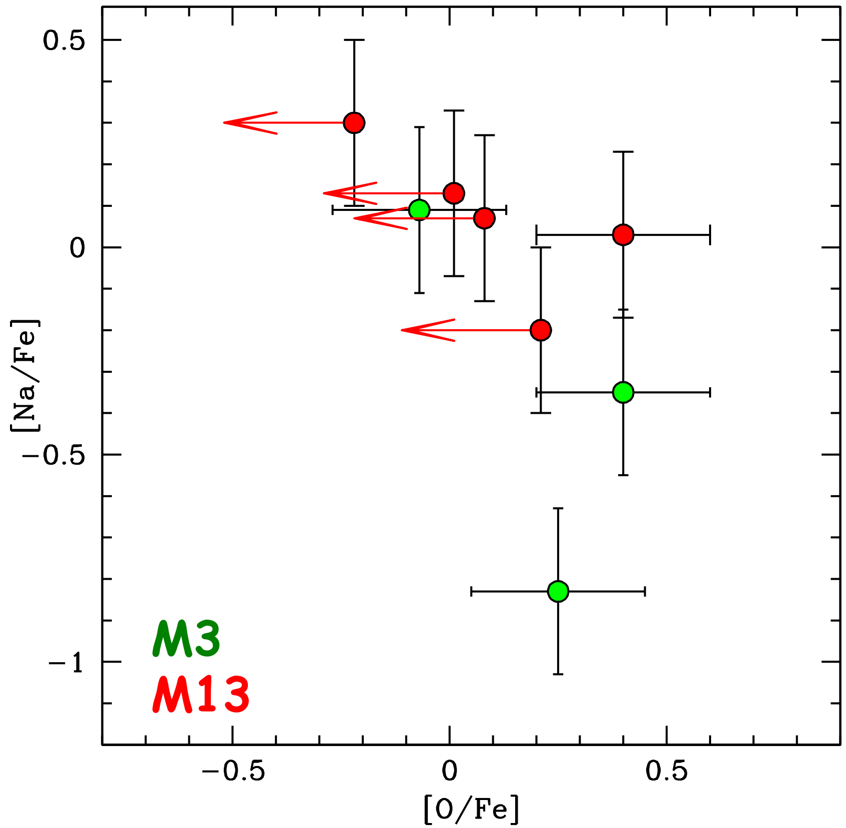
CNO-cycle plays a role

Mixing is unlikely

# The second cornerstone: Na-O anticorrelation

A note of caution: Na can be measured also at low resolution
but oxygen needs at least R~20000

Data from Cohen (1978)




Probably the first spectroscopic evidence of Na-O anticorrelation but discussed only in terms of Na spread

Mixing?
*"Psychologically unsatisfactory"*

*"The only viable explanation, although a most unsatisfactory one, is incomplete mixing of supernova ejecta through the gas cloud out of which M3 and M13 formed."*

# The second cornerstone: Na-O anticorrelation

Cottrell & Da Costa 1981: first correlation between CN and Na/Al

In NGC6752 and 47Tuc the CN-strong stars are Na- and Al-rich
(Na is not involved in the CNO-cycle)

**The two chemical anomalies (CN-CH and Na/Al) are correlated each other**

# The second cornerstone: Na-O anticorrelation

Which is the first explicit Na-O anticorrelation?



**Title:** High resolution spectroscopy: quantitative results and critical tests.
**Authors:** Pilachowski, C. A.
**Publication:** IAU meetings JCM 5 and CM 37/3 during the 20th General Assembly: The abundance spread within globular clusters: spectroscopy of individual stars, p. 1 - 7
**Publication Date:** 00/1989
**Origin:** ARI
**ARI Keywords:** Globular Clusters: Element Abundances, Globular Clusters: Ages, Globular Clusters: Temperatures
**Bibliographic Code:** 1989asgc.conf....1P

**Abstract**

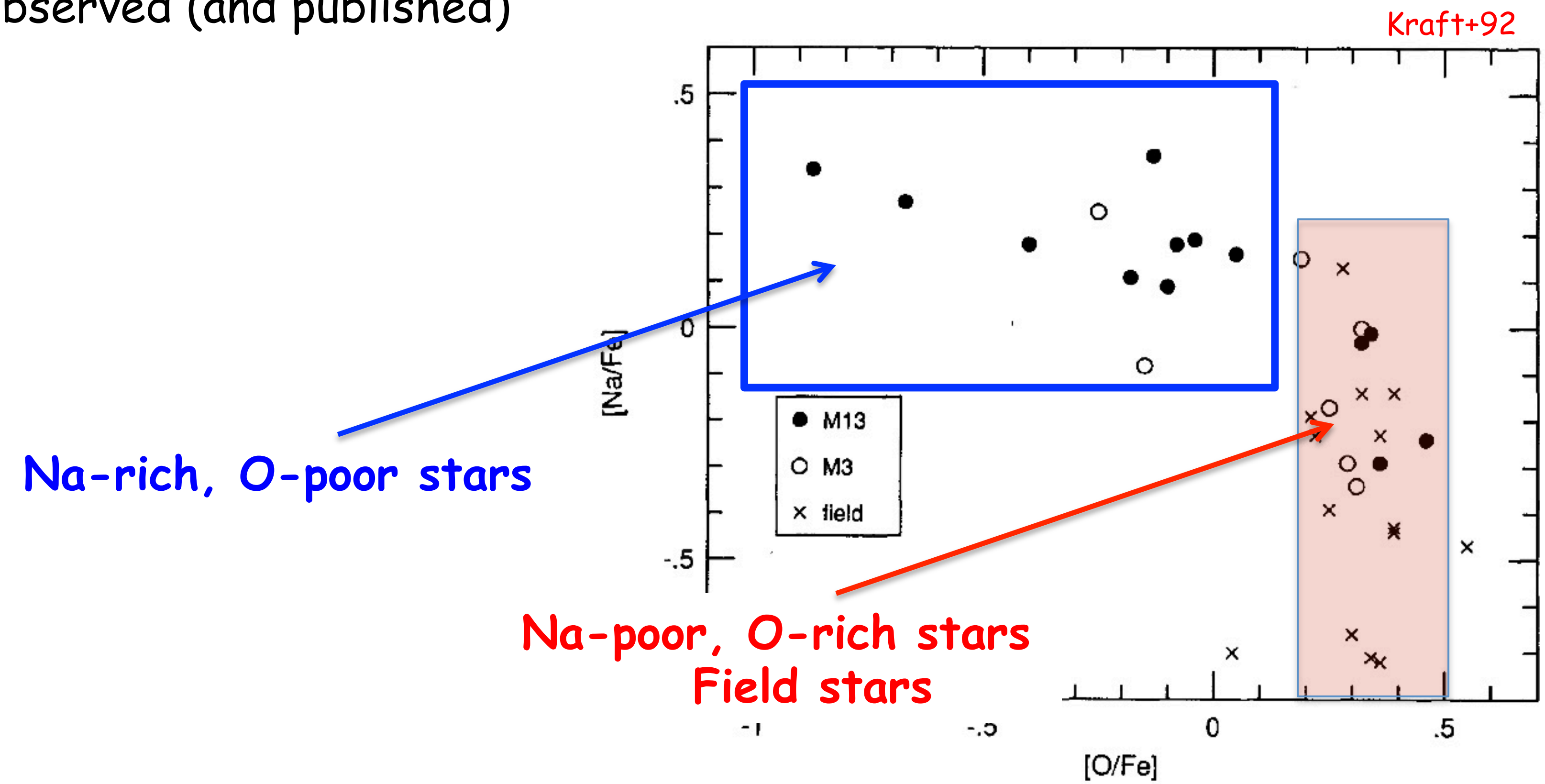
This paper concentrates on two problems of current interest in the study of the compositions of globular clusters: (1) determining the original cluster oxygen abundances for age determinations and (2) understanding the spread in "abundance" seen in sodium and aluminum in clusters. The strengths of sodium and aluminum lines are correlated with the nitrogen abundance or CN strength, and anti-correlated with oxygen abundance. Quantitative results concerning 8 stars in M13 and 15 stars in M92 are based on spectra taken with the KPNO 4 m echelle spectrograph with CCD. In M13 the stars observed for oxygen all have temperatures near 4250K, while the stars in M92 fall in the temperature range from 5100K to 4200K.

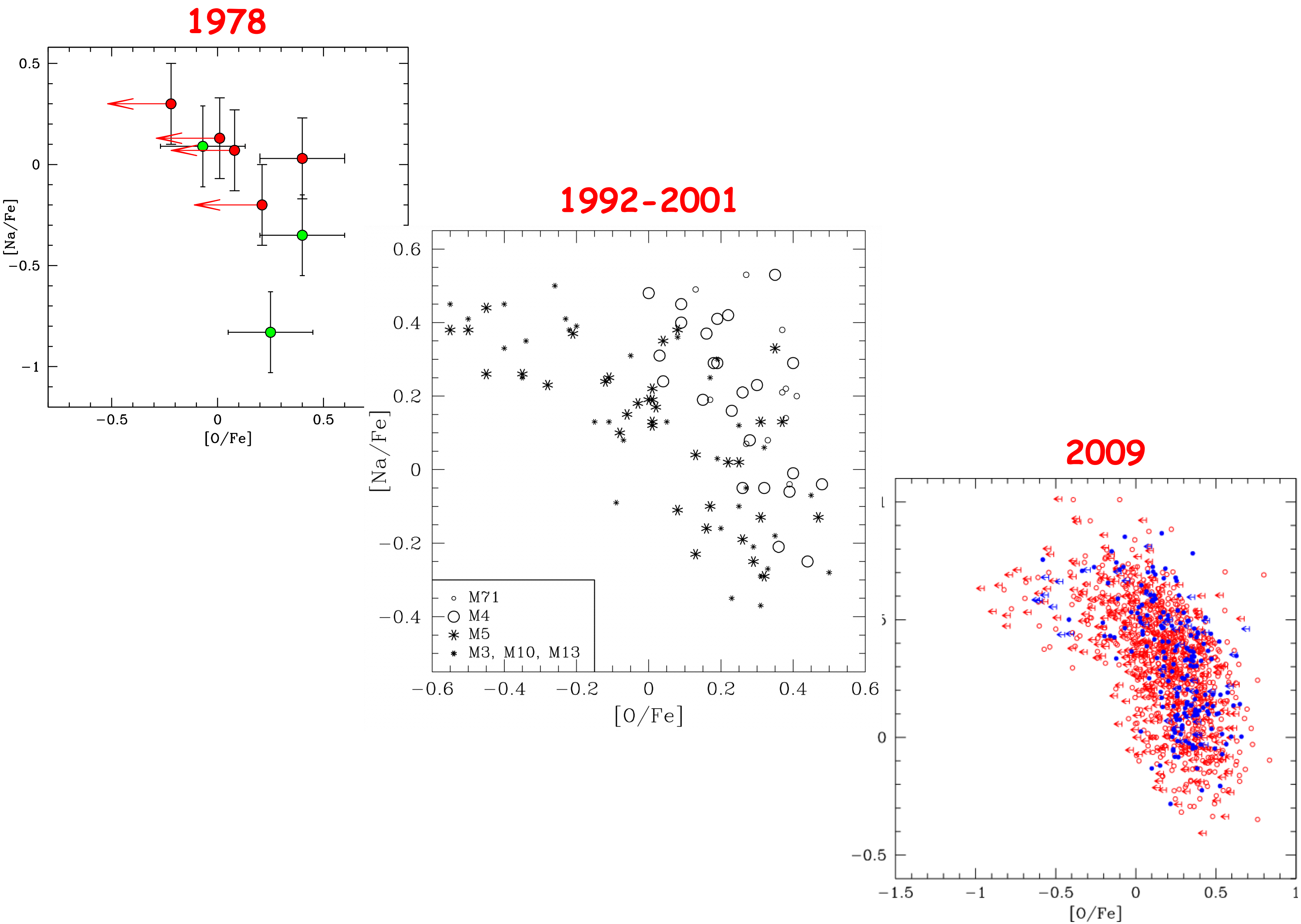
First (but unpublished) explicit evidence
of Na-O anticorrelation

# The second cornerstone: Na-O anticorrelation

A major step forward comes from the Lick-Texas group
High-resolution, homogeneous survey of the chemical composition
in RGB giants in several GCs

- **Sneden+91** found large O spreads in M92 and M15 (but not measures of Na)
- **Kraft+92**: for the first time a Na-O anticorrelation (in M3 and M13) is observed (and published)




1978
[Na/Fe]
[O/Fe]
1992-2001
[Na/Fe]
[O/Fe]
M71
M4
M5
M3, M10, M13
2009
[O/Fe]

# What we know about MPs ?

- CN and CH vary in RGB stars of GCs
- ... but also in dwarf stars
- CN-CH anticorrelations
- No CN-CH variations in field stars

→ CNO-cycle plays a role

Mixing is unlikely

- Na, O and Al vary in RGB stars
- Na-O anticorrelation
- Na-Al correlation
- CN-Na and CN-Al correlations
- Not in field stars

→ A nucleosynthesis process able to link CNO and other light elements

# The third cornerstone: down to the turnoff

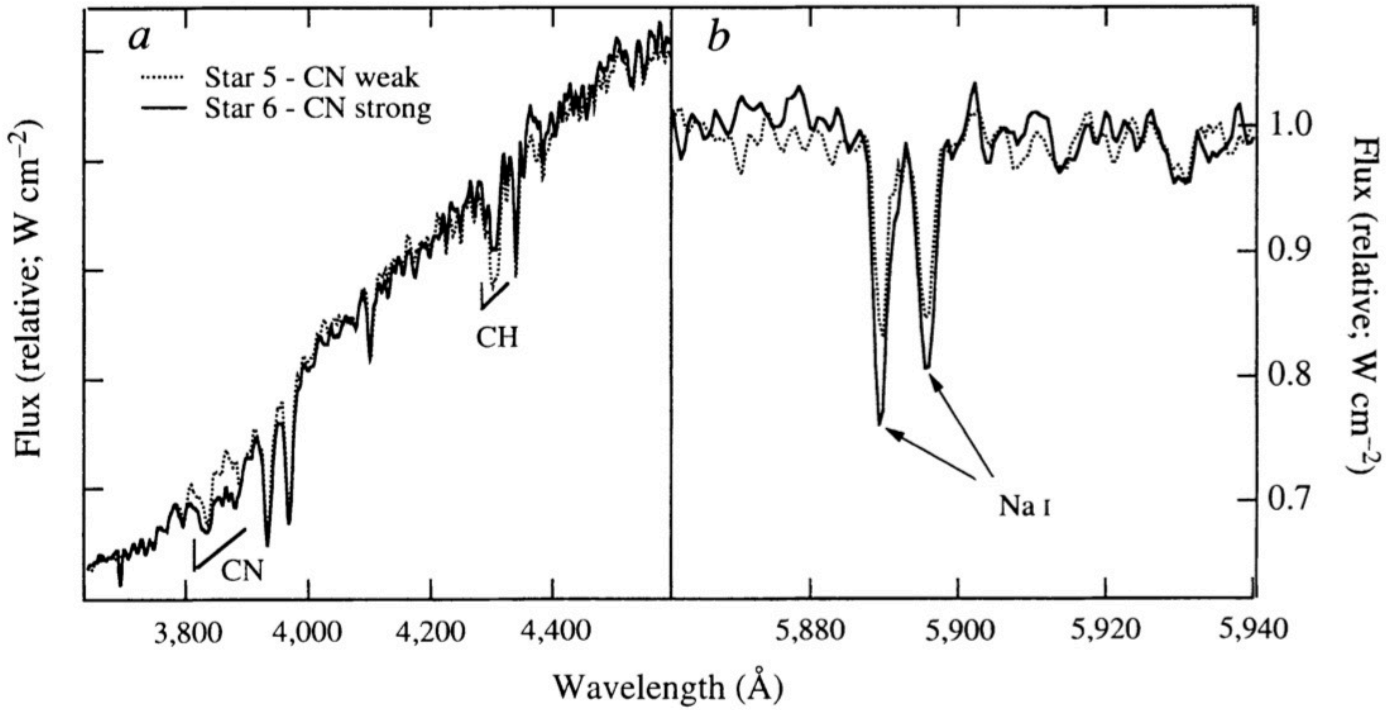
*Since 1978 we know that CN variations are also in dwarf stars !!!*

**Briley+96** found Na variations in dwarf stars of 47 Tuc
CN-strong stars are Na-rich, CN-weak stars are Na-poor

Same finding of Cottrell & Da Costa 1981 but in dwarf stars

**First evidence of Na spread among dwarf stars**

Briley+96



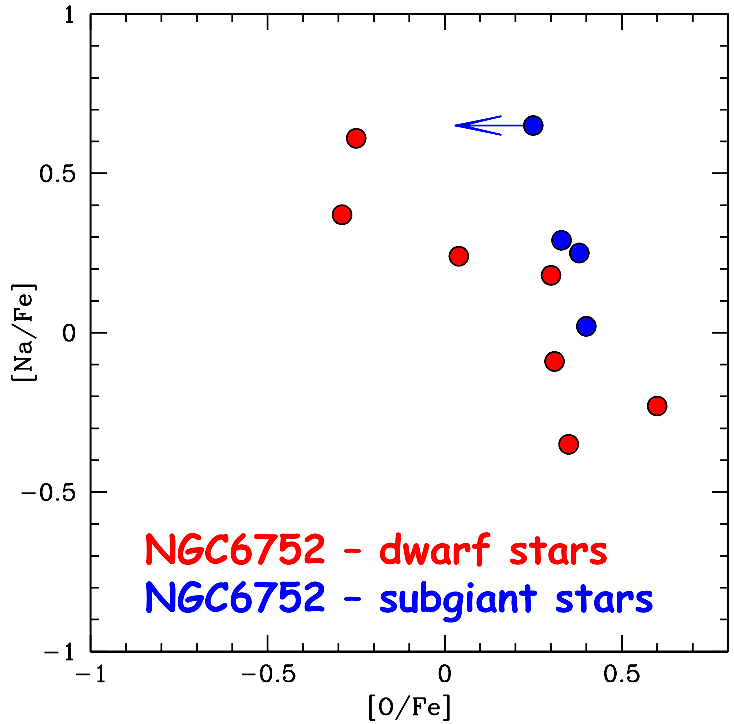
# The third cornerstone: down to the turnoff

With the advent of 8-10 meter class telescopes (VLT) high-resolution spectra of dwarf stars can be secured

High-resolution UVES spectroscopy of dwarf and sub-giant stars in NGC6397 and NGC6752

First evidence of Na-O anticorrelation among dwarf stars in NGC6752 (but not in NGC6397)

Data from Gratton+01



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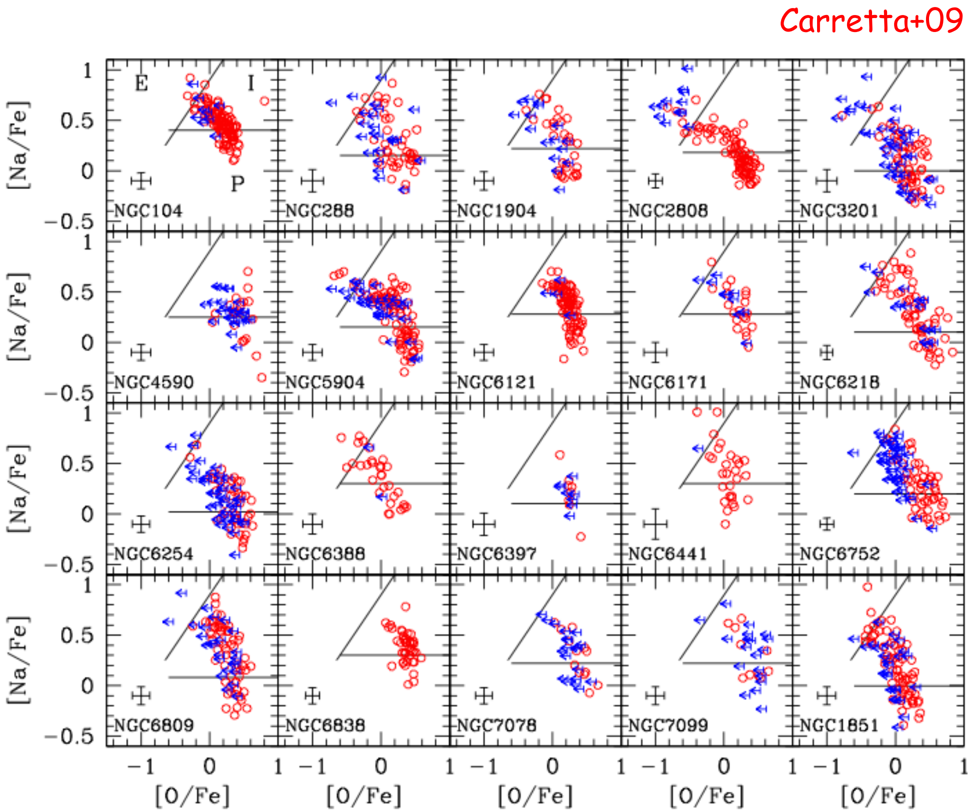
- Na, O and Al vary in RGB stars
- Na-O anticorrelation
- Na-Al correlation
- CN-Na and CN-Al correlations
- Not in field stars

→ A nucleosynthesis process able to link CNO and other light elements

- CN-Na/Al correlation also in dwarf stars
- Na-O anticorrelations also in dwarf stars

→ The chemical anomalies are primordial

# Na-O anticorrelation: in all the GCs



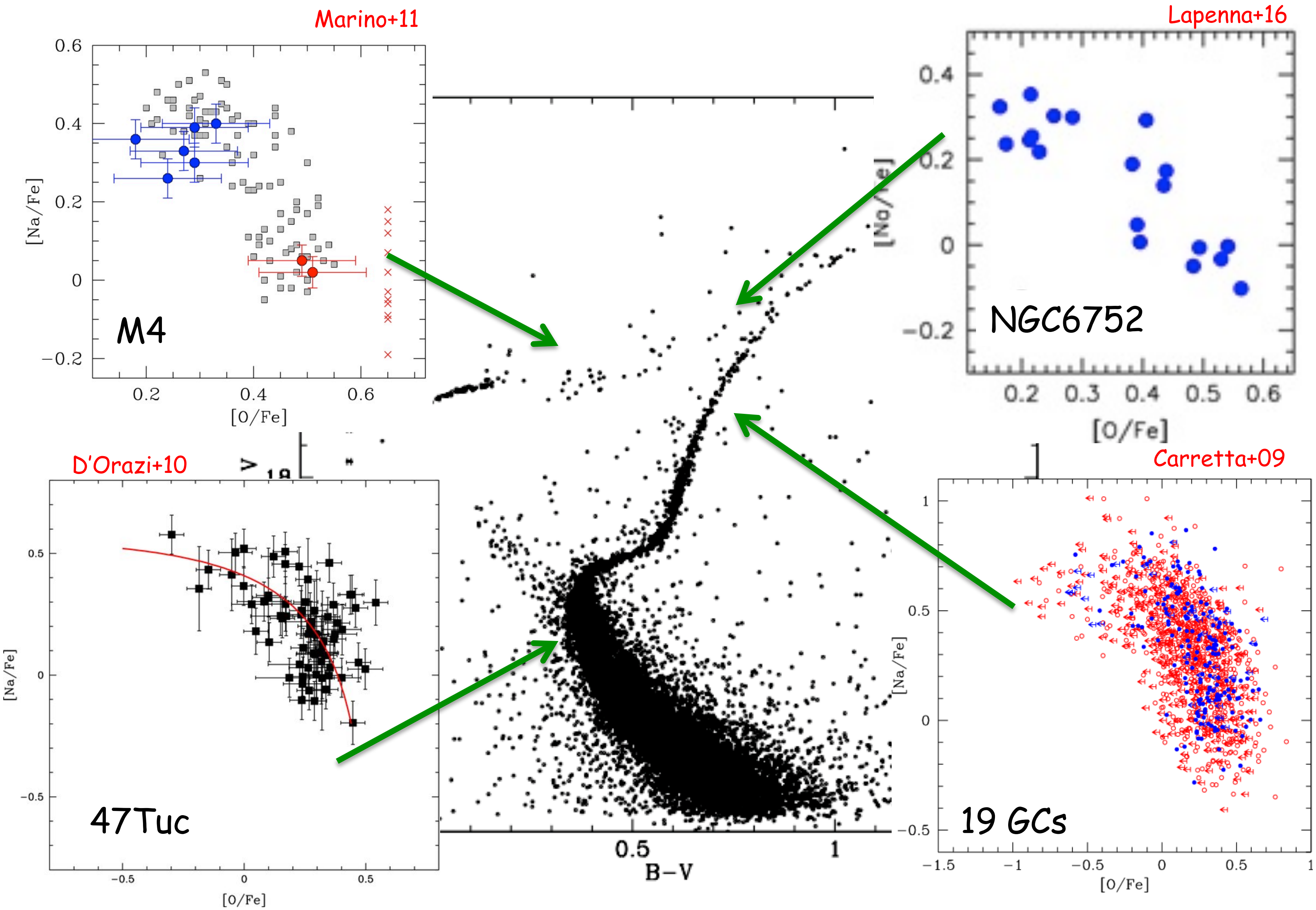

**Current state-of-art**
(updated at August 2017, see Bragaglia+17)

63 GCs with Na-O signatures from spectroscopy

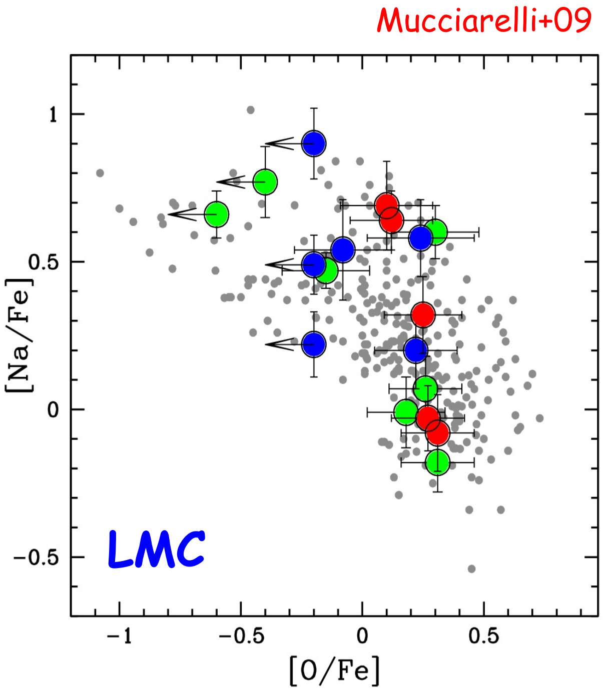
Only a bunch of GCs with no evidence of Na-O anticorr. (but based on a few stars) Terzan 7, Palomar 3, Palomar 12, Ruprecht 106, IC4499

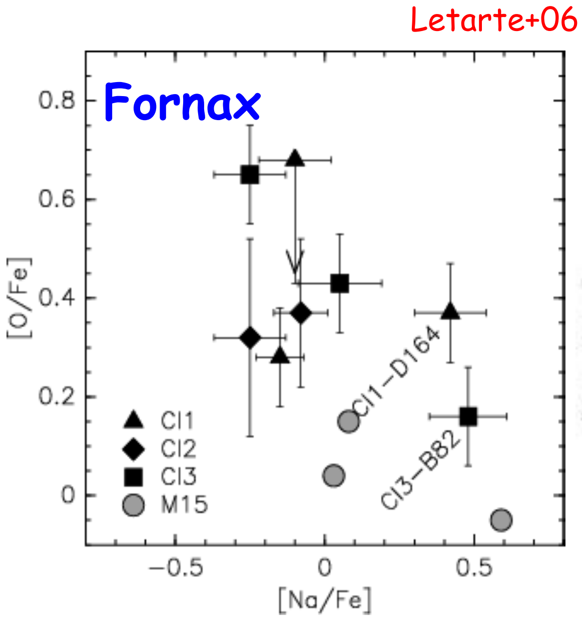
*But other GCs with MPs based on low-resolution spectroscopic and/or photometry*

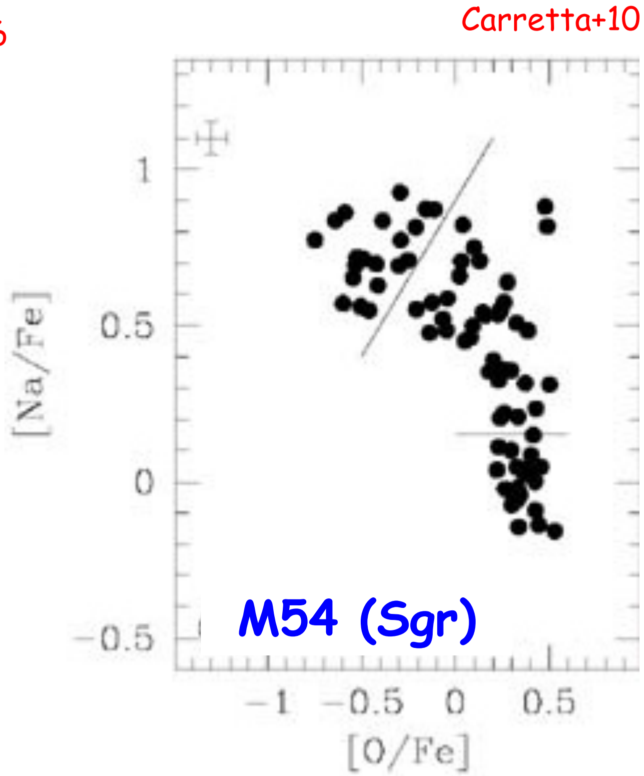
# Na-O anticorrelation: in all the evolutionary phases



# Na-O anticorrelation: in all the galactic environments




But photometric evidence of MPs also in SMC (Dalessandro+16, Niederhofer+17)

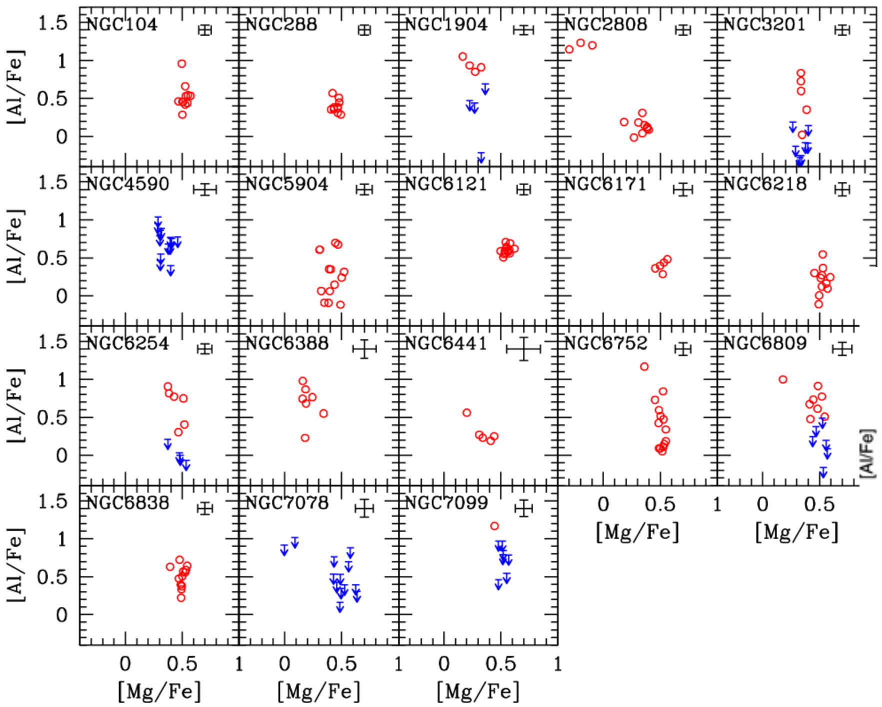
**MPs are ubiquitous features of GCs, regardless of the parent galaxy**

# Other anticorrelations: Mg-Al

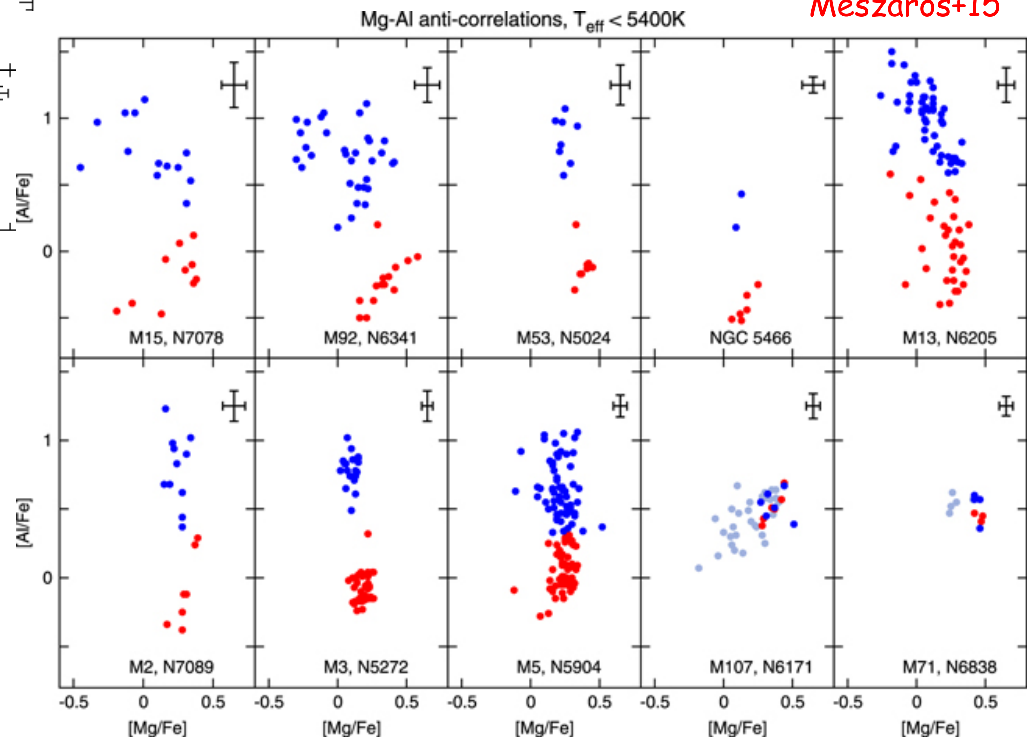
Not in all GCs

Al spread increases with decreasing the metallicity

Carretta+09



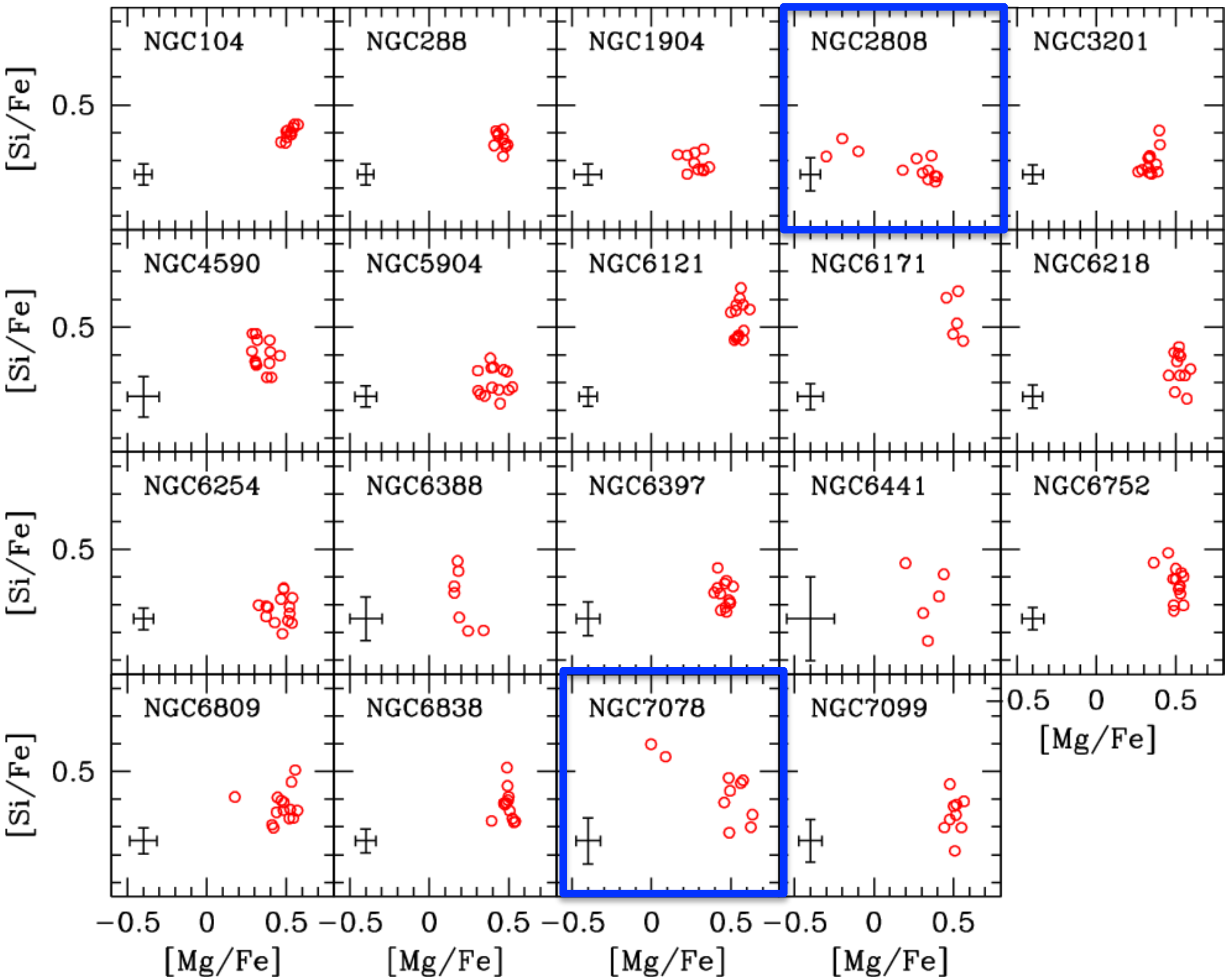

Meszaros+15



# Other anticorrelations: Mg-Si

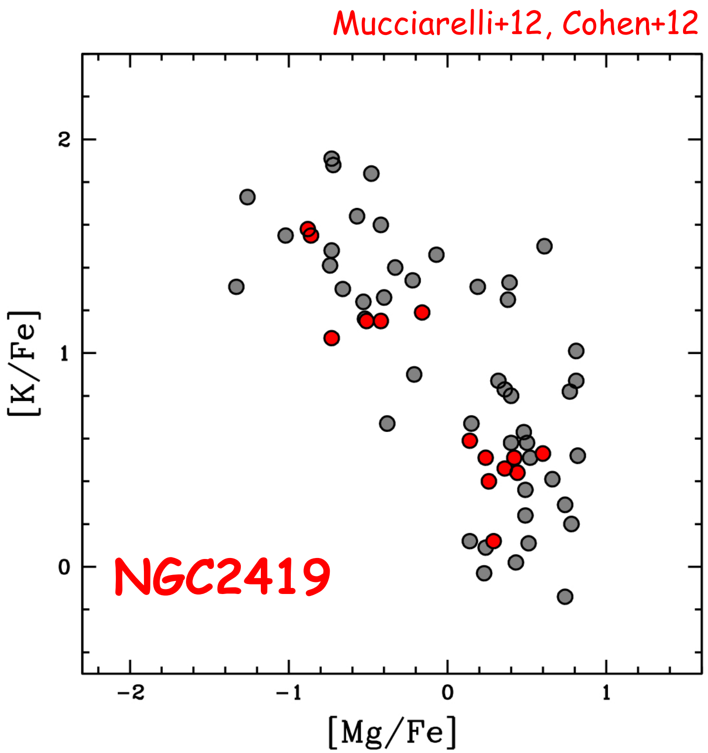
Weak Mg-Si anticorrelations only in some GCs

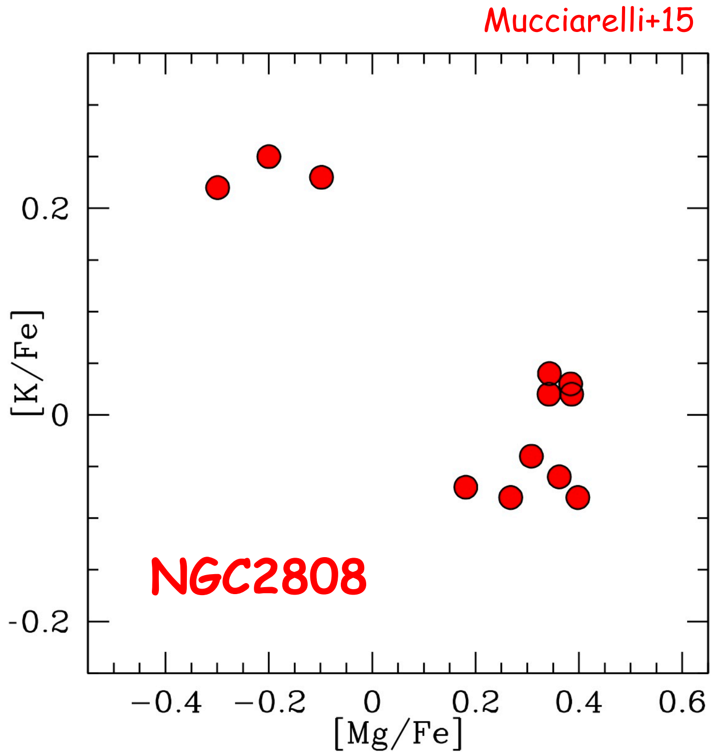
Carretta+09



# Other anticorrelations: Mg-K

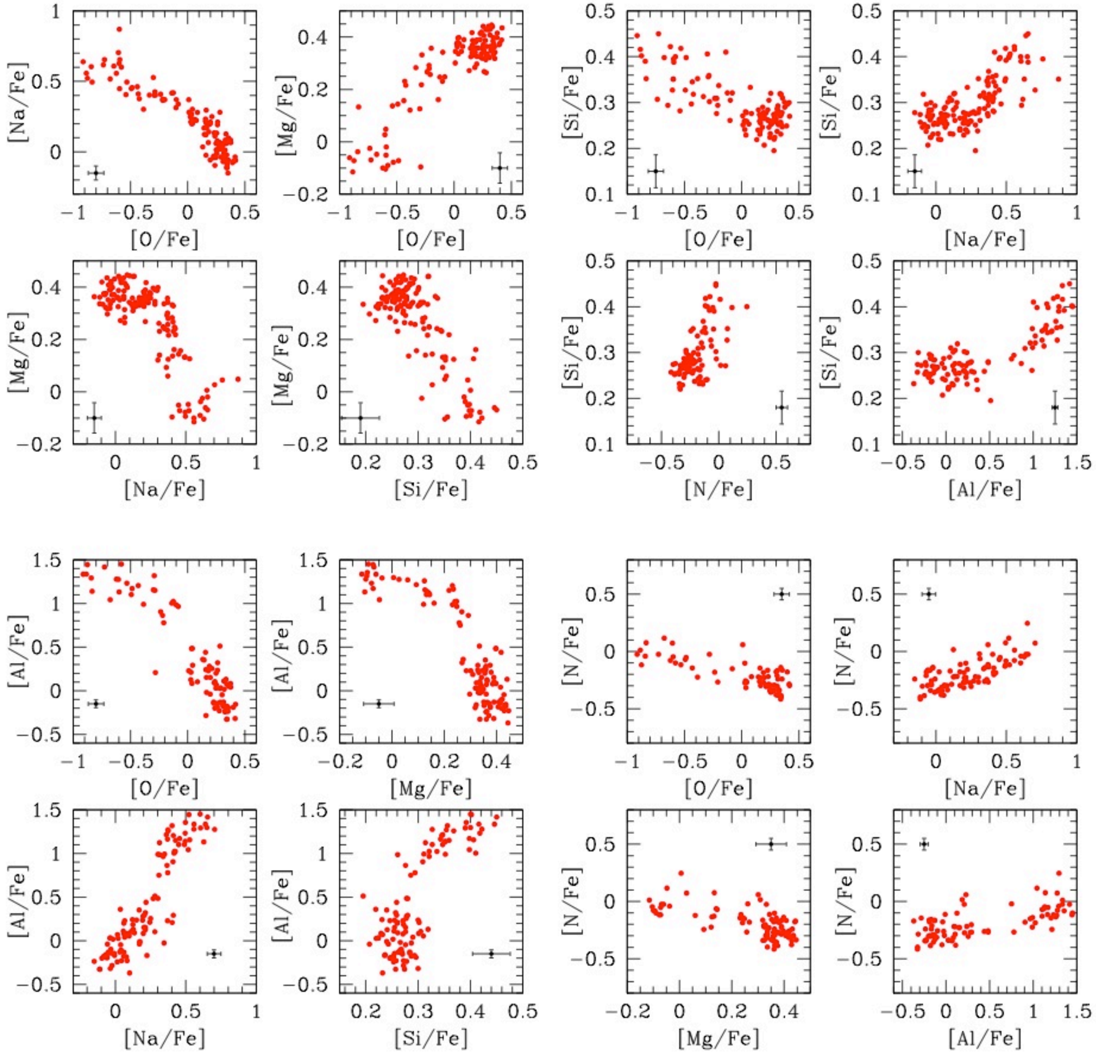
Observed in the two clusters with the most large Mg range.
Not observed in other clusters (Carretta+13, Mucciarelli+16)



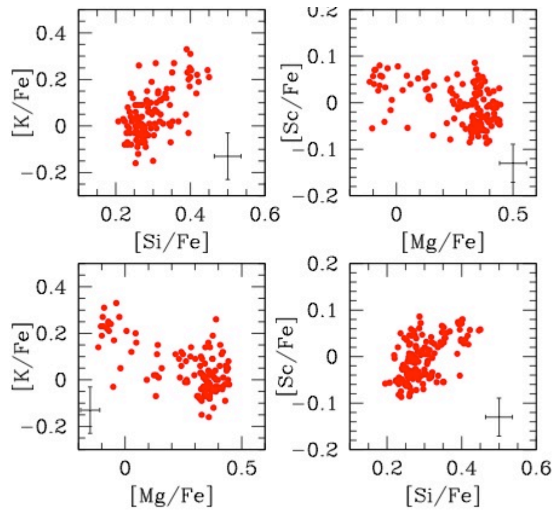



# NGC 2808

*Everything correlates/anti-correlates with everything*




Carretta (2016)




Data from Carretta+05, Carretta+15, Mucciarelli+15

# Origin of the chemical anomalies

- First hypothesis (based on CN variations in RGB stars): **evolutionary mixing**

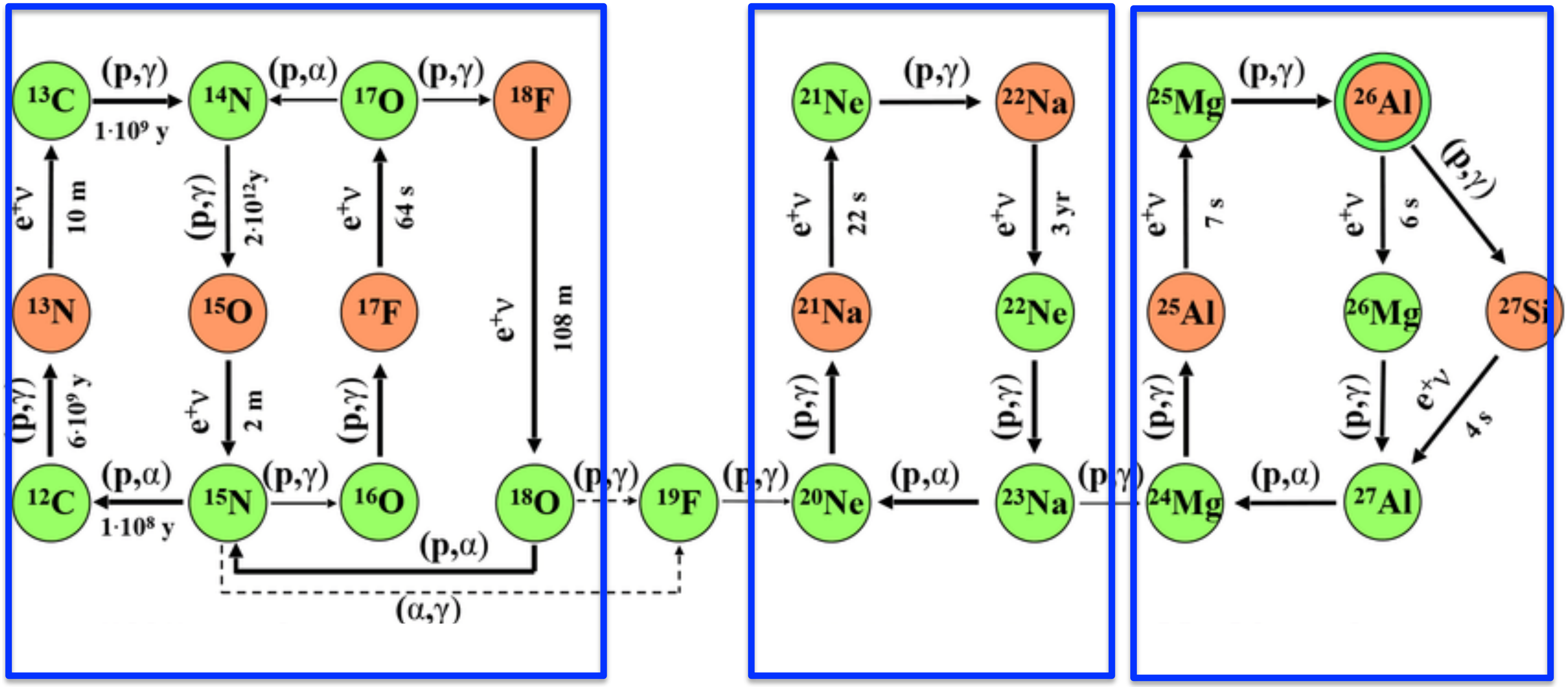
**NO**

- Anomalies observed also in dwarf stars
- CN-CH anomalies linked to other elements

- **Primordial scenario**: all the observed chemical patterns are compatible with the products of **proton-capture reactions**, as proposed by Denissenkov & Denissenkova (1990) and Langer+93

→ But the first idea of these reactions is from Boyarchuk & Luybimkov (1983) [in russian]

# All the chemical anomalies suggest proton-capture reactions




CNO cycle
T~20/40 MK

NeNa cycle
T~50 MK

MgAl cycle
T > 70 MK

Explain the CN-CH anomalies

Explain NaO anticorrelation

Explain MgAl anticorrelation (but also MgSi and MgK)

## All the chemical anomalies suggest proton-capture reactions

CNO cycle
T~20/40 MK

NeNa cycle
T~50 MK

MgAl cycle
T > 70 MK

**Too high temperatures**

Not reached in the interior of the presently observed GC low mass stars

**This nuclear burning occurred in stars more massive than those evolving today**

## Our current view of MPs in GCs:

**enriched (or second-generation) stars are formed from the ejecta processed in the most massive primordial (or first-generation) stars, diluted with different amounts of unprocessed gas.**

# Which polluters?

The best candidates should

- be able to modify only the light element abundances without producing variations in heavier elements (i.e. Fe)
- have low-velocity ejecta to be retained in the cluster potential well

**AGB and super-AGB stars** (4-8 $M_\odot$ ) (timescale ~$10^7$ yrs)
(Ventura+01,+13,Ventura & D'Antona 2008, D'Ercole+08,+10,D'Antona+16)

**Fast rotating massive stars** (timescale ~$10^6$ yrs)
(Decressin+7, Decressin, Charbonnel & Meynet 2007, Meynet, Decressin & Charbonnel 2008)

**Super-massive stars** (timescale ~ $10^5$ yrs)
(Denissenkov & Hartwick 2014, Denissenkov+15)

**Interacting massive binaries** (timescale ~ $10^6$ yrs)
(De Mink+09)

## Spectroscopy is magnifying lens for the MPs in GCs … but not the only one

To fully understand MPs in GCs we need to combine spectroscopy with

→ *Multi-bands photometry* See Milone's talk

→ *Kinematics/Dynamics* See Vesperini's talk

→ *Theoretical models* See D'Antona's talk

# The End