Globular clusters as building blocks of galaxies

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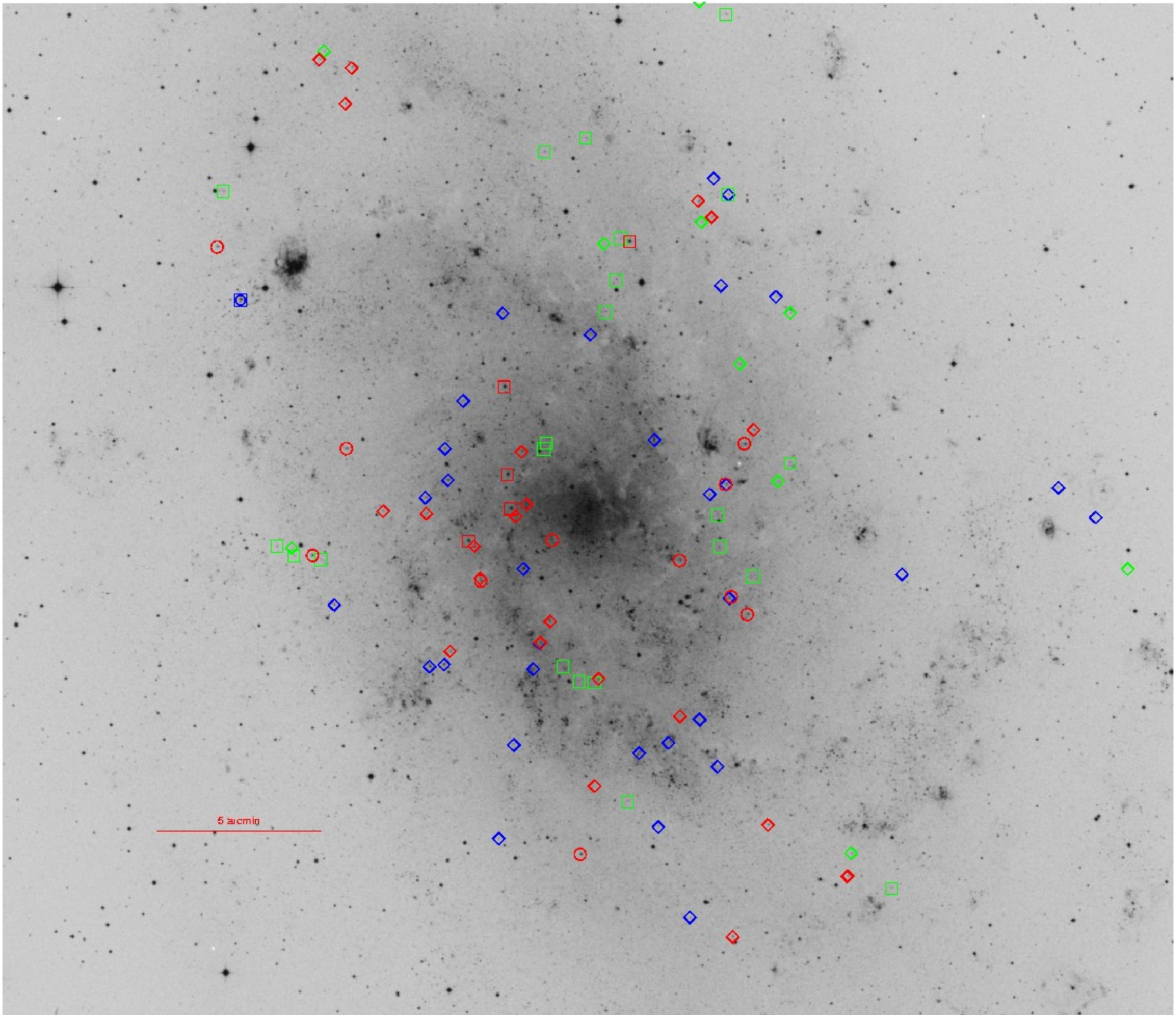
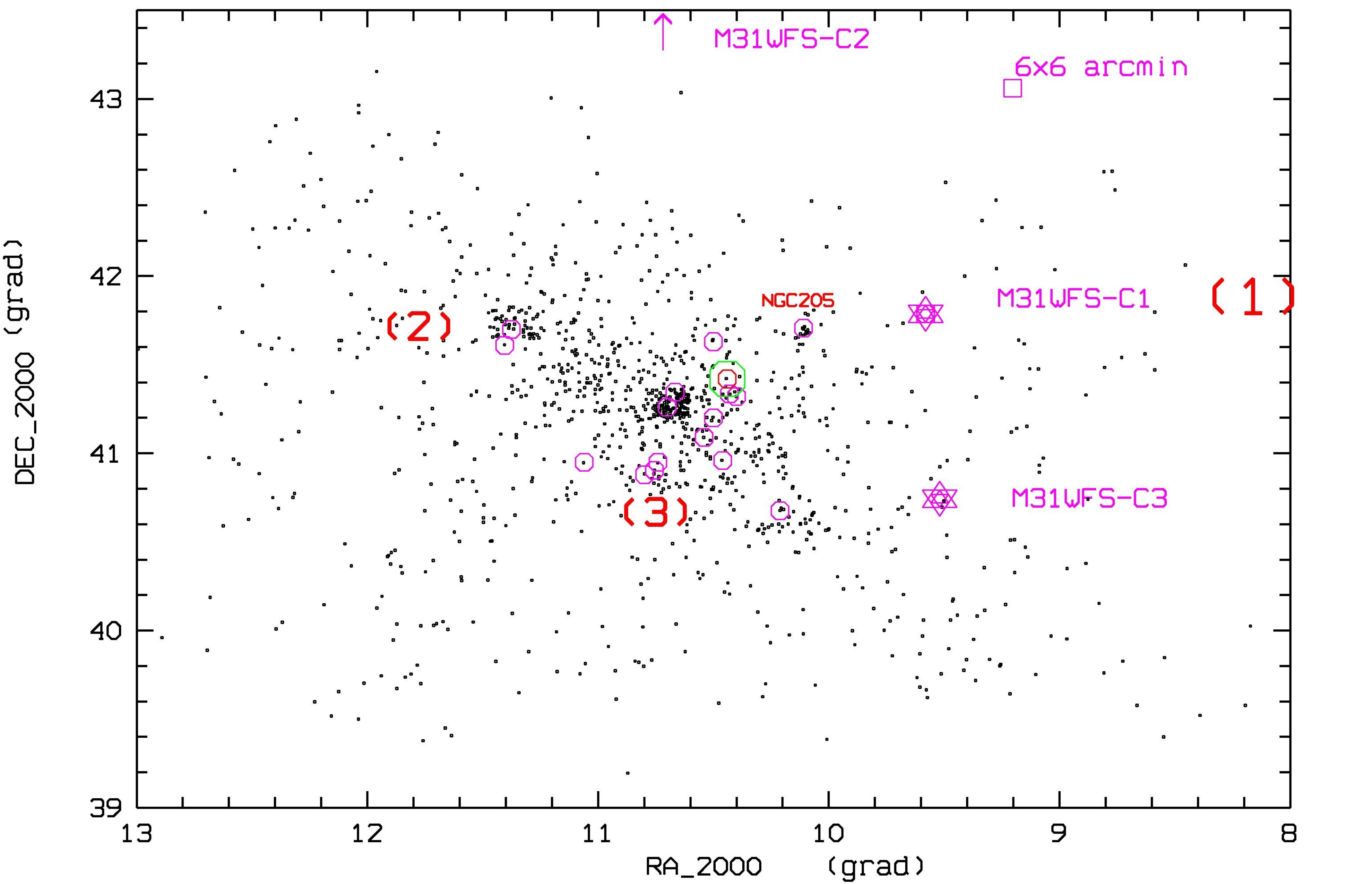
N_GC obs.	Galaxy (MD)	M_B mag.	Morf. Type	A_B mag.	D Mpc	V_h km/s	D_{MD} kpc	M_{HI} $10^9 M_\odot$	M_{tot} $10^9 M_\odot$
3	**M31**	-21.6	SA(s)b	0.27	0.77	-300	–	5.0^b	$\sim 340^b$
15	**M33** (M31)	-18.9	SA(s)cd	0.18	0.85	-180	200	2.0^c	50^c
7	**IC 10** (M31)	-15.6	BCD/dIr	3.65	0.66	-344	250	0.2^d	1.6^g
4	**UA 86** (IC342)	-17.6	dIr	4.06	2.96^a	67	331^i	1.0^e	20^h
1	**D71** (M81)	-12.1	dSph	0.41	3.5	-129	210	≥ 0	0.1::
1	**HoIX** (M81)	-13.7	dIr	0.35	3.7	46	70	0.3^f	0.3::

[10] The de-projected spatial separation between UA86 and IC342 (in Mpc) was calculated as $R^2 = D^2_{UA86} + D^2_{I342} - 2D_{UA86} \cdot D^2_{I342} \cdot cos\Theta$, where Θ is the angular separation in degrees, and the distances to the galaxies are: $D_{UA86} = 2.96$ Mpc, and $D_{I342} = 3.28$ Mpc (Karachentsev et al. 2006, 2004, 2002).

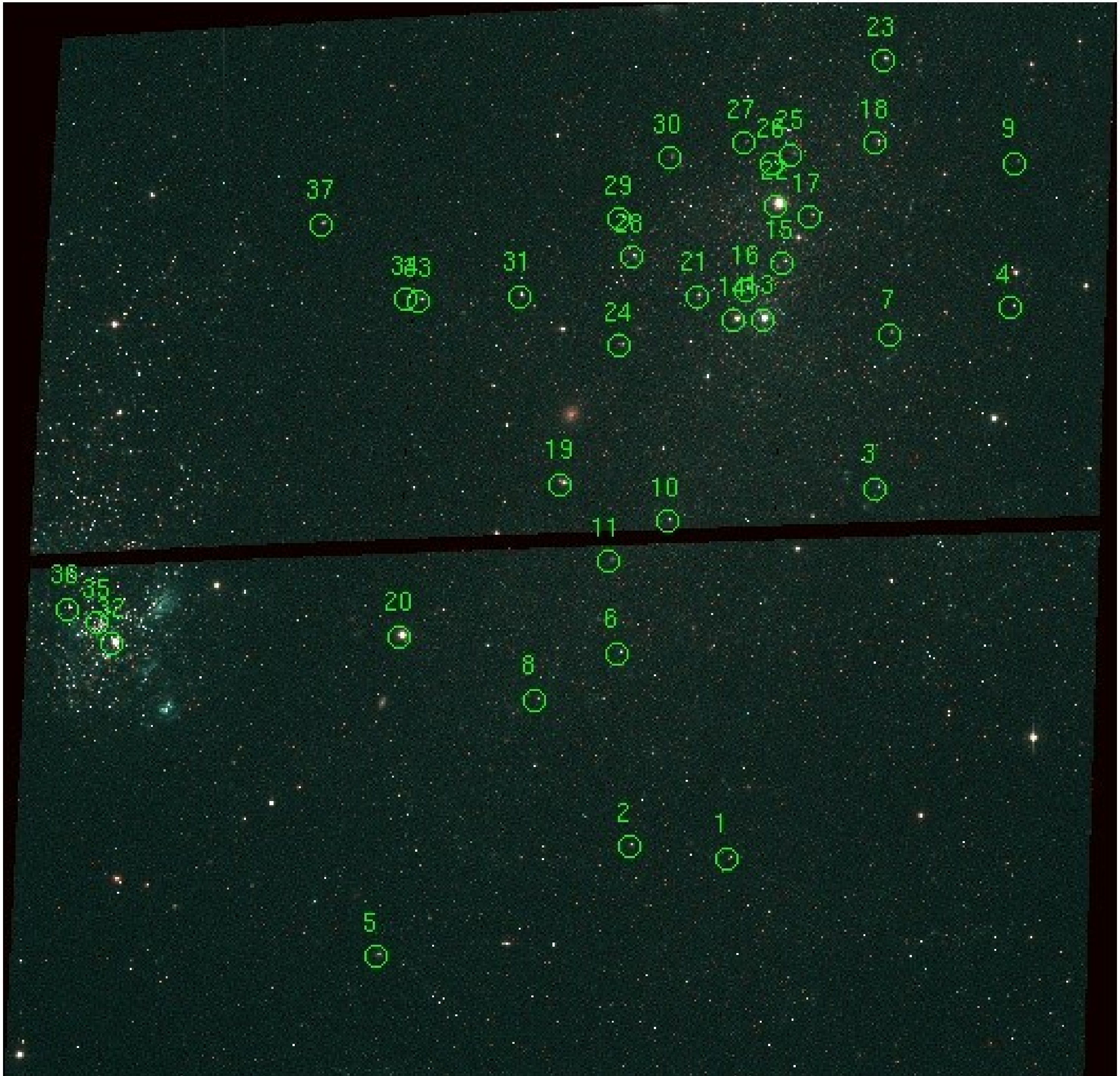
Literature sources for coordinates and magnitudes of the studied GCs. The acronym is given in the first column.

Abbreviation	Reference
M31	
CCS85	Crampton et al. (1985)
MKKSS98	Mochejska et al. (1998)
Bol	Battistini et al. (1980, 1987)
BHB2000	Barmby et al. (2000)
M33	
CS82	Christian & Schommer (1982, 1988)
KM60	Kron & Mayall (1960)
MKKSS98	Mochejska et al. (1998)
MD78	Melnick & D'Odorico (1978)
KK97	Kunchev & Kaltcheva (1997)
CBF	Chandar, Bianchi, & Ford (1999)
IC10	
H X-X	Hunter (2001)
DDO 71 and HoIX	
SPM2005	Sharina, Puzia, & Makarov (2005)

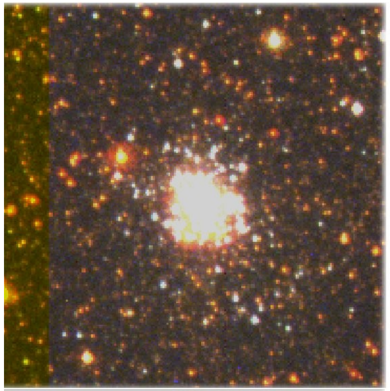

5 arcmin



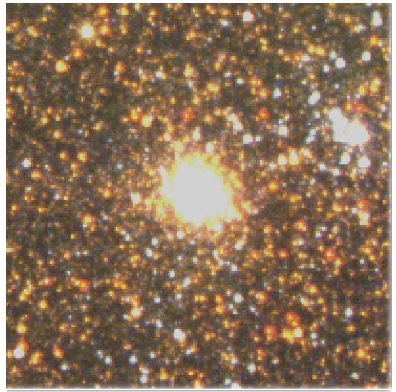
M31WFS-C2
6x6 arcmin
NGC205
M31WFS-C1
(1)
(2)
(3)
M31WFS-C3
DEC_2000 (grad)
RA_2000 (grad)
43
42
41
40
39
13
12
11
10
9
8



UGCA86

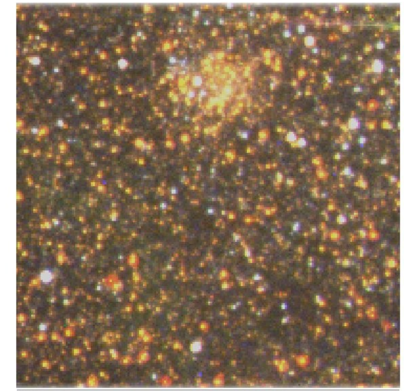


00 20 12.45,+59 17 28.0, **20**

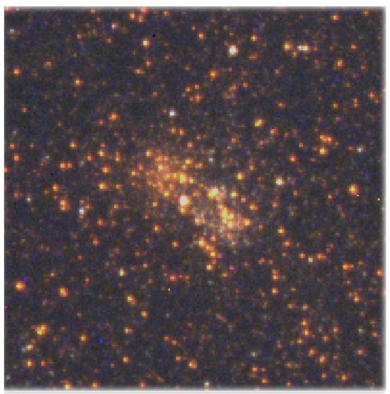


00 20 17.24,+59 17 45.3, **25**

00 20 17.91,+59 19 49.5, **27**

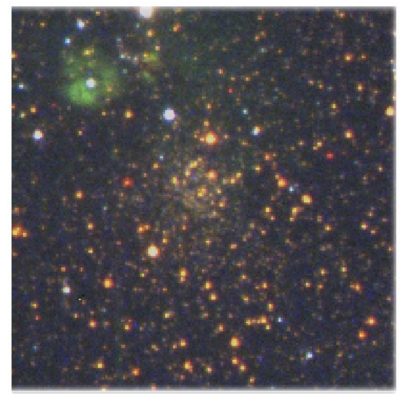


00 20 19.33,+59 17 30.6, **29**

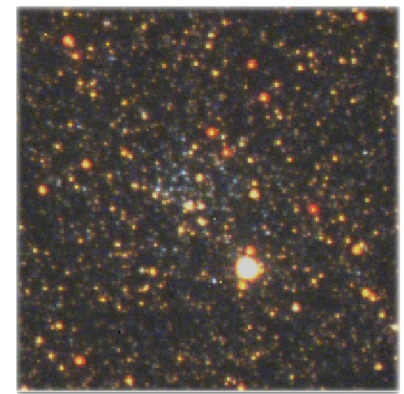


00 20 05.76,+59 18 26.0, **12**

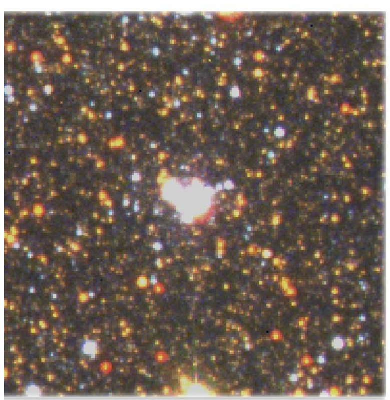
00 20 32.50,+59 17 12.8, **d23**



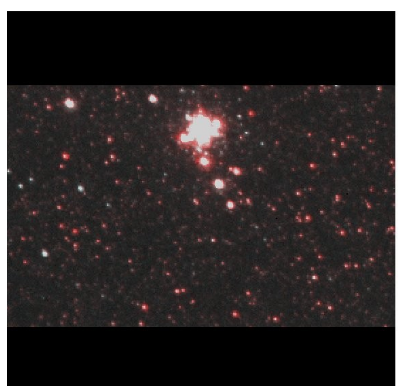
00 20 13.44,+59 20 16.1, **21**



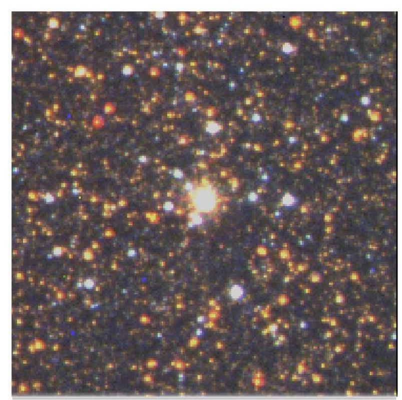
00 20 24.36,+59 19 10.1, **H2-2**



00 20 24.62,+59 18 11.9, **H1-2**



00 20 09.72 +59 17 19.3, **18**



00 20 21.53,+59 18 33.1, **33**

00 20 26.51,+59 16 36.3, **H4-6**

Star clusters in IC10

Spectra of globular clusters taken at the resolution < 1 nm

Measurements of absorption line Lick indices

$$I_t(\lambda) = \left(1 - \frac{\int F_l(\lambda) d\lambda}{\int F_c(\lambda) d\lambda}\right) \cdot \Delta\lambda,$$

$F_c(\lambda)$ flux in the feature

$F_l(\lambda)$ - flux in the continuum

Passband definitions: Worthey 94

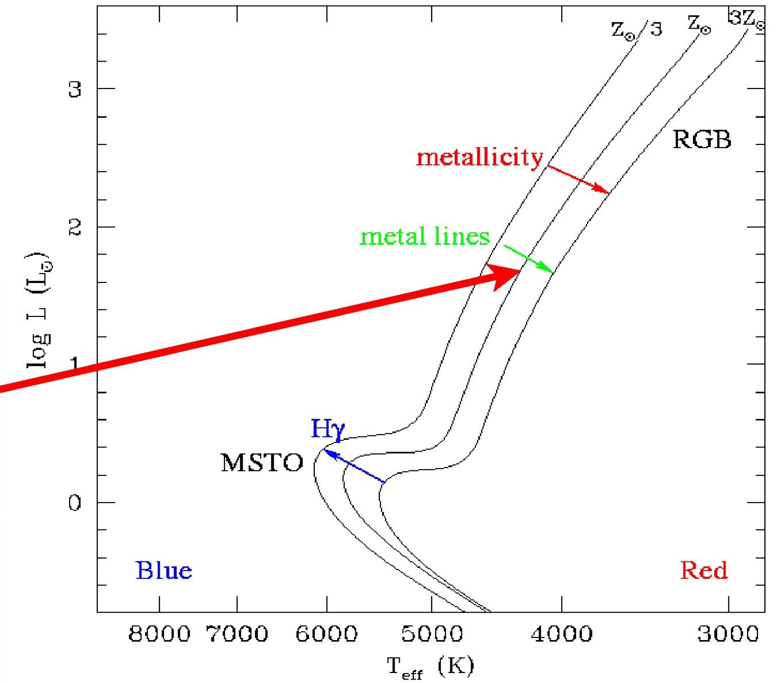
Determination of ages, metallicities and [a/Fe] ratios for the studied globular clusters

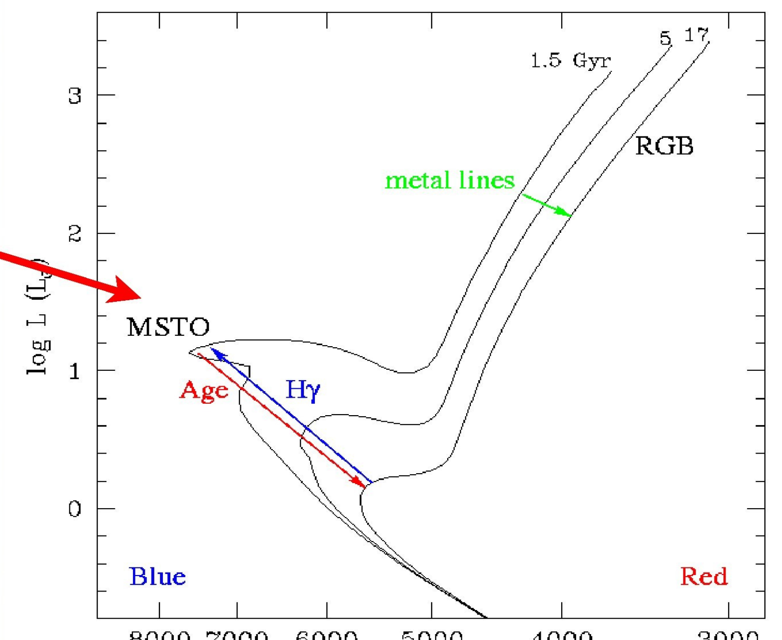
We use the SSP model predictions of Thomas et al. 2003, 2004)

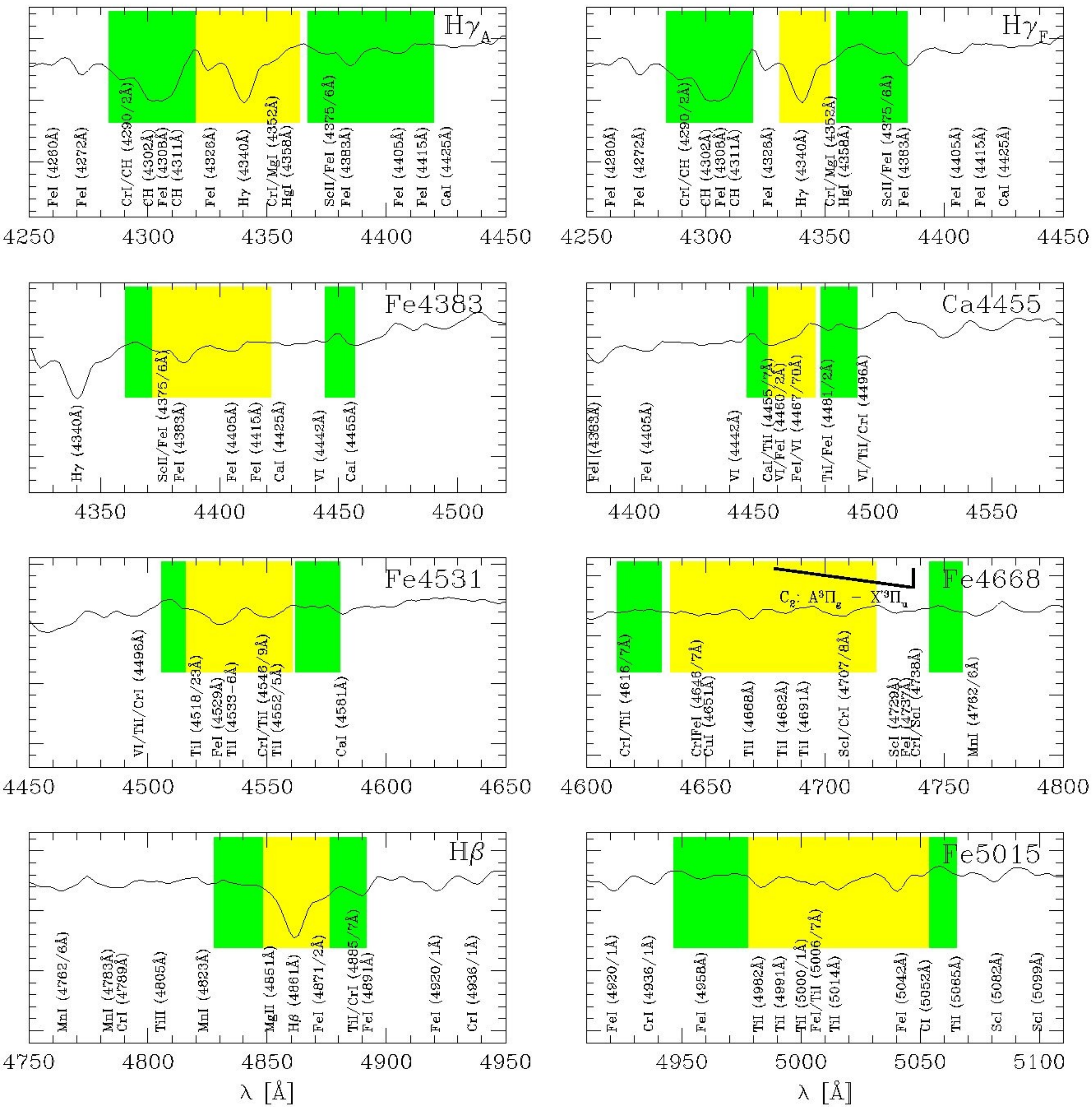
How can we break **the age - metallicity degeneracy ?**

- Metal lines arise from *coolest* stars: RGB & lower MS (invisible at optical wavelengths)
- Balmer lines of H arise from *hottest* stars (cooler than mid-B): MSTO
  - *nonlinearly* sensitive to temperature

Isochrones from Worthey (1994)







Passband definitions

(Worthey 1994)

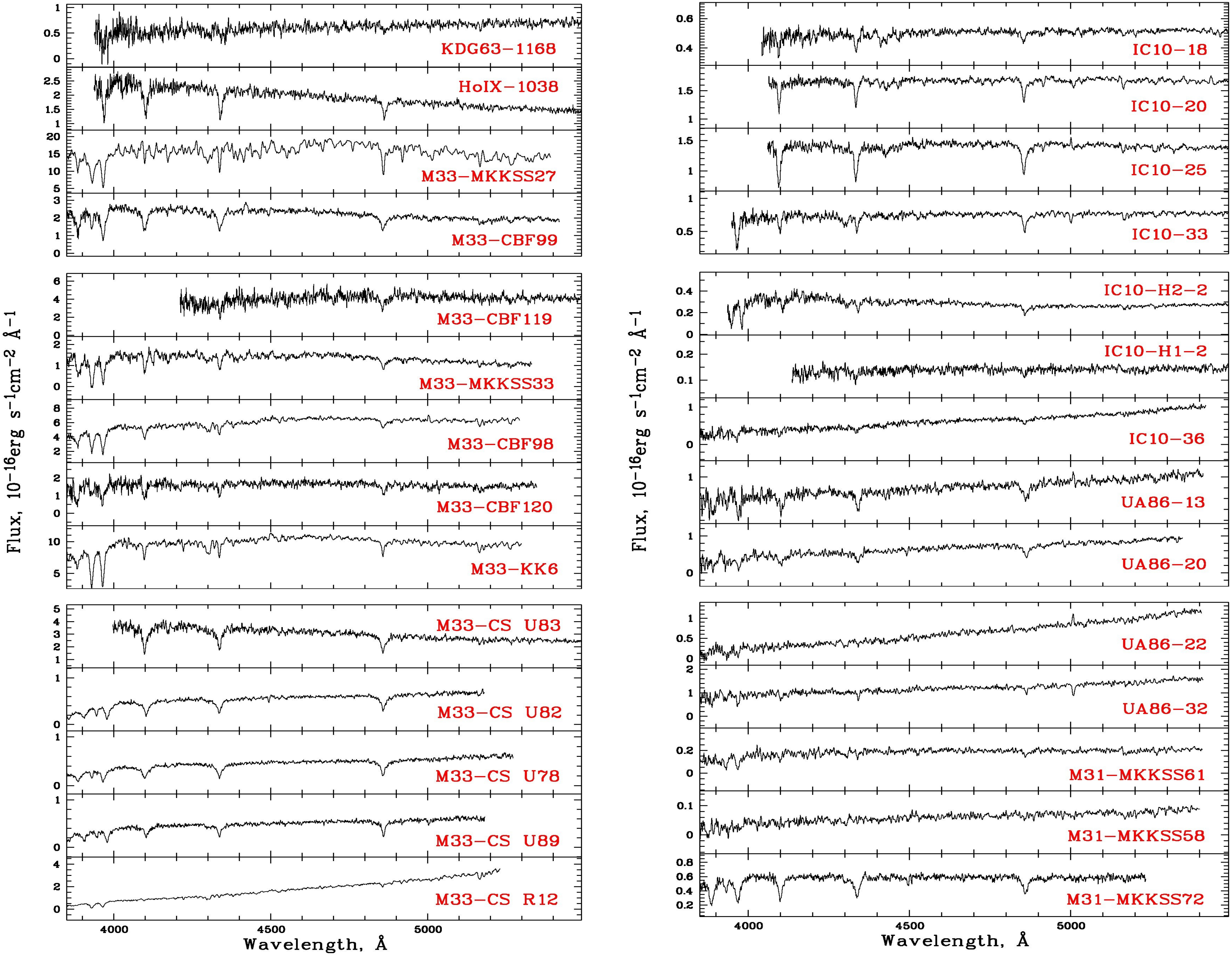
Figure: PhD Thesis Th.H.Puzia

With our method (see also SAP06), we first obtain a full set of theoretical Lick indices for any age, metallicity and [α/Fe] via three-dimensional linear interpolation. Then we minimize the following χ^2 function:

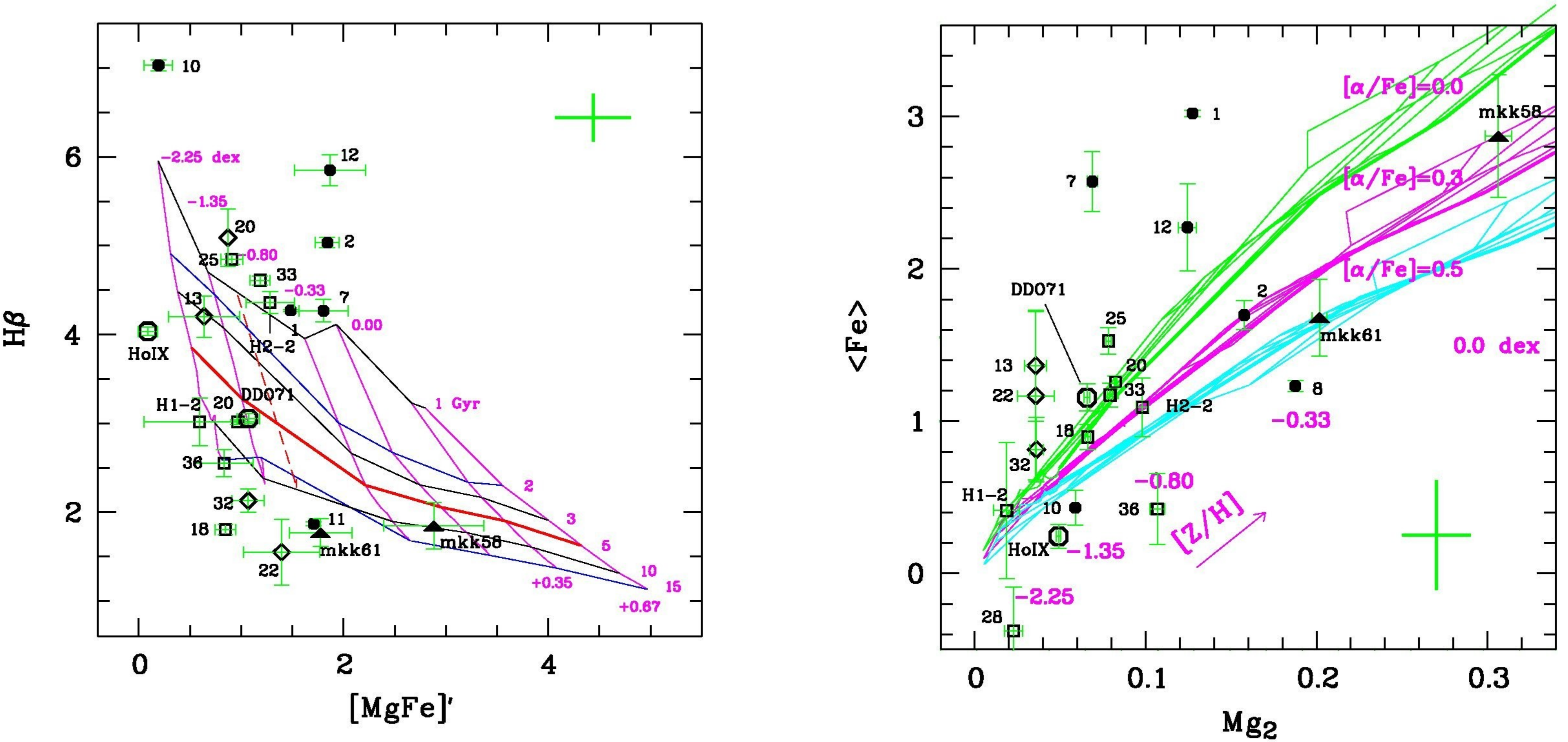
$$\chi^2 = \sum_{i=1}^{N} \left(\frac{I_i - I_i(\mathrm{age}, [\mathrm{Z/H}], [\alpha/\mathrm{Fe}])}{\sigma_{I_i}} \right)^2,$$

where N is the number of Lick indices involved in the analysis, I_i is an observed index, σ_{I_i} is the total uncertainty of the index, including rms error of transformations to the Lick/IDS system, $I_i(\mathrm{age}, [\mathrm{Z/H}], [\alpha/\mathrm{Fe}])$ is the theoretical index prediction.

We use the standard definition, $[X/Y] = log(X/Y) - log(X_\odot/Y_\odot)$, where X and Y are masses of specific elements. [Z/H] is the overall metallicity.



Flux, 10^{-16}erg s^{-1}cm^{-2} Å^{-1}
Wavelength, Å
KDG63−1168
HoIX−1038
M33−MKKSS27
M33−CBF99
M33−CBF119
M33−MKKSS33
M33−CBF98
M33−CBF120
M33−KK6
M33−CS U83
M33−CS U82
M33−CS U78
M33−CS U89
M33−CS R12
IC10−18
IC10−20
IC10−25
IC10−33
IC10−H2−2
IC10−H1−2
IC10−36
UA86−13
UA86−20
UA86−22
UA86−32
M31−MKKSS61
M31−MKKSS58
M31−MKKSS72



Age -- metallicity (left), and [a/Fe]-- metallicity (right) diagnostic plots. Symbols indicate GCs in different galaxies: M31 (triangles), M33 (dots), IC10 (open squares), UGCA86 (open lozenges), LSB dwarf galaxies DDO71, and HoIX (large open circles)

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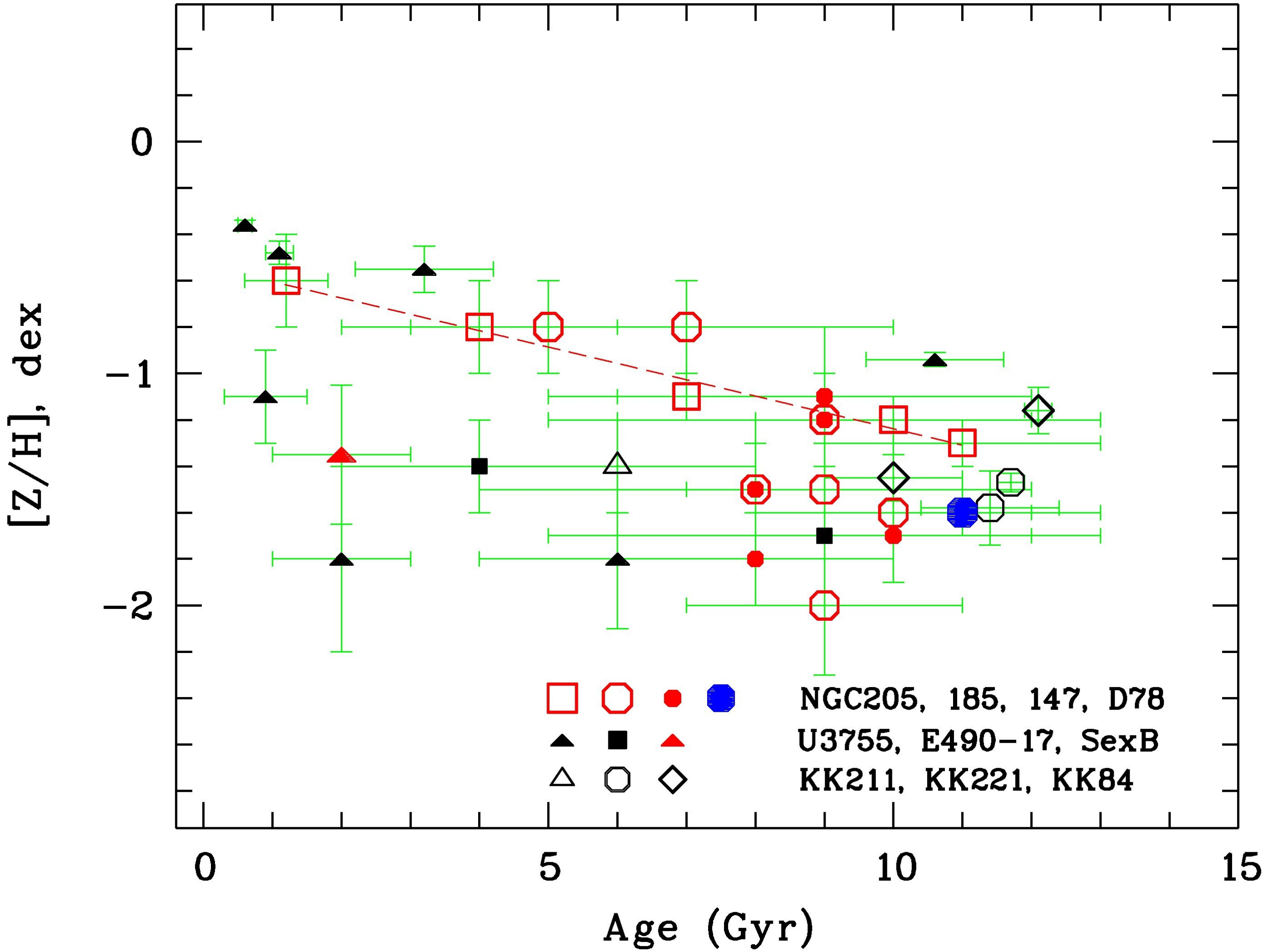
* $[\mathrm{MgFe}]' = \{\mathrm{Mg}b \cdot (0.72 \cdot \mathrm{Fe5270} + 0.28 \cdot \mathrm{Fe5335})\}^{1/2}$

$\langle Fe \rangle = (Fe5270 + Fe5335)/2$

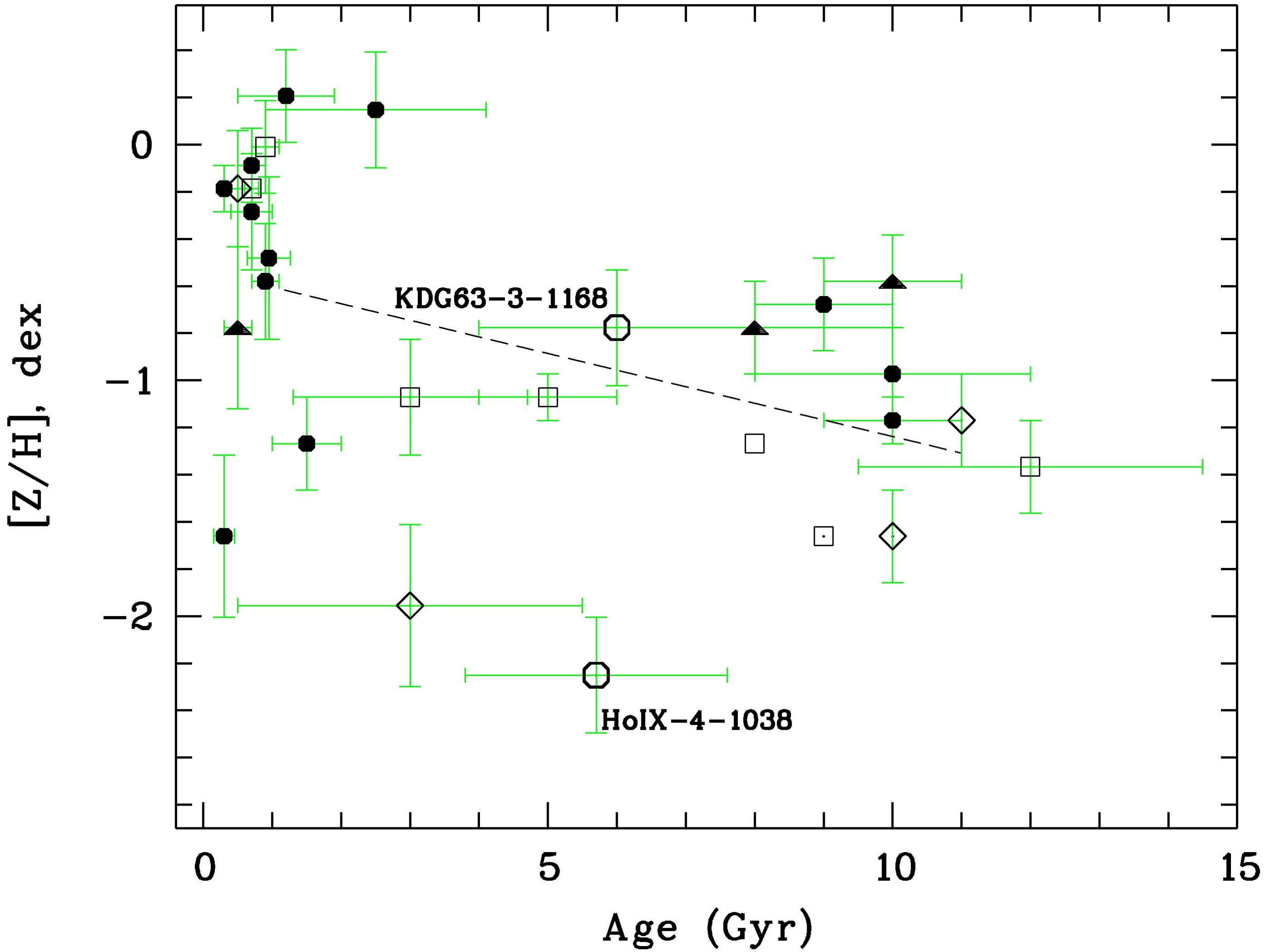
Evolutionary parameters:

- We obtain high S/N spectra of 12 star clusters in M33. Among them: 3 old metal-poor ([Z/H] < 1.3 dex), 2 young metal-poor, 7 young metal-rich objects.
- The central GC in DDO71 (S/N=20) : [Z/H]~ - 0.8, Age~ 6 Gyr.
- GC in HoIX (S/N=24) likely belongs to M81 halo ([Z/H]~ -2.3, Age~ 6 Gyr). The age of HoIX is ~200 Myr (Makarova et al. 2002, Sabbi et al. 2008).
- Clusters in a wide range of ages and metallicities in IC10 and UA86. Continues cluster formation in IC10.
- The mean metallicity, age, and a/Fe obtained for the three GCs in the disc of M31 ([Z/H] ~ -0.8 dex, Age~ 9 Gyr, [a/Fe] ~ 0.3 dex agree well with the values found for the thin disc GCs in M31 by Puzia et al. (2005).
- Alpha-element ratios tend to be lower for dwarf galaxies.

Continuous star cluster formation in NGC205



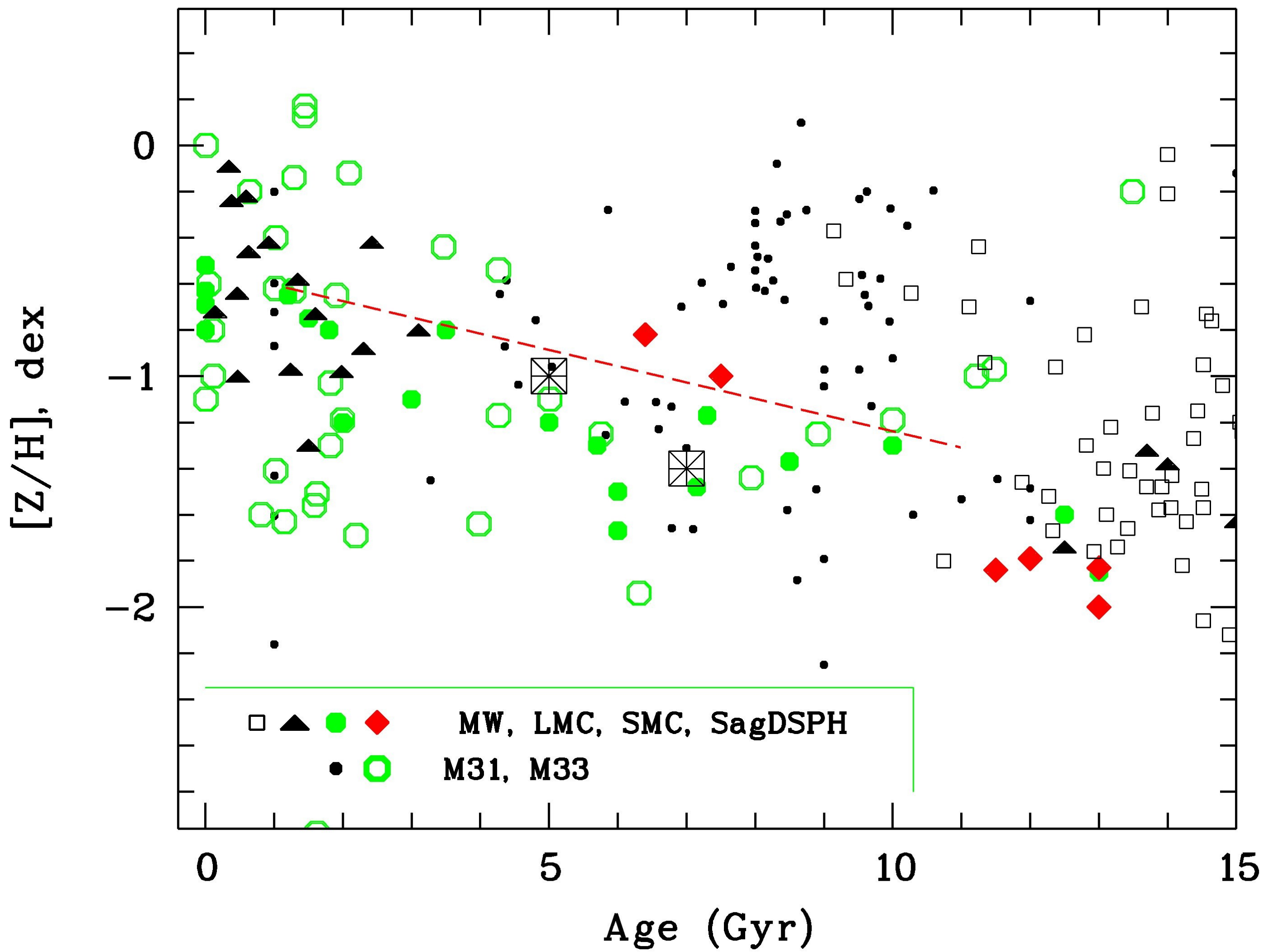
Age-metallicity relation for GCs in LSB dwarf galaxies (Sharina et al. 2003, 2006; Sharina and Puzia, 2008) and in the satellites of M31: NGC147, 185, and 205



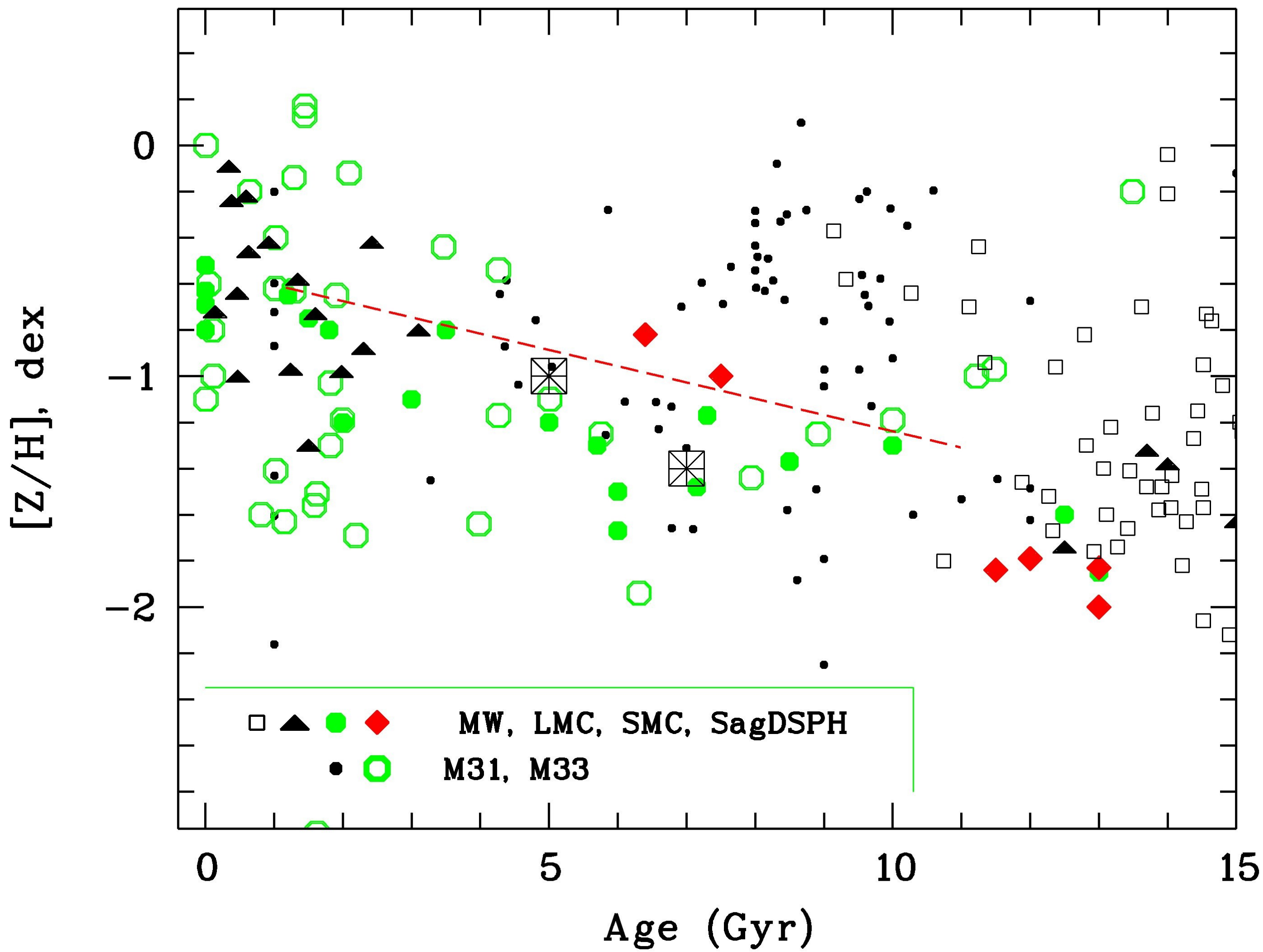
Age-metallicity relation for our sample of GCs.

Symbols indicate GCs in different galaxies: M31 (triangles), M33 (dots), IC10 (open squares), UGCA86 (open lozenges), LSB dwarf galaxies DDO71 and HoIX (large open circles)

Literature data



Age-metallicity relation for GCs in LMC, SMC, Sagittarius dSph, and nearby spirals M31 and M33. Intermediate-age and extended GCs in M33 are indicated by crossed squares (Chandar et al. 2006, Stonkutė et al., 2008).



M31 instantaneous inflow of weakly enriched gas (Morison et al. 2004).

M33 Sarajedini et al. (2000): the build up of the M81 halo extended over many Gyr.

Intermediate-age and extended GCs in M33 (Chandar et al. 2006, Stonkute et al., 2008).

Closed-box model of continuous SF for SagDSPH (Layden & Sarajedini 2000)

LMC, SMC: Da Costa 1991, 2002, Da Costa & Hatzidimitriou 1998.

AGE – METALLICITY RELATION:

- The metallicity spread in GC systems is wider for larger galaxies
- Metal-rich clusters are young and preferentially found in galaxies more massive than 10^9 M_sun.
- Old and intermediate-age globular clusters in luminous early-type dwarf galaxies (Mv < -16 mag.) are richer in metals than in irregular galaxies of similar luminosity;
- The AMR is special for each galaxy, and depends not only on its mass, but also on some other factors, probably environmental conditions.

Gas content of galaxies and properties of their GC systems

- The brightest star clusters found by us have masses ~10^7 M_sun in UGCA86, and ~10^6 M_sun in IC10.

- The HI distribution and kinematics of UGCA86, IC10, and M33 are complex.
  IC10 : interaction with M31 (Wilcots 2002);
  UGCA86 : infalling gaseous clouds (Stil et al. 2005);
  M33 : huge warped HI disk (Rogstad et al. 1976, Corbelli et al. 1989)

- LSB dwarfs : gas-free, single ancient SF period

Gas content of galaxies and properties of their GC systems

- Stellar groups and associations, open, globular, and super star clusters are members of one family (e.g. Elmegreen 2002, Kroupa & Boily, 2002).

- Formation of super-massive (10^6 – 10^7 M_sun) gravitationally bound star clusters is a consequence of higher virial densities, and higher ambient pressures (e.g. Elmegreen & Efremov 1997, Ashman et al. 1994).
  The SF rate in galaxies is a power-law of gas density (Schmidt 1959, Kennicutt 1998) .

- Fundamental stellar upper mass limit, M_max – M_ecl relation (Weidner & Kroupa, 2004)