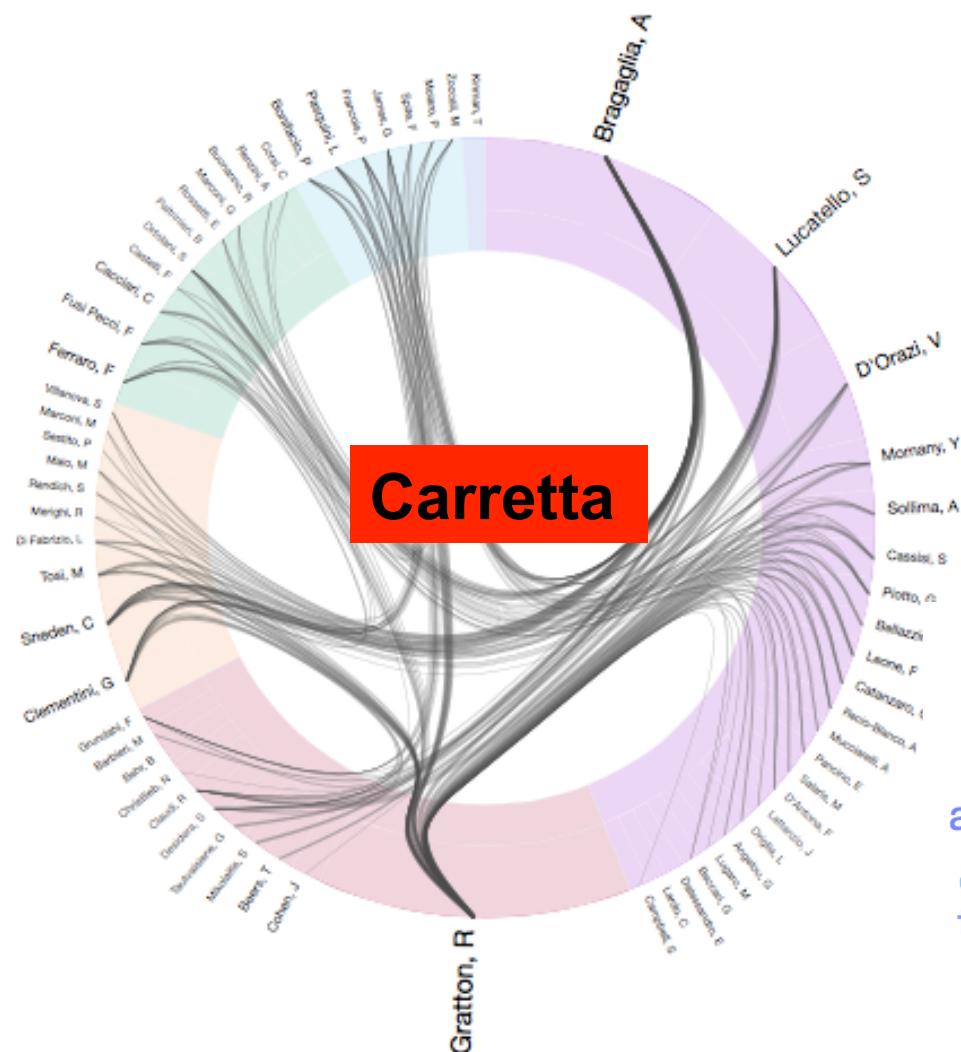


Eugenio Carretta – INAF Osservatorio Astronomico di Bologna



**in a nutshell:
collaborations
and key words**

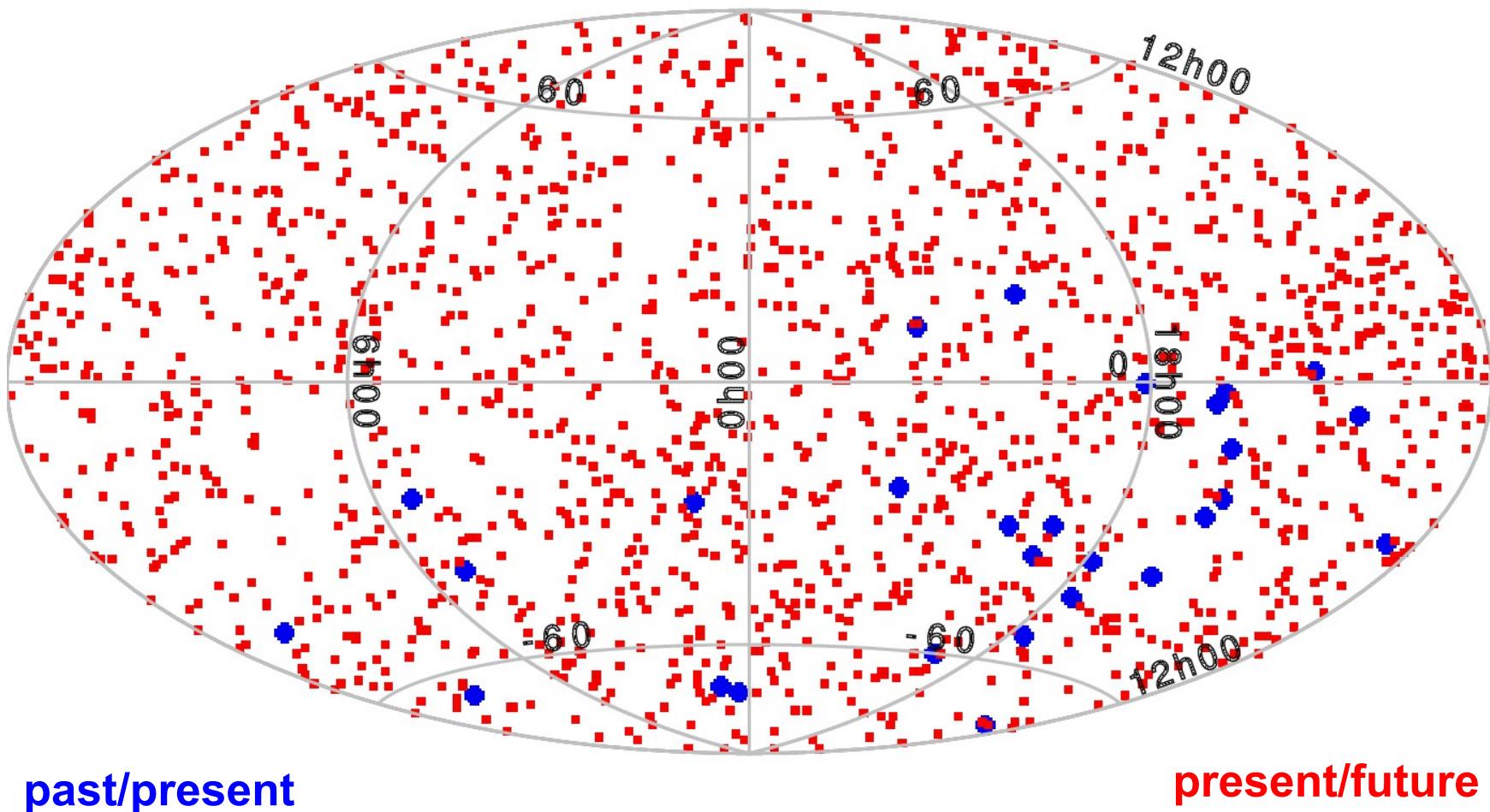
generation ratios collected
field sample more mass
RGB metallicity feh red large first
population study
chemical dex observations results
anticorrelation gcs spectra very
determined data NGC globular rgb
telescopes branch cluster different
abundances stars find
present based eso high giant HB stellar
two derived elements most
previous ESO analysis

Minisurveys:



Multiple populations in
globular clusters

Accretion and dissipative
components of the Milky Way's halo

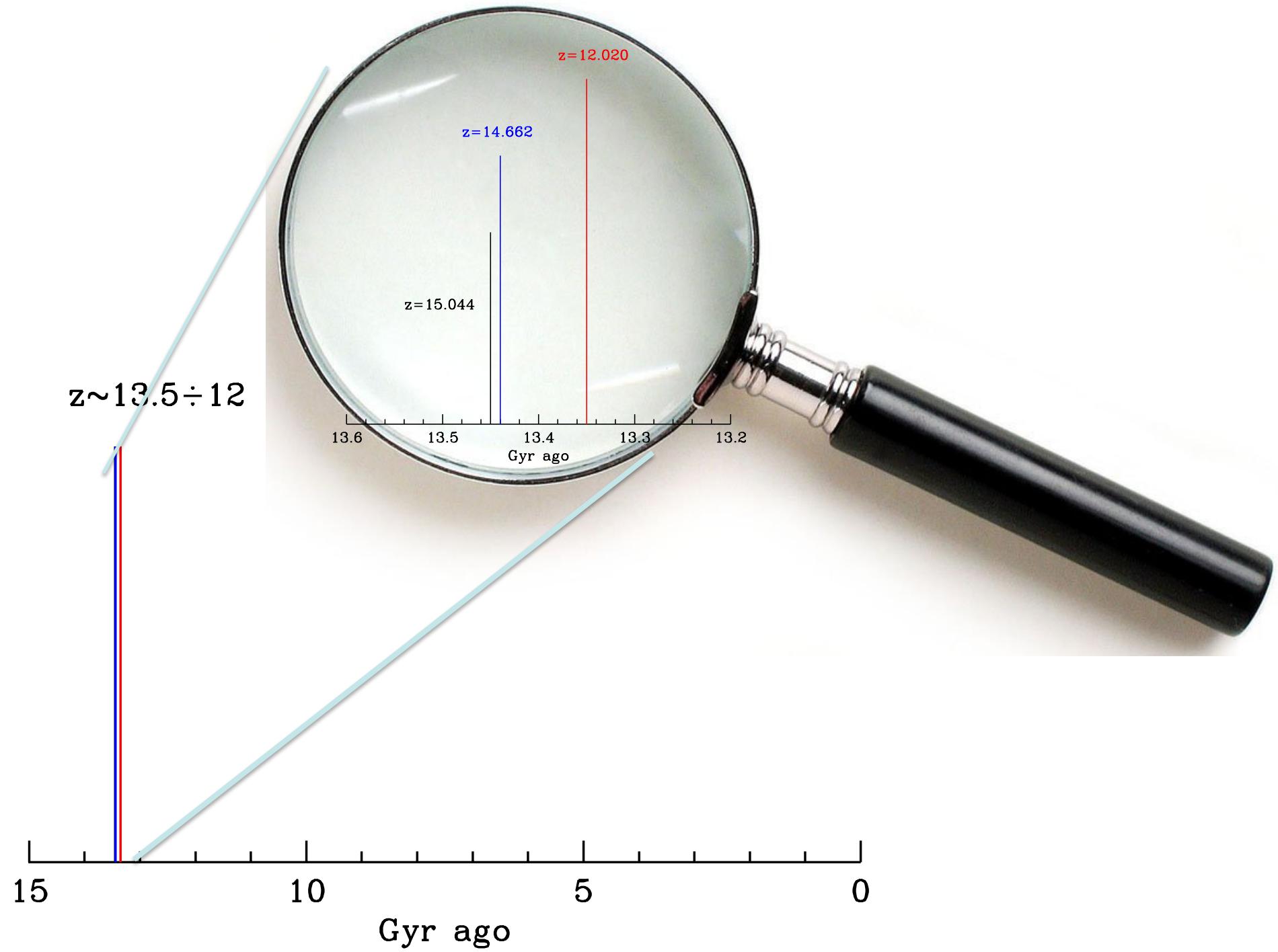


Na-O anticorrelation and HB

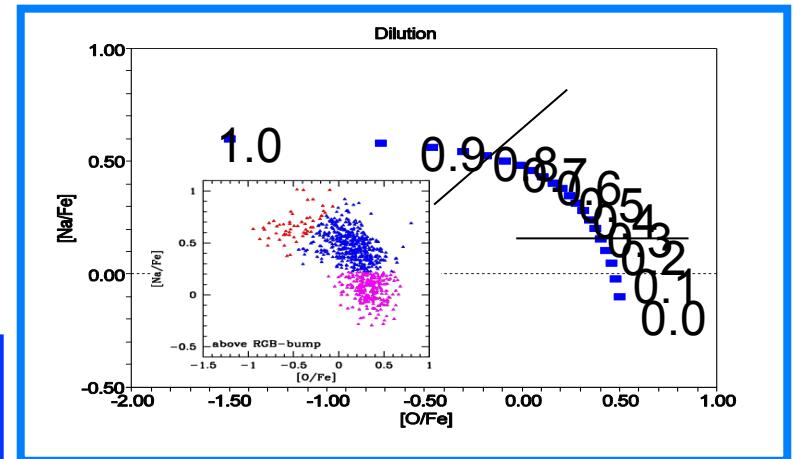
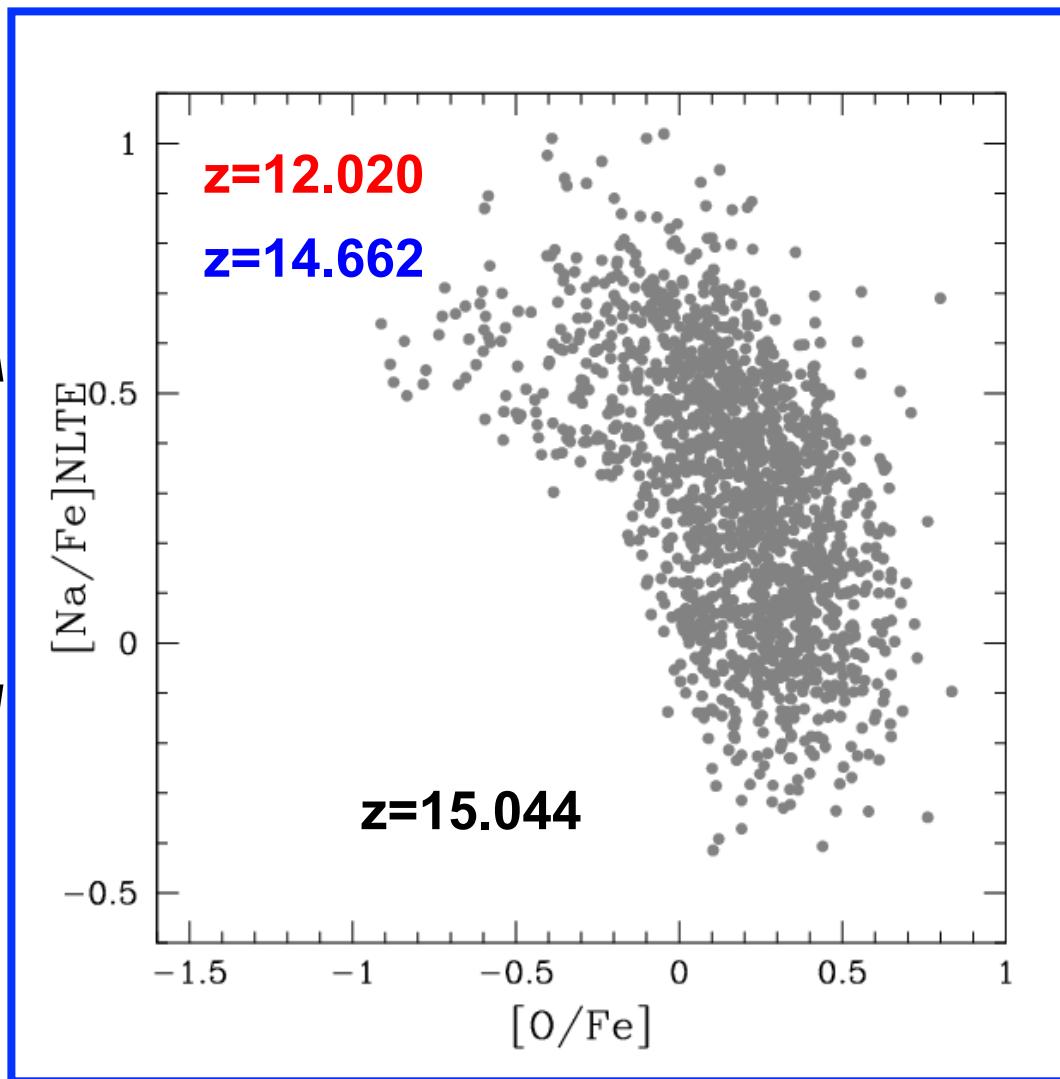
Core team: Carretta, Bragaglia, D’Orazi, Gratton, Lucatello, Sollima

Main purposes of the survey

- How GCs formed (origin and early evolution)
- Link of multiple populations to global parameters
- Whether and how they contribute(d) to the Galactic halo



Time span between stellar generations: few 10^6 – 10^7 yrs



second generation(s)

first generation

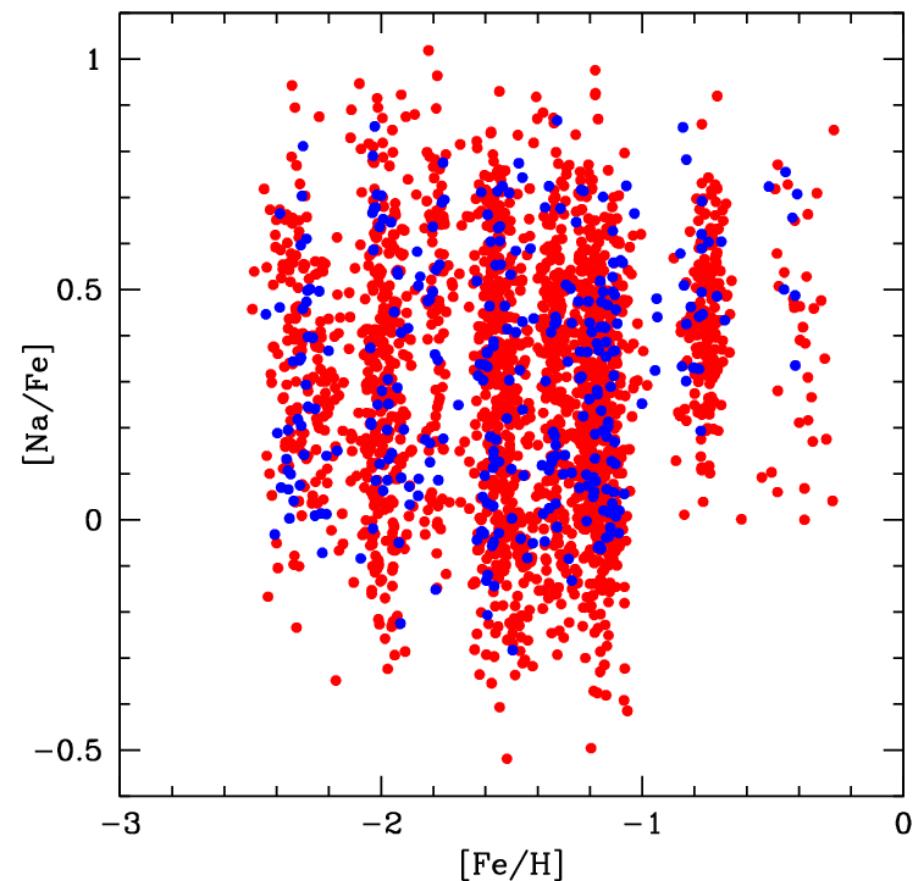
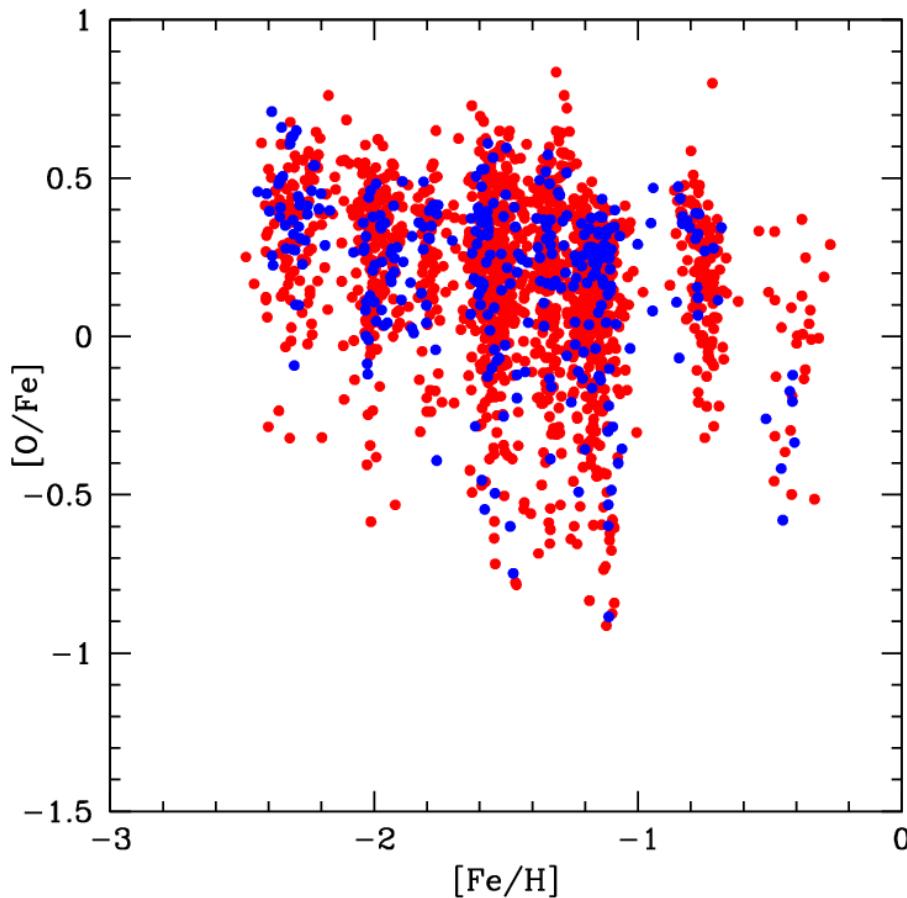
Na,O:
proton-
captures in H-
burning at high
temperature

Na,O:
hydrostatic
burning + α -
captures in
massive stars

Immediate aim:

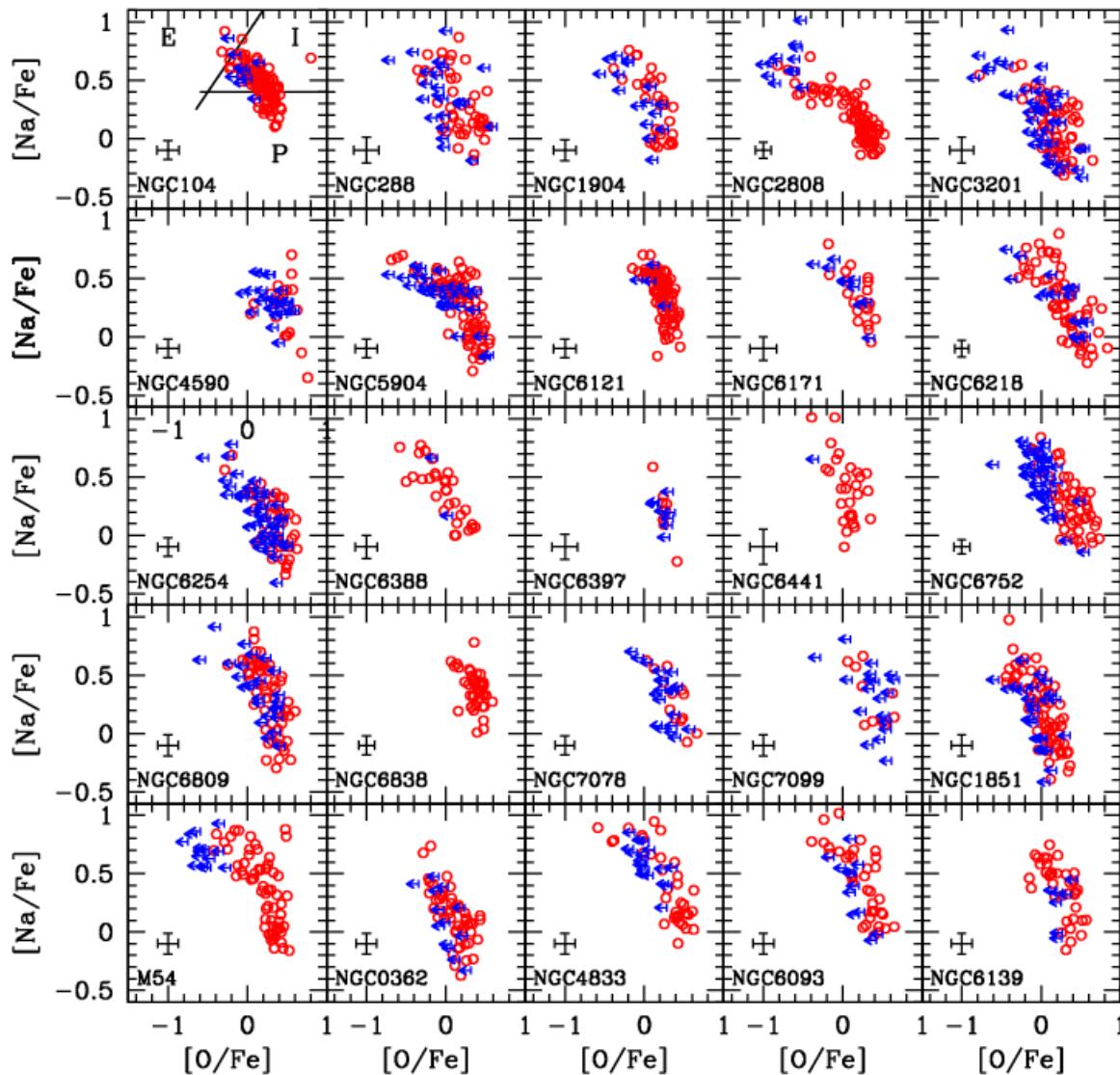
- ✓ homogeneous Fe, O, Na abundances for ~100 red giants in each of many GCs with different HB morphology
- ~ 2600 stars analyzed in 25 GCs

by-product: new high-resolution metallicity scale (Carretta et al. 2009)



DNA of Galactic globular clusters:

- ✓ Na-O anticorrelations → multiple stellar generations → intrinsic feature of bona fide GCs

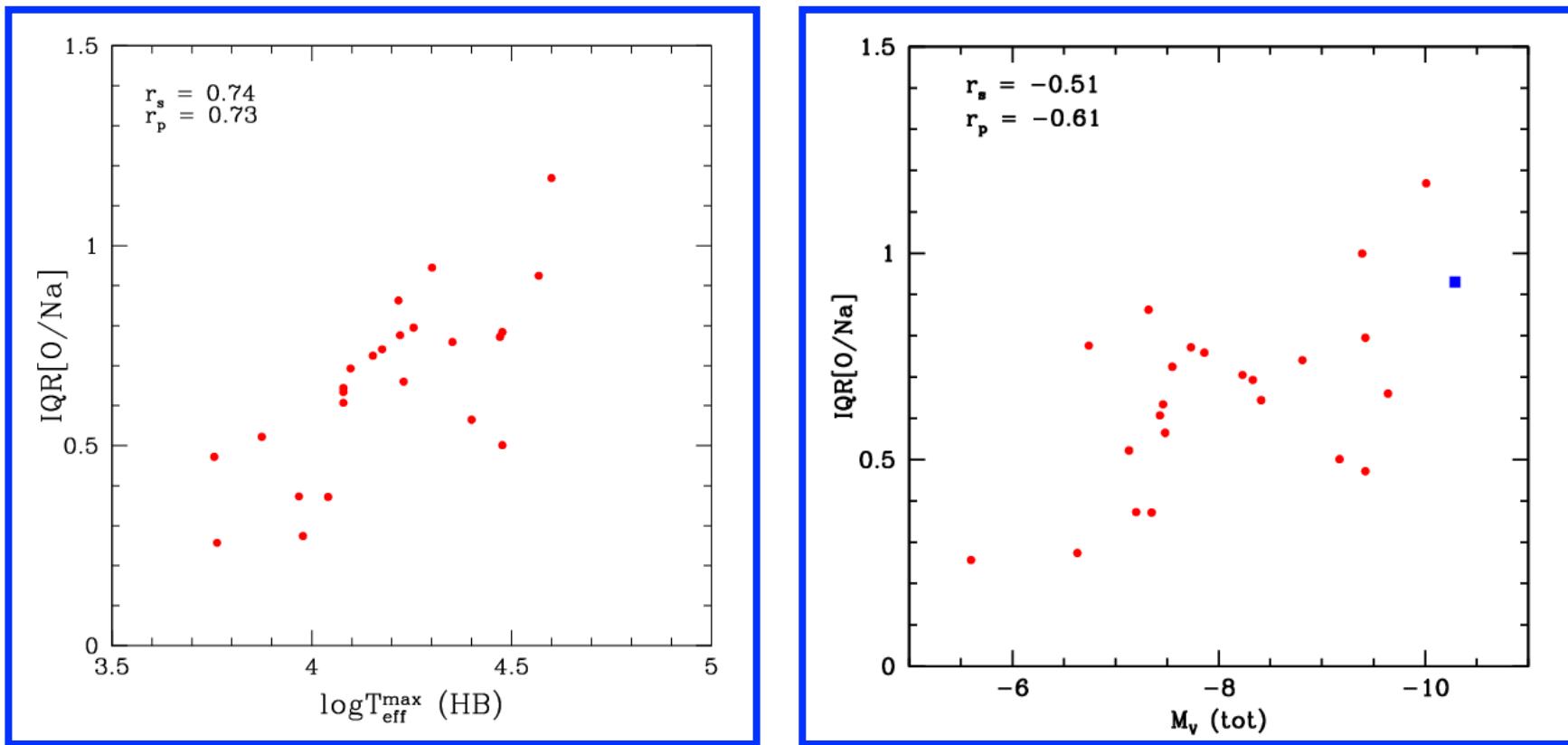


Carretta et al. 2006
Carretta et al. 2007a,b,c
Gratton et al. 2006
Gratton et al. 2007
Carretta et al. 2009a,b,c
Carretta et al. 2010a,b,c,d,e
Carretta et al. 2011
Carretta et al. 2012a,b,c
Carretta et al. 2013a,b
Carretta 2013
Carretta et al. 2014a,b,c
Carretta 2014
Carretta et al. 2015
Bragaglia et al. 2015
Carretta 2015

Link with global properties:

- ✓ Link with horizontal branch morphology
- ✓ Total mass (proxy: absolute magnitude M_V): driving parameter

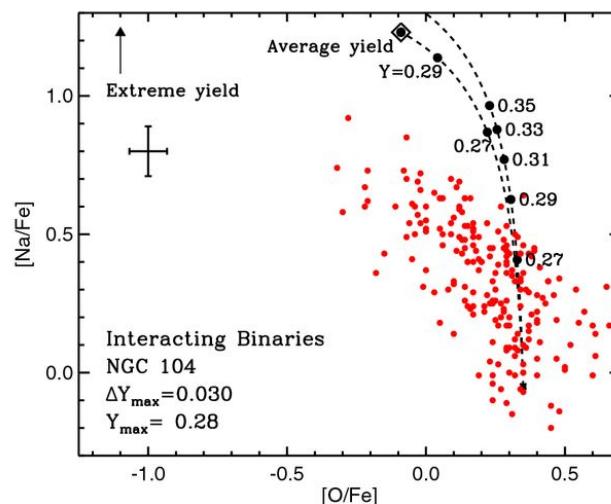
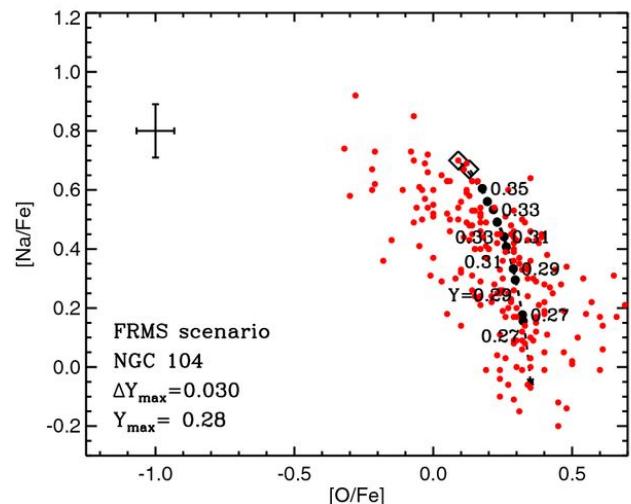
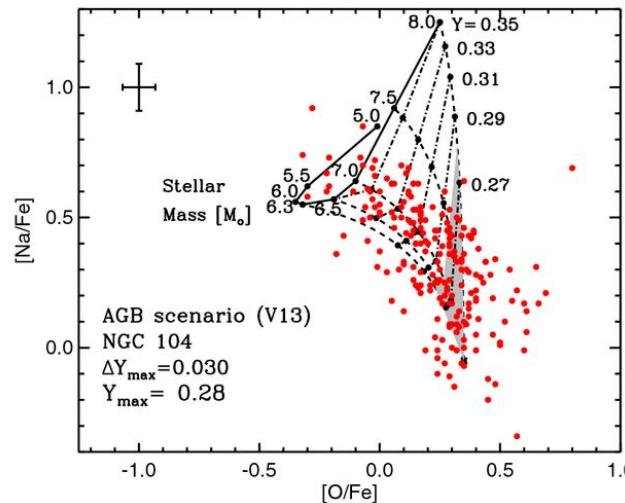
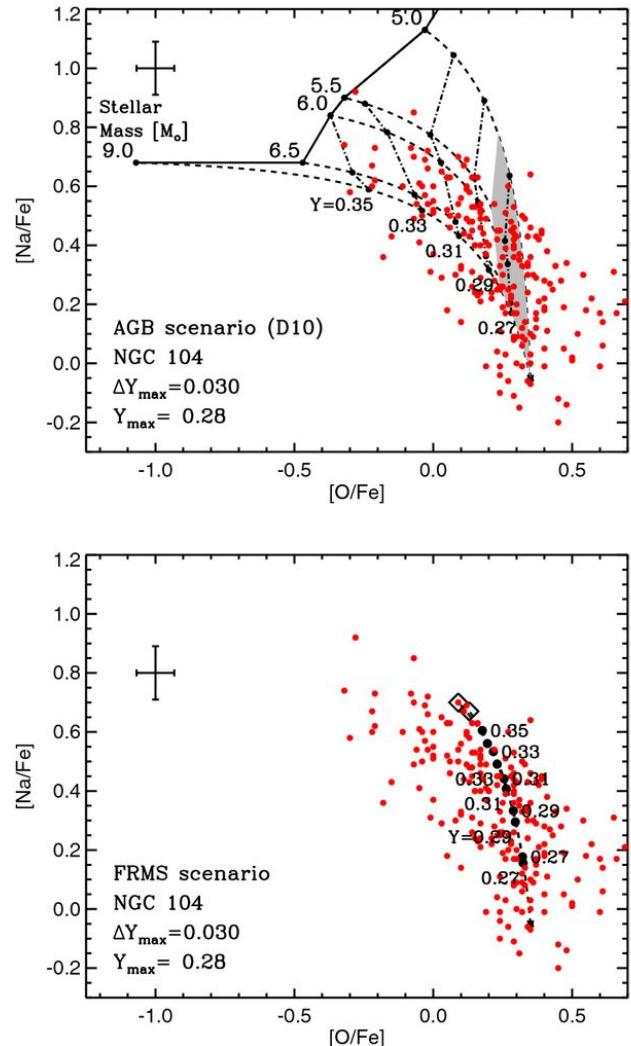
$\text{IQR}[\text{O/Na}]$ = interquartile range of the [O/Na] ratio = extension of the Na-O anticorrelation



■ ω Centauri (Johnson & Pilachowski 2009)

Origin of globular clusters:

✗ No one still knows for sure

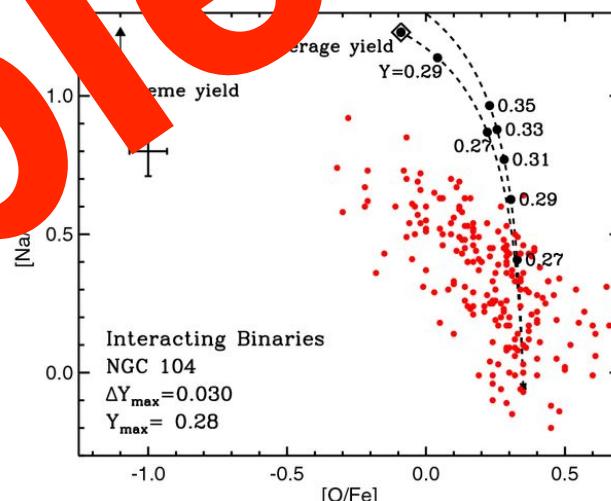
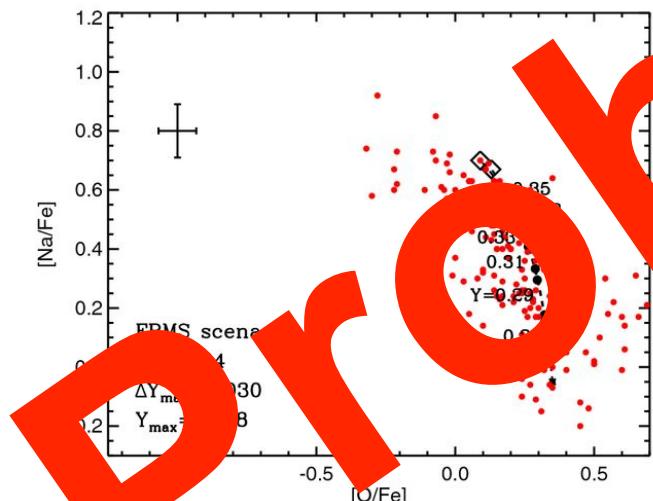
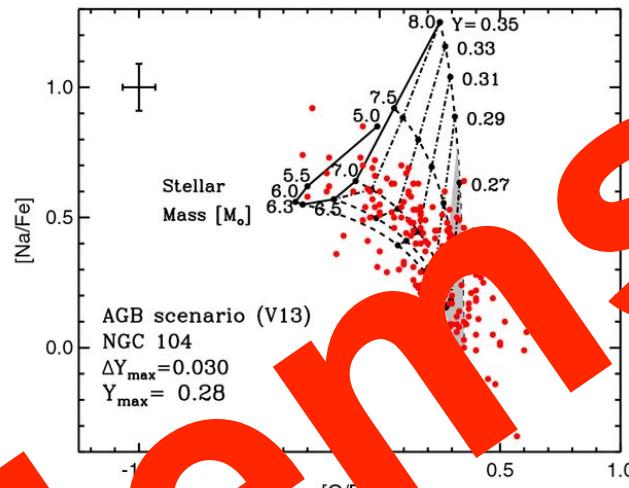
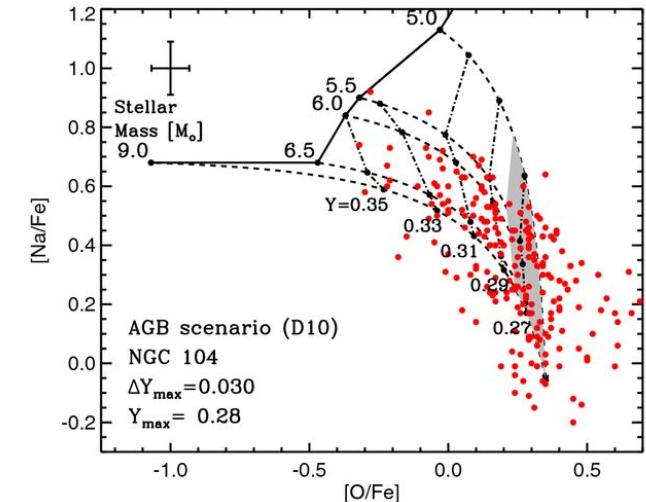


Bastian et al. 2015

Fast rotating massive stars
(Decressin et al. 2007)
Intermediate-mass AGB stars (Ventura et al. 2001)
Intermediate-mass binaries (de Mink et al. 2009)
Very massive stars (Denissenkov & Hartwick 2014)

Origin of globular clusters:

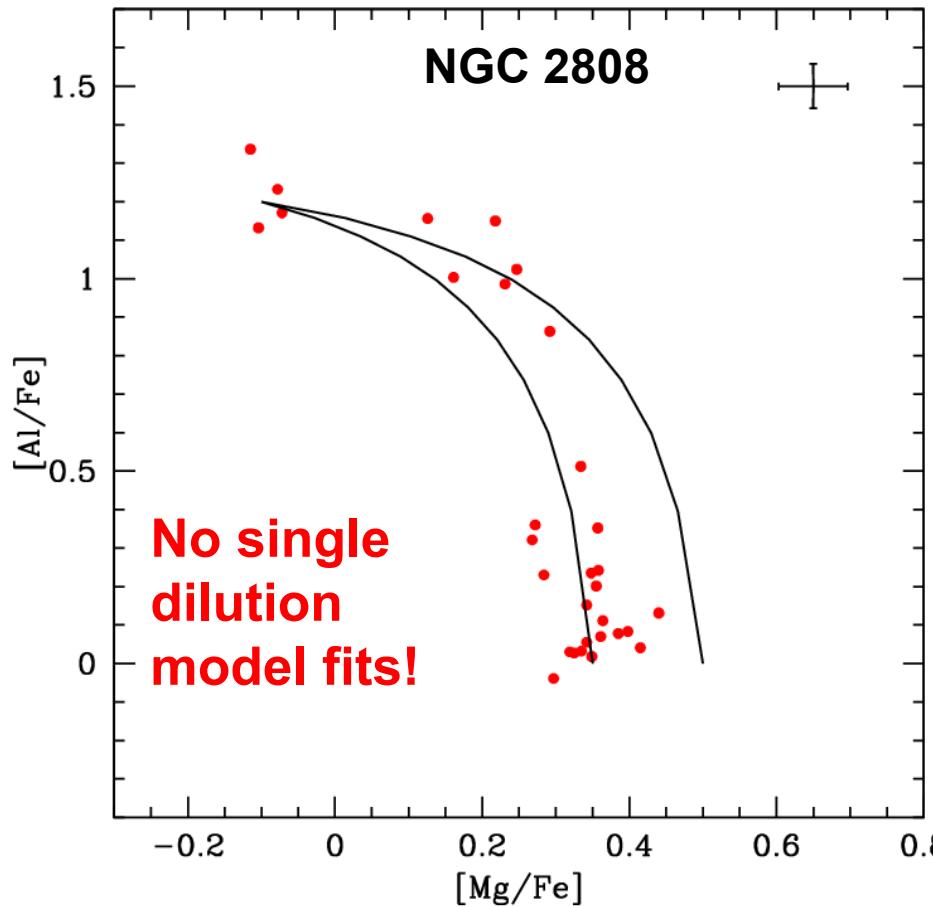
✗ No one still knows for sure



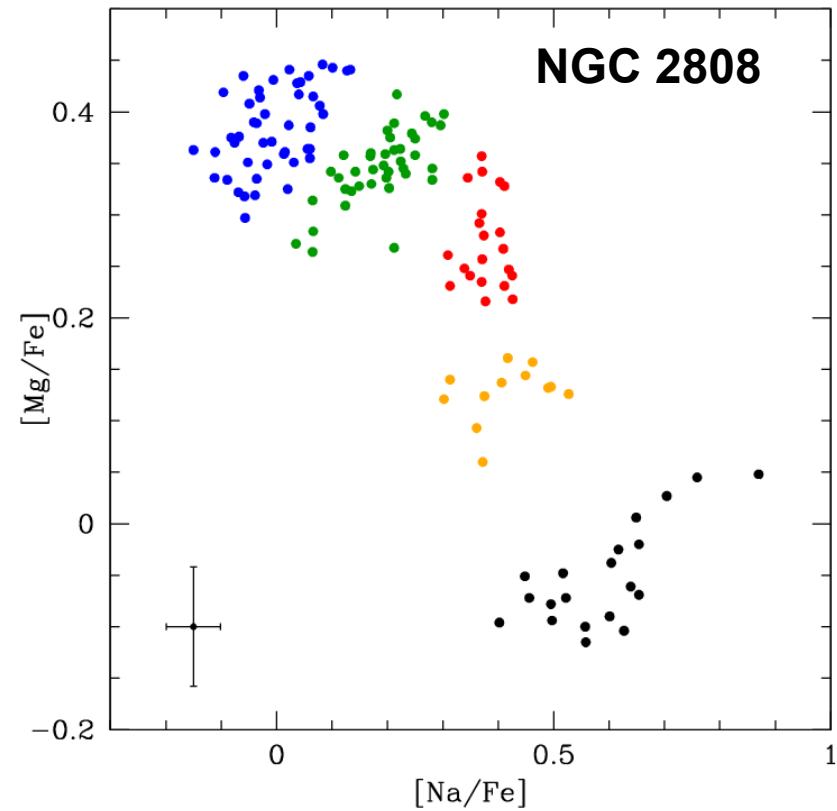
Baumian et al. 2015

Fast rotating massive stars
(Decressin et al. 2007)
Intermediate-mass AGB stars (Ventura et al. 2001)
Intermediate-mass binaries (de Mink et al. 2009)
Very massive stars (Denissenkov & Hartwick 2014)

Discrete groups: further complexity in multiple populations



spectroscopy:

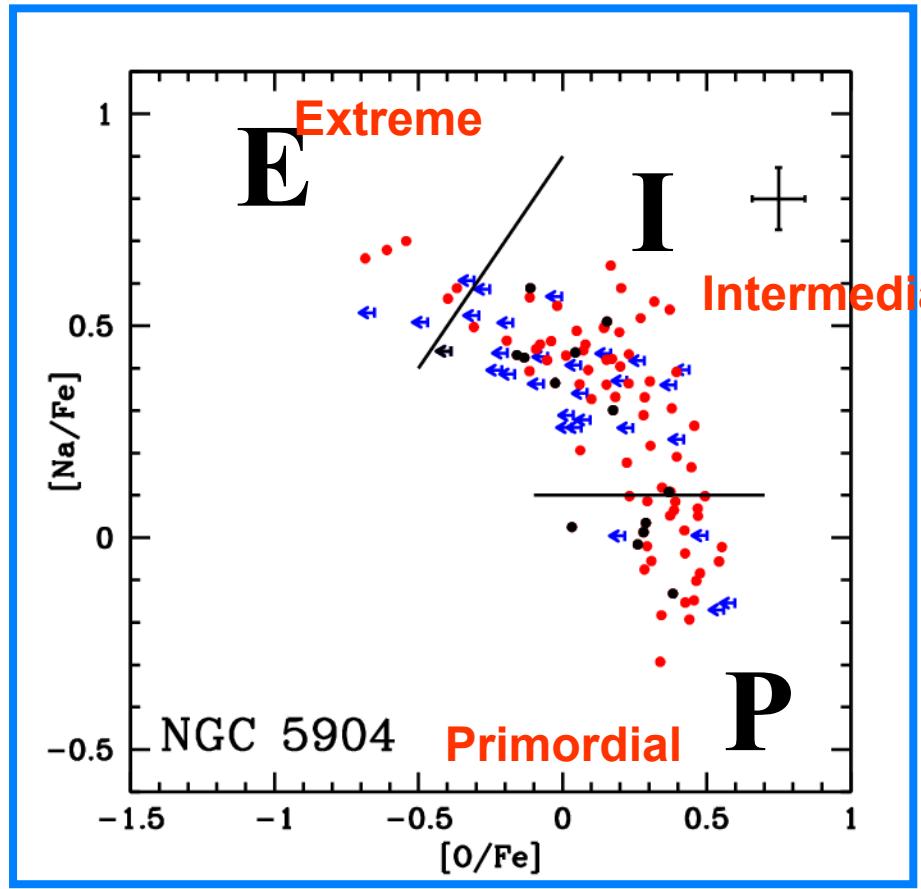


NGC 6752 (Carretta et al. 2012)
NGC 2808 (Carretta 2015)

photometry:

NGC 2808 (Milone et al. 2015)
and other GCs

Constraints on GC mass $P \approx 33\% I \approx 50-70\%$



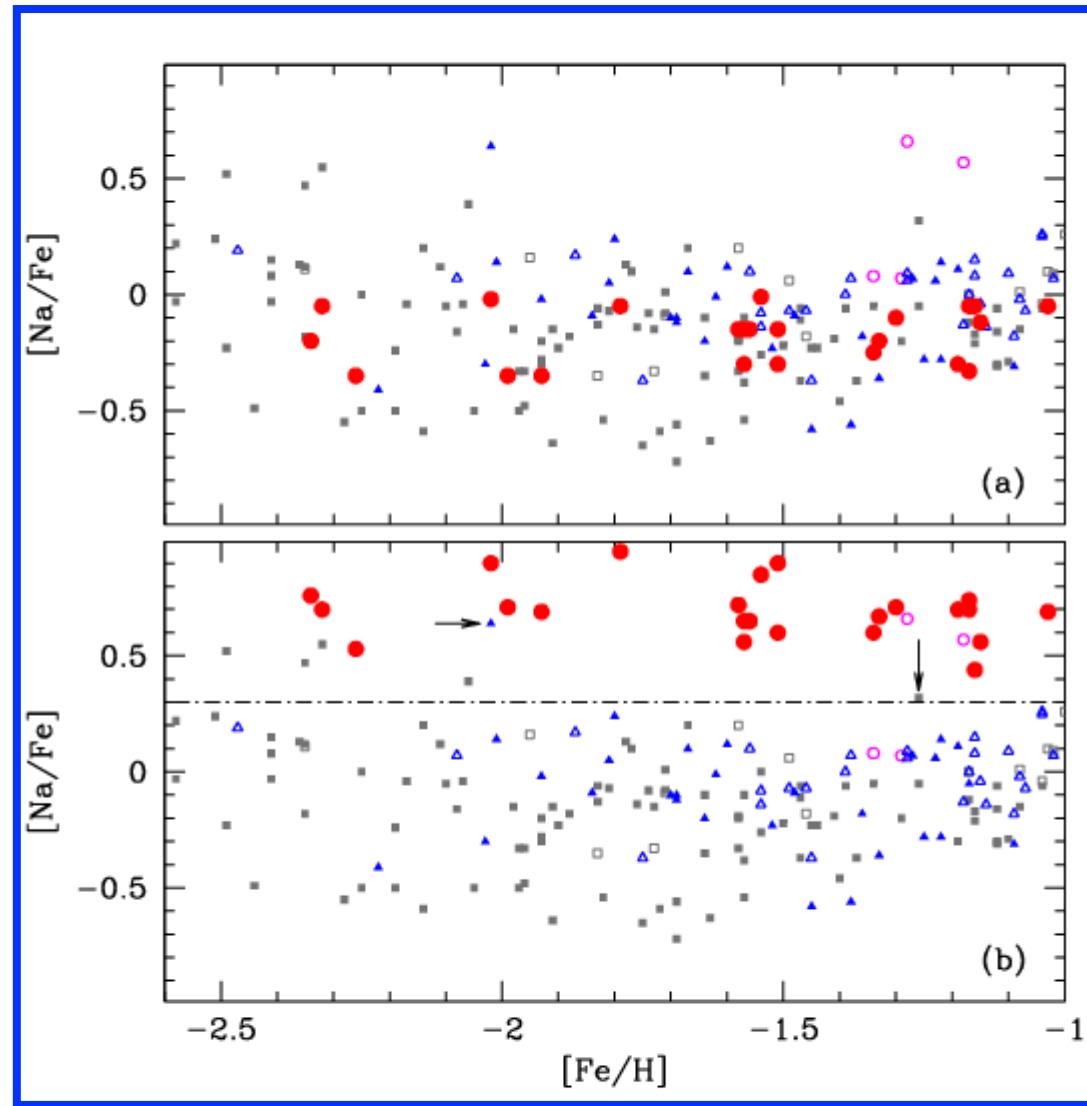
The most massive P stars contribute to form second generation stars (I,E), currently 2/3 of GC stars



- precursor of GCs were 10-20 times more massive than present end products (Bekki et al. 2007 and many others) **and**
- proto-GC lost ~90% of their stars → **possibly main contribution to halo**

First attempt: SG stars in halo

- **Na min GC
(Primordial)
SN nucleosy.**
- **Na max GC
p-capture**
- □ **Venn et al. (2004)**
- **Fulbright
(2006)**
- ▲ △ **Gratton et al.
(2003)**



6 Na-rich stars

**Excluding
binaries:**

CS22898027

CS22947187

G246-38

HD178443

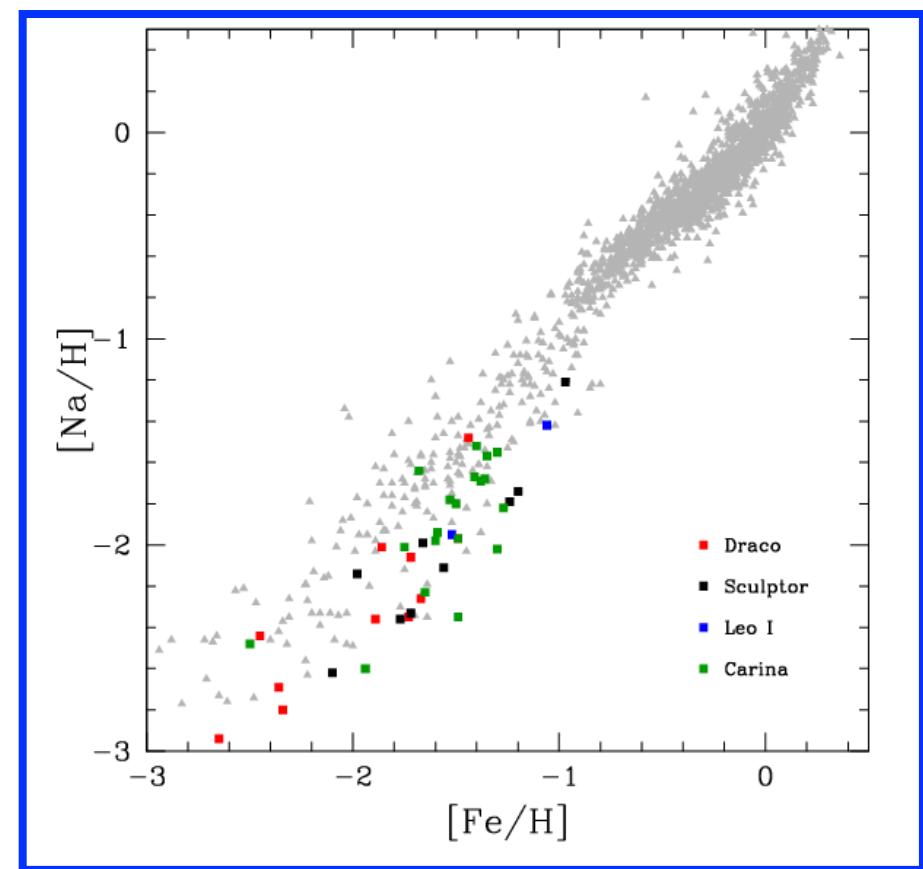
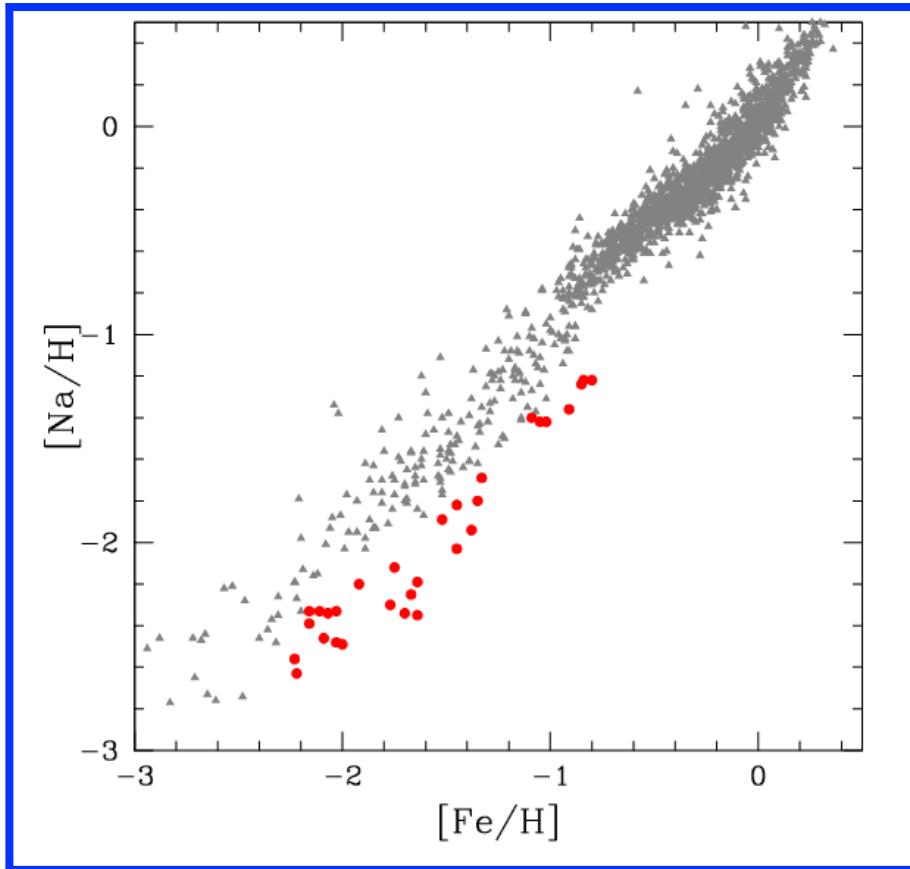
**2/144=1.4%
stars with
Na of SG
stars in GCs**



**~2.8% metal-poor
component of
MW**



stars of accretion component/low-a/retrograde orbits



Draco: Cohen & Huang 2009, Shetrone et al. 2001

Sculptor: Kirby & Cohen 2012, Shetrone et al. 2003, Geisler et al. 2005

Carina: Shetrone et al. 2003, Venn et al. 2012, Koch et al. 2008

Leo I: Shetrone et al. 2003

INFERENCE 1:

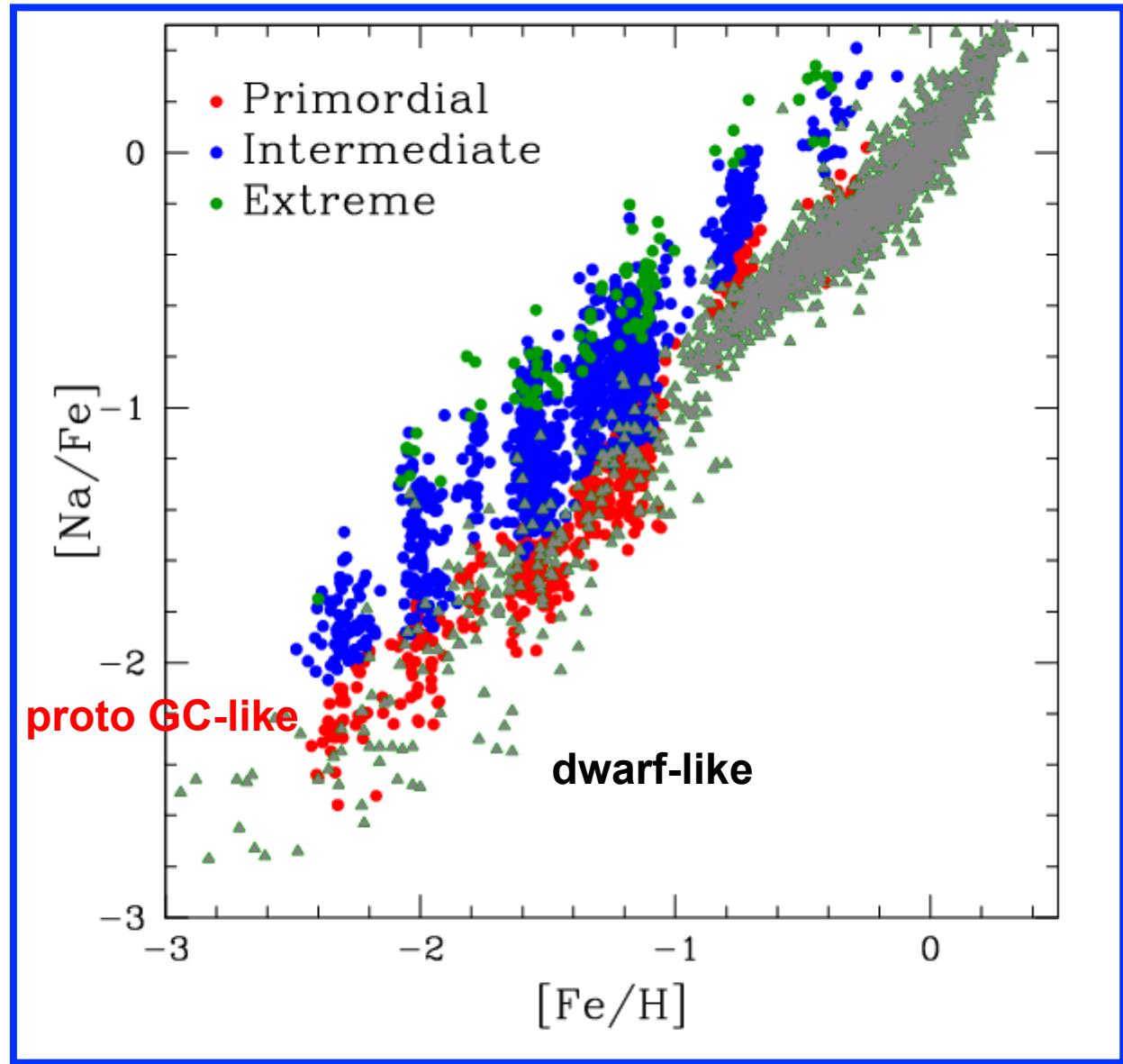
2 classes of contributors to the halo

Minority: dwarf-like composition ($\sim 10\%$)

Bulk: proto GC-like composition (P component in GCs)
 $\sim 90\%$

INFERENCE 2:

Masses proto-GC
 \gg masses present-day dSphs



AGV

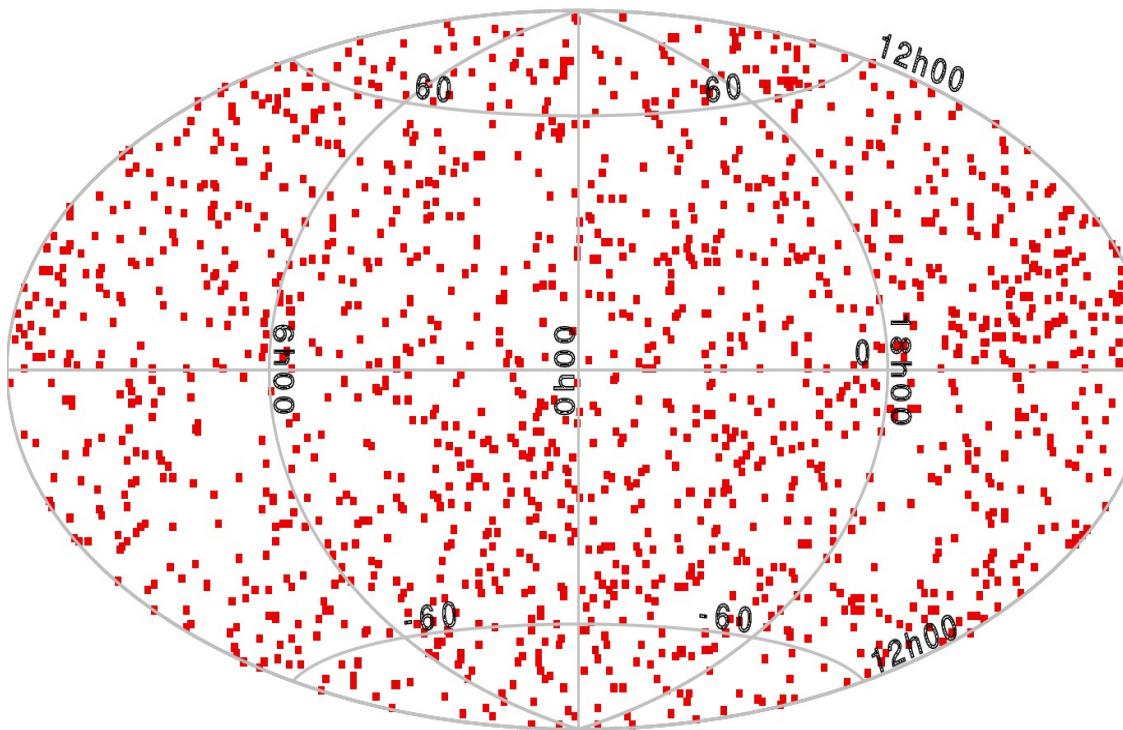
Aspettando **Gaia** al Varco Awaiting for **Gaia** Venture

Eugenio
Carretta

Angela
Bragaglia

Donatella
Romano

OABo



Monika
Adamów

UTexas,Austin

Chris
Sneden

Raffaele
Gratton

Sara
Lucatello

Valentina
D'Orazi

OAPd

project AGV

1466 Galactic field stars (accretion
+dissipative components)
selected from Hipparcos catalogue

UVES

HARPS

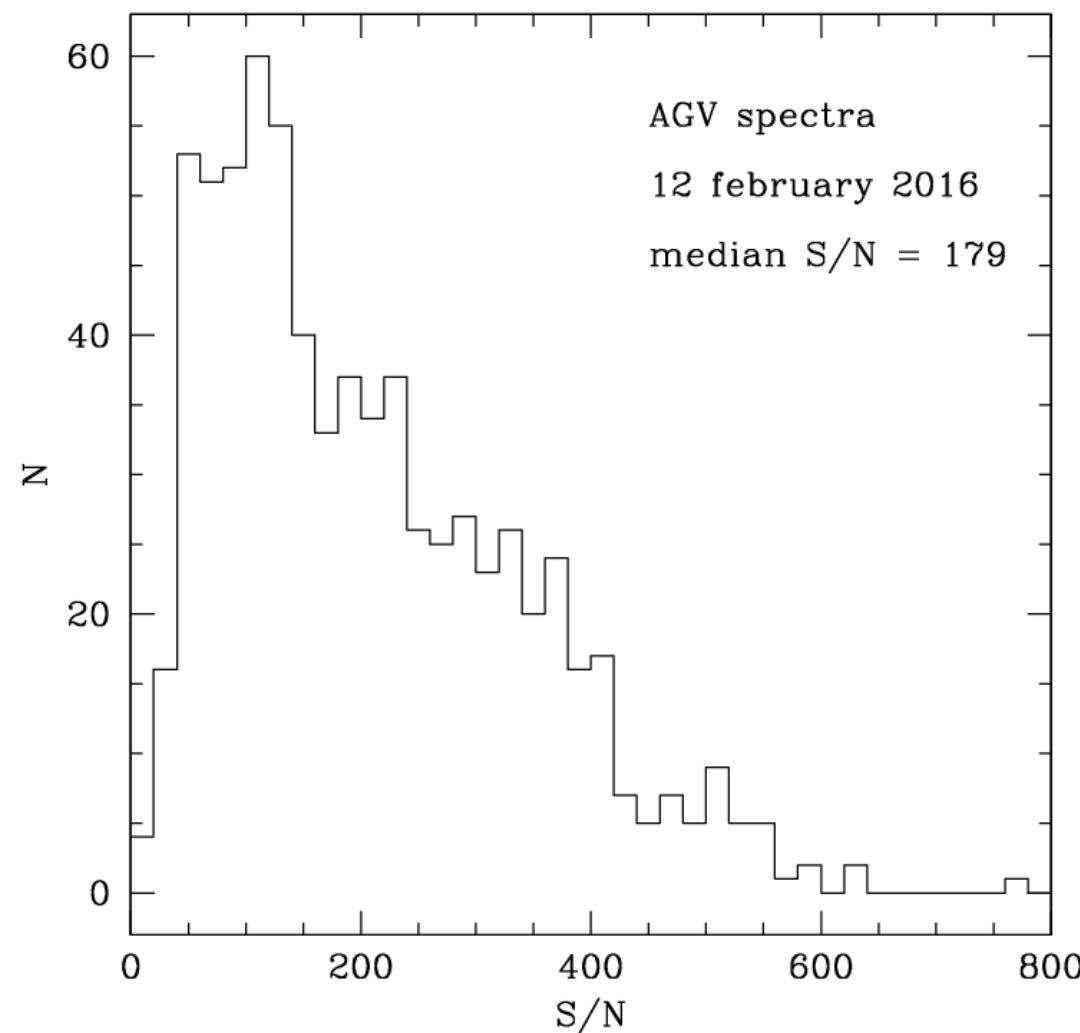
FEROS

HIRES

FIES

McDonald

SOPHIE



errors
~1 mÅ
(giants)
~3 mÅ
(dwarfs)



< 0.05 dex

Large spectral coverage,
high resolution, high S/N



accurate
abundances

hydrogen 1 H 1.0079	lithium 3 Li 6.941	boron 4 Be 9.0122
helium 2 He 4.0026	magnesium 12 Mg 24.305	
lithium 3 Li 6.941	calcium 20 Ca 40.078	
potassium 19 K 39.098	strontium 38 Sr 86.469	
rubidium 37 Rb 85.469	barium 56 Ba 132.91	
cesium 55 Cs 132.91	lanthanum 57 La 140.91	
francium 87 Fr 223	cerium 58 Ce 140.117	
radium 88 Ra 226	praseodymium 59 Pr 140.91	
	neodymium 60 Nd 144.24	

- r-process
- Light Element Primary Production
- α -element
- spallation
- iron peak
-  Big Bang
- AGB stars
- s-process

scandium 21 Sc 45.06	tinanium 22 Ti 47.967	vandium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.409	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	sulfur 34 S 78.96	chlorine 19 F 18.998
yttrium 39 Y 88.905	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	tantalum 42 Ta 101.96	technetium 43 Tc 98.0	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	thallium 50 Tl 118.73	antimony 51 Sb 121.76	tin 52 Te 127.60	polonium 84 Po 209
cerium 58 Ce 140.117	europium 62 Eu 151.96	thulium 63 Tm 160.96	ytterbium 64 Yb 173.93	dysprosium 65 Dy 162.50	holmium 66 Ho 164.93	erbium 67 Er 167.26	thulium 69 Tm 169.93	ytterbium 70 Yb 173.04						radon 86 Rn 222
lanthanum 57 La 138.91	cerium 58 Ce 140.117	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm 145	neptunium 62 Pu 150.36	plutonium 94 Pu 196	americium 95 Am 147	curium 96 Cm 147	berkelium 97 Bk 148.93	californium 98 Cf 158.51	einsteinium 99 Es 159.51	fermium 100 Fm 159.51	mendelevium 101 Md 158.51	nobelium 102 No 159
actinium 89 Ac 227	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uraniium 92 U 238.03	neptunium 93 Np 237	plutonium 94 Pu 244	americium 95 Am 243	curium 96 Cm 247	berkelium 97 Bk 247	californium 98 Cf 251	einsteinium 99 Es 252	fermium 100 Fm 257	mendelevium 101 Md 258	nobelium 102 No 259	

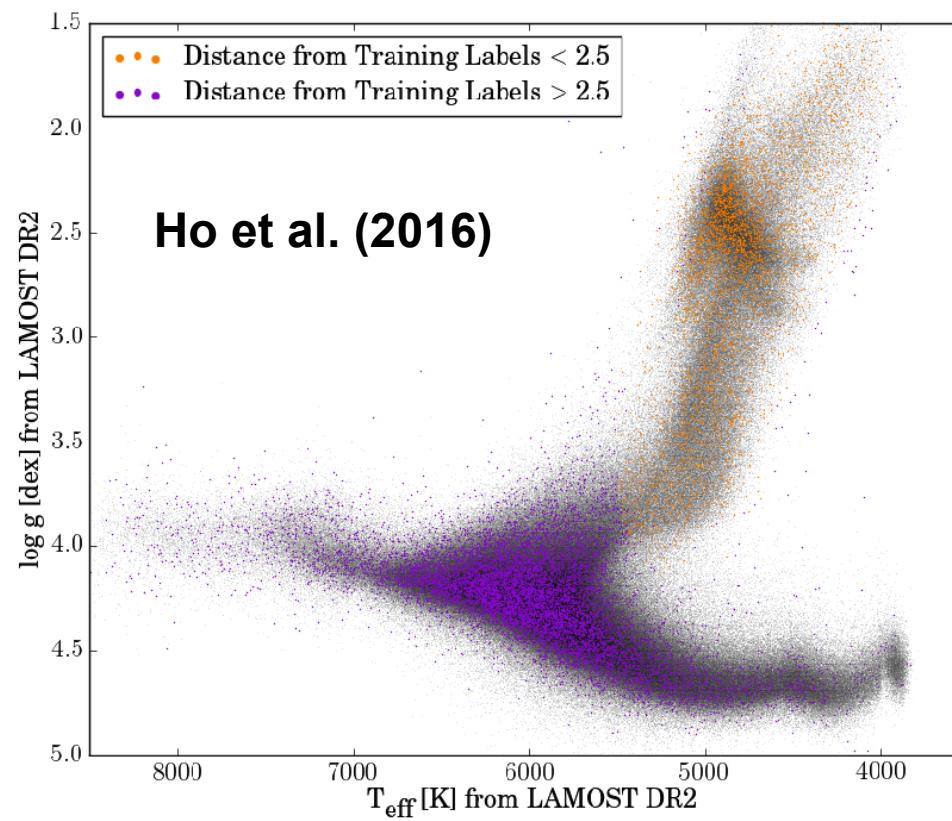
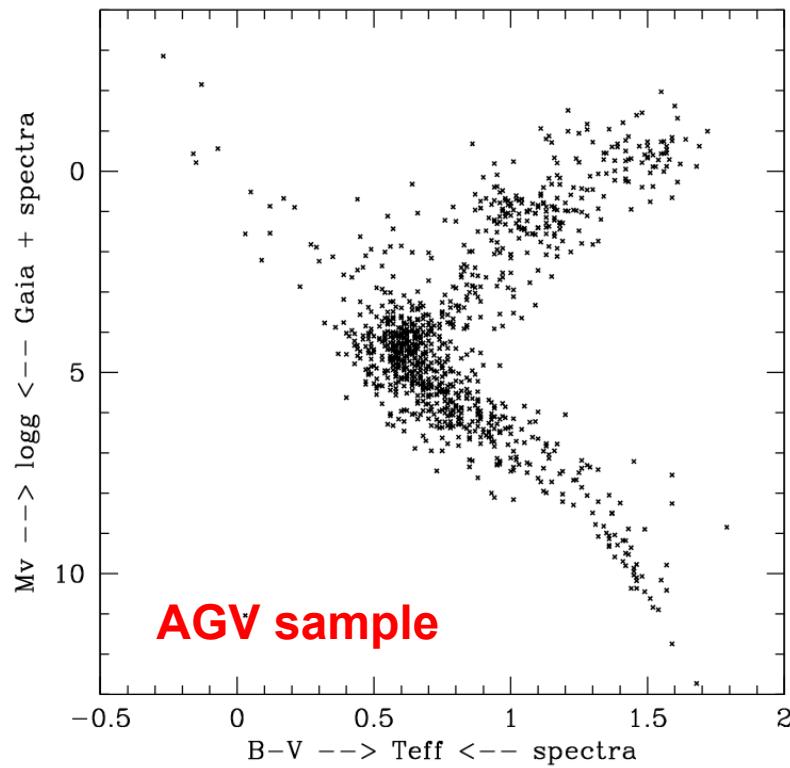
* Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.117	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm 145	neptunium 62 Pu 150.36	plutonium 94 Pu 196	americium 95 Am 147	curium 96 Cm 147	berkelium 97 Bk 148.93	californium 98 Cf 158.51	einsteinium 99 Es 159.51	fermium 100 Fm 159	mendelevium 101 Md 158.51	nobelium 102 No 159
** Actinide series	actinium 89 Ac 227	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uraniium 92 U 238.03	neptunium 93 Np 237	plutonium 94 Pu 244	americium 95 Am 243	curium 96 Cm 247	berkelium 97 Bk 247	californium 98 Cf 251	einsteinium 99 Es 252	fermium 100 Fm 257	mendelevium 101 Md 258	nobelium 102 No 259	

(colouring by Jennifer Johnson and Inese Ivans)

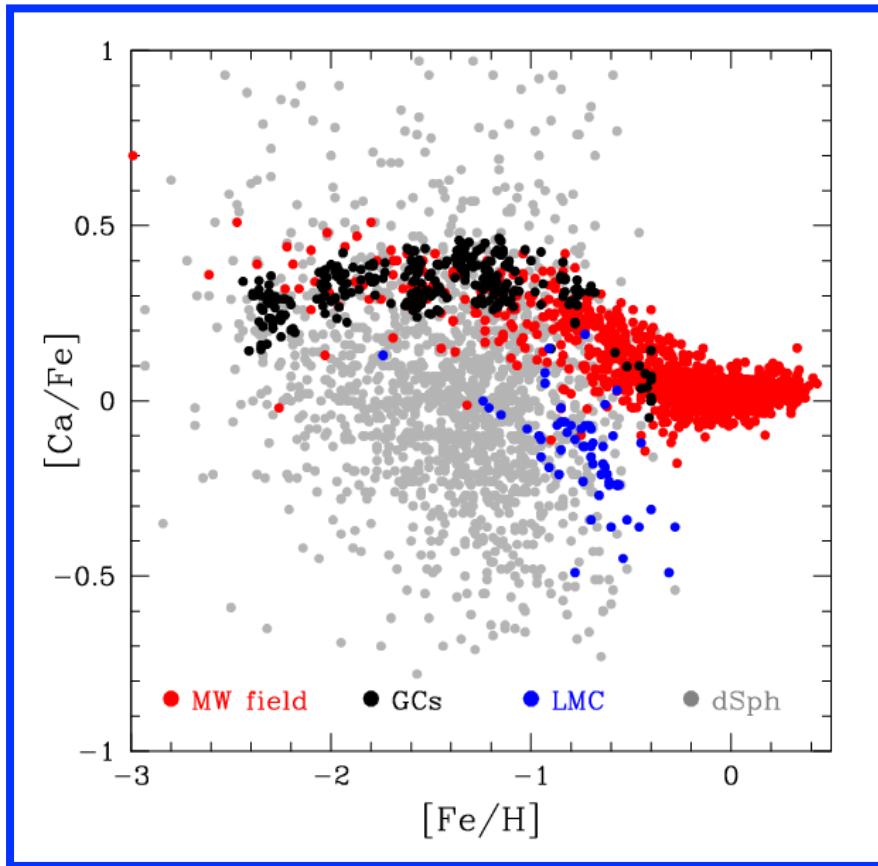
Accurate distances (and space velocities) from Gaia + precise abundances



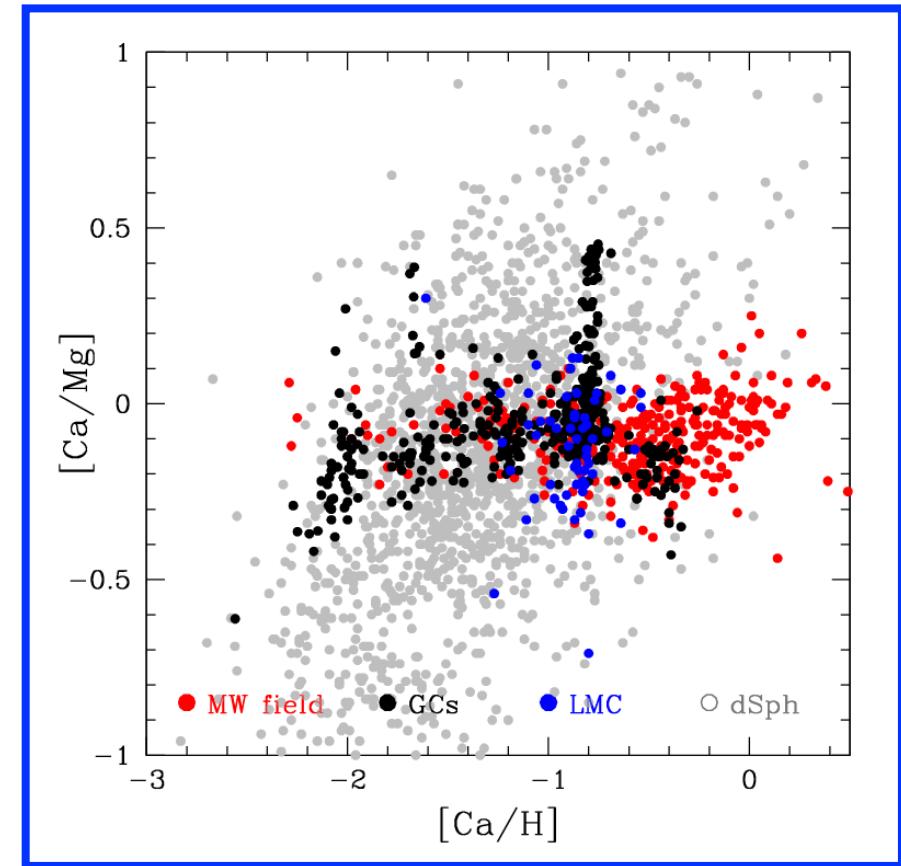
AGV: reference sample for calibrating other, lower resolution, spectroscopic surveys and GCE models



**[Ca/Fe] may resolve
GC stars from dSph
stars, **not** from field
halo MW stars**



**[Ca/Mg] may
resolve extreme
second generation
GC stars from field
halo MW stars**



Adibekyan et al. (2012), Chen (2000), Gratton et al. (2003), Jonsell et al. (2005),
Pompeia et al. (2008), Carretta et al. (2010), Kirby et al. (2011)