Observational constraints on GC formation scenarios

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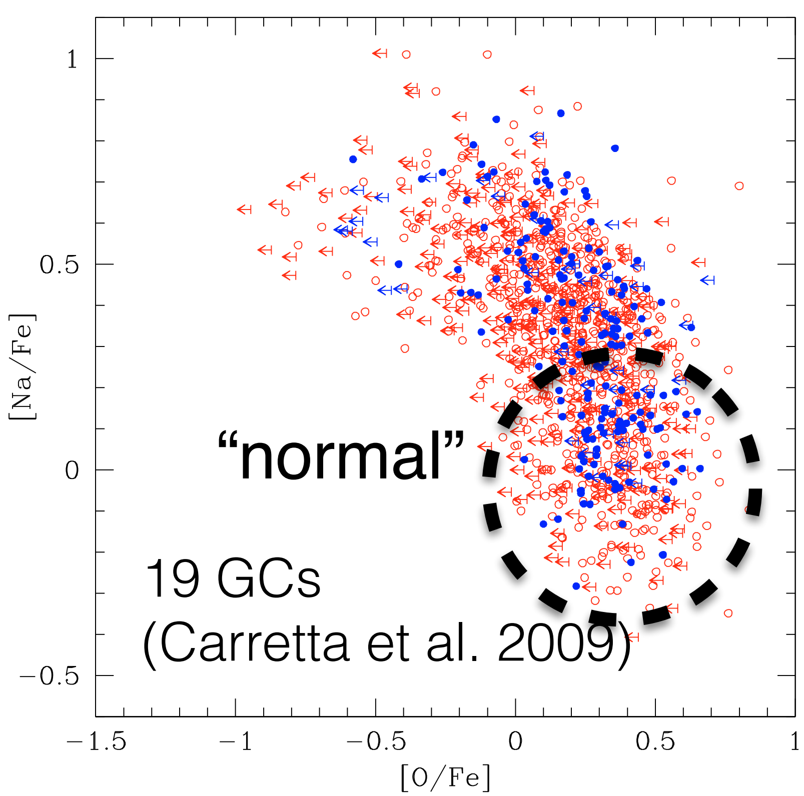
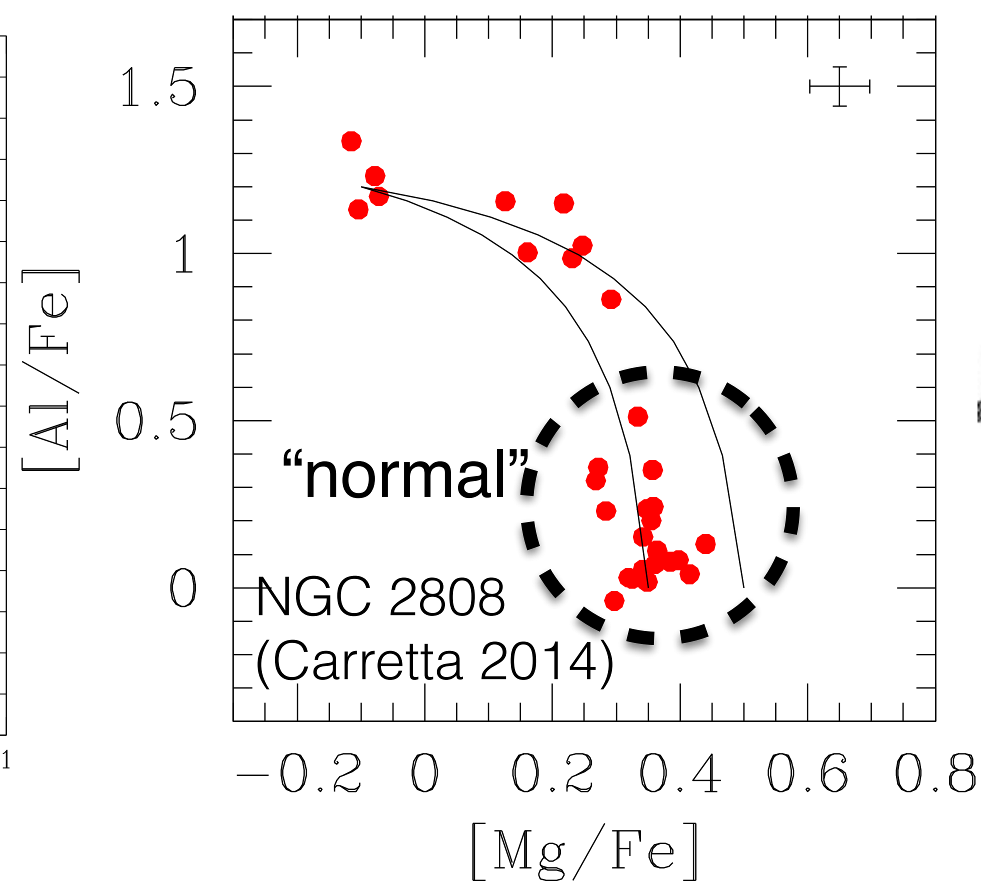
Multiple populations in GCs - key points:

- *Ubiquitous*; Na/O anti-correlation is present in all *old* GCs observed to date (though Mg/Al and large He spreads only in some).
- Most GCs show no, or only very small (≲0.05 dex), spreads in Ca, Fe
- Fraction of “anomalous” stars is *large*; 50% or more.

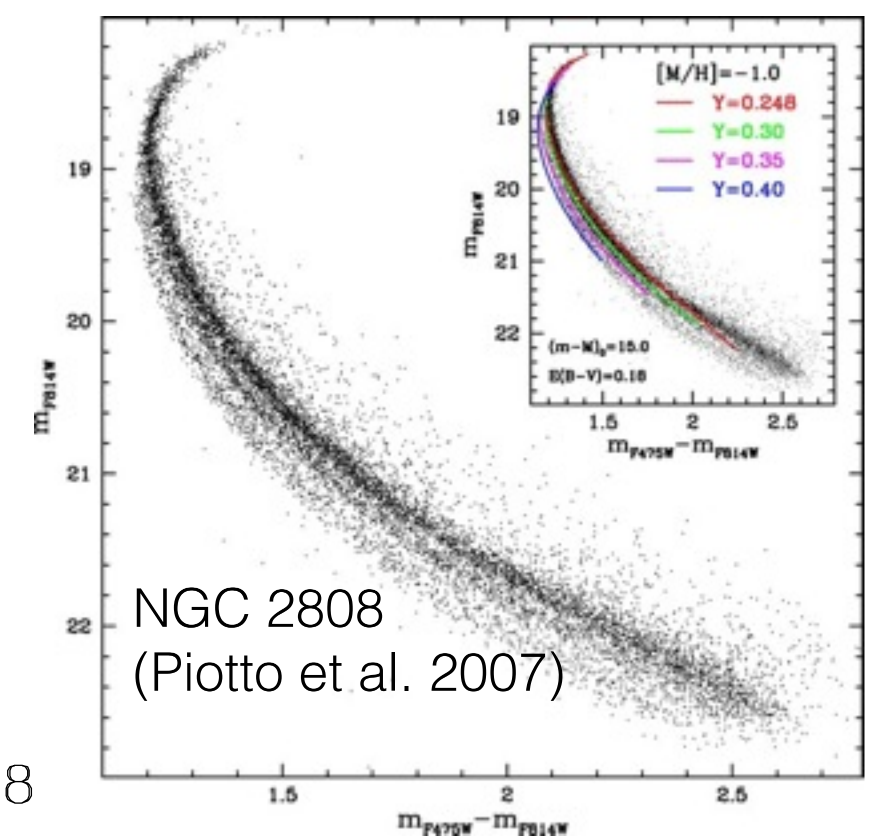
Na/O anti-correlation



Mg/Al anti-correlation



Complex CMDs



The Mass Budget Problem

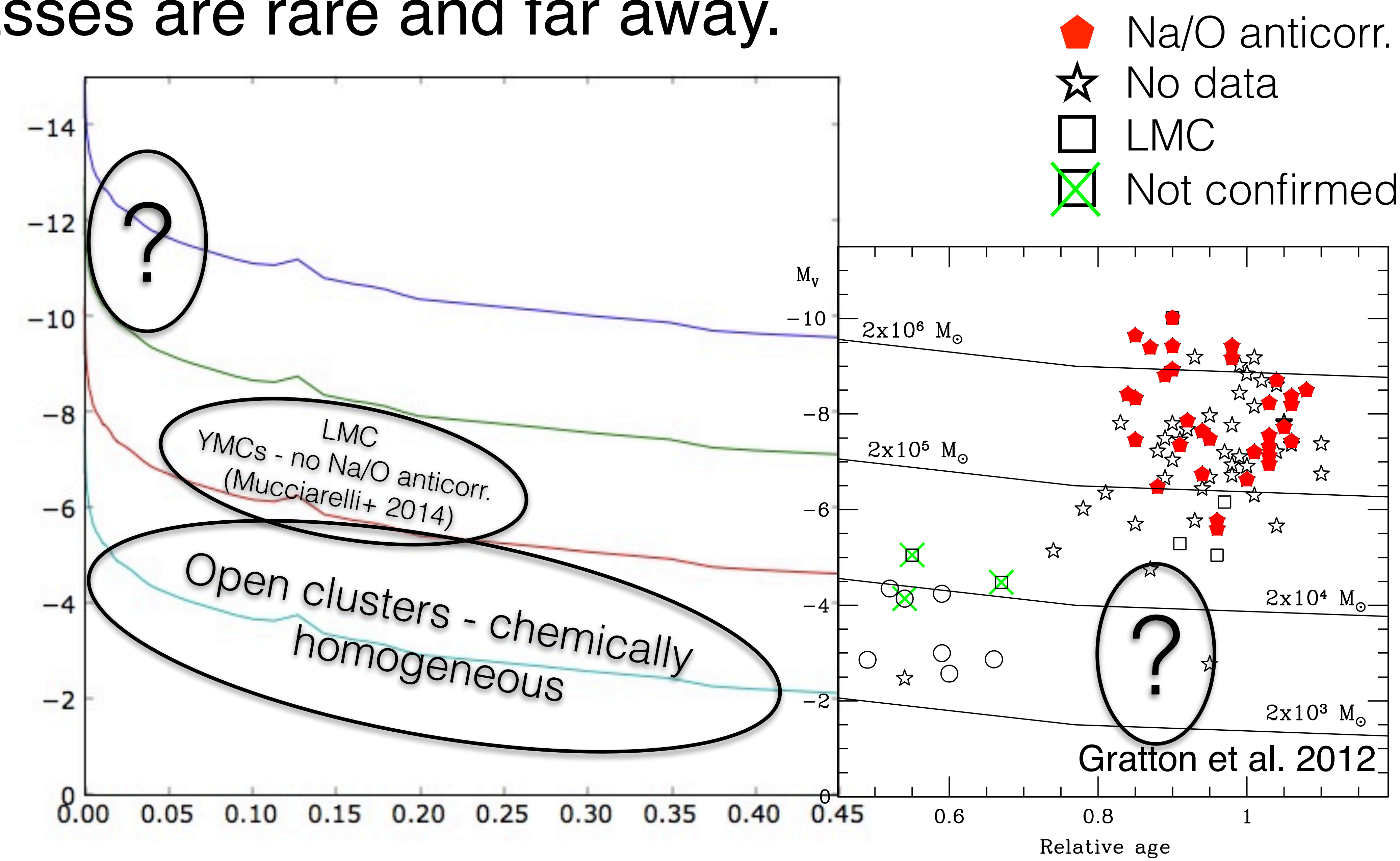
- Enriched wind material (whether from AGB or MS stars) is insufficient to form a 2nd generation that is as massive as the 1st gen.

- Initial masses of GCs predicted to have been 10-20 x higher than currently observed
  (Decressin et al. 2007; D'Ercole et al. 2008; Vesperini et al. 2010; Bekki 2011; Valcarce & Catelan 2011; Conroy 2012)
  - More than 50% of the Galactic halo might consist of "lost" GC stars (e.g. Martell et al. 2011; Gratton et al. 2012).

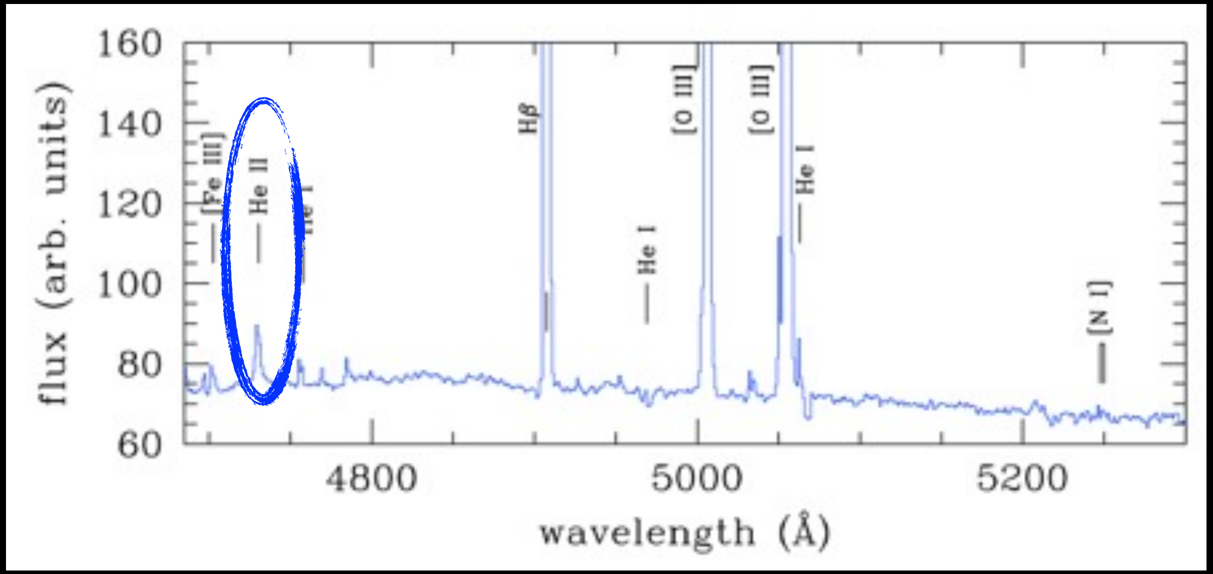
- "Early disc accretion" scenario:
  - polluted material is swept up by discs around "1st gen" low-mass stars.
  - Massive interacting binaries provide enough ejecta to avoid mass-budget problem (Bastian et al. 2013).

The Na/O anticorrelation

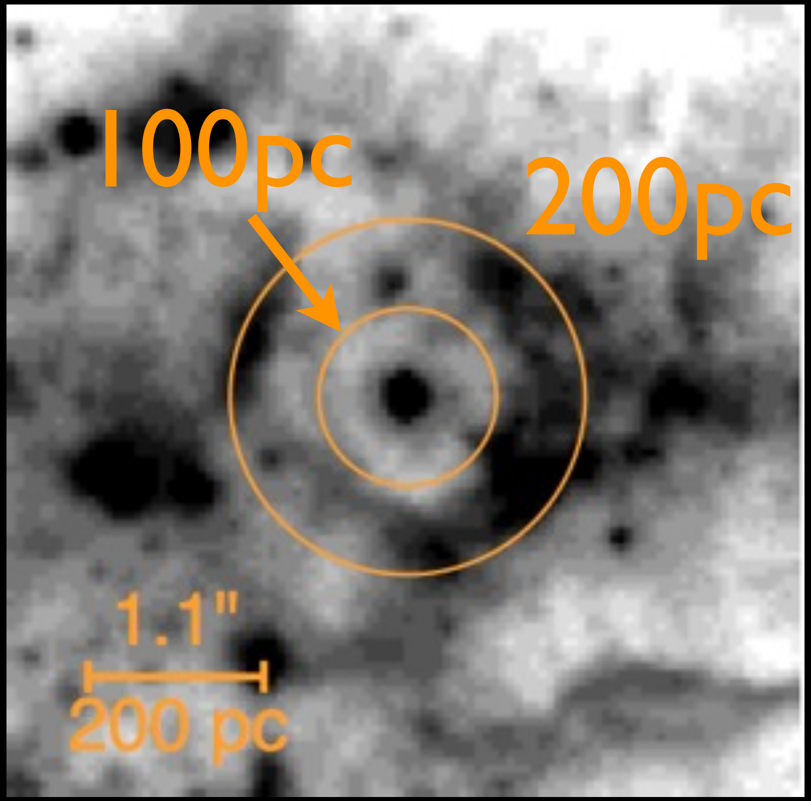
Only found in old GCs so far. But YMCs with comparable masses are rare and far away.



ESO 338-IG04 - Cluster 23



$t = 6^{+4}_{-2}$ Myr
$A_v = 0$
$M \sim 1\times10^7$ Msun
$R_{bubble} \sim 120\text{-}200$pc
$Z = 0.2\ Z_{sun}$



Östlin et al. 2007

- Bubble began expanding 1-3 Myr after formation
- Efficiently removed any pristine material out to hundreds of parsecs (still expanding at 40 km/s)
- Metallicity below that of Galactic globular clusters that show anomalies

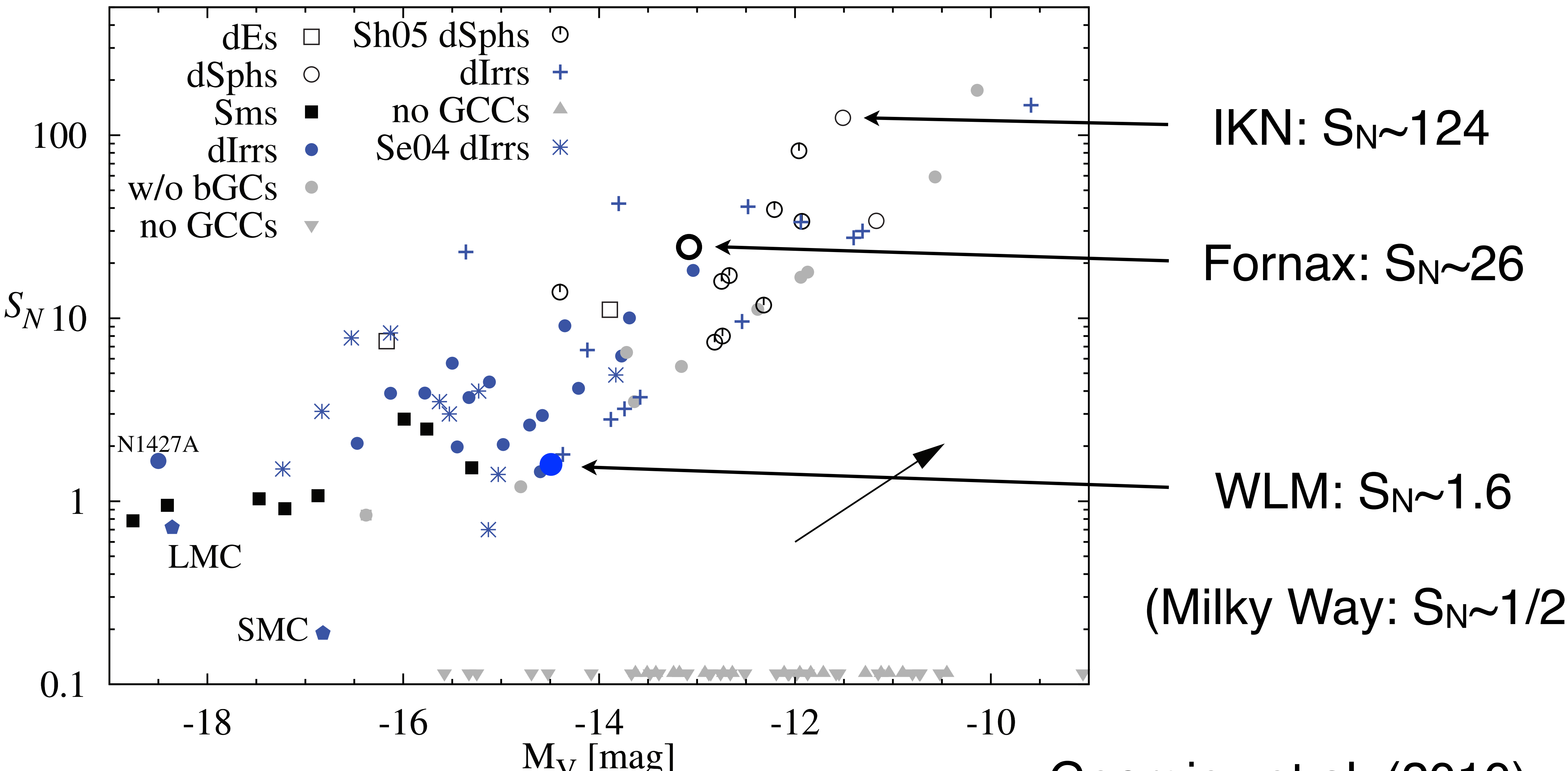
Courtesy N. Bastian

Bastian, Hollyhead, & Cabrera-Ziri 2014

GCs in dwarf galaxies

Some dwarf galaxies have extremely rich GC systems for their sizes

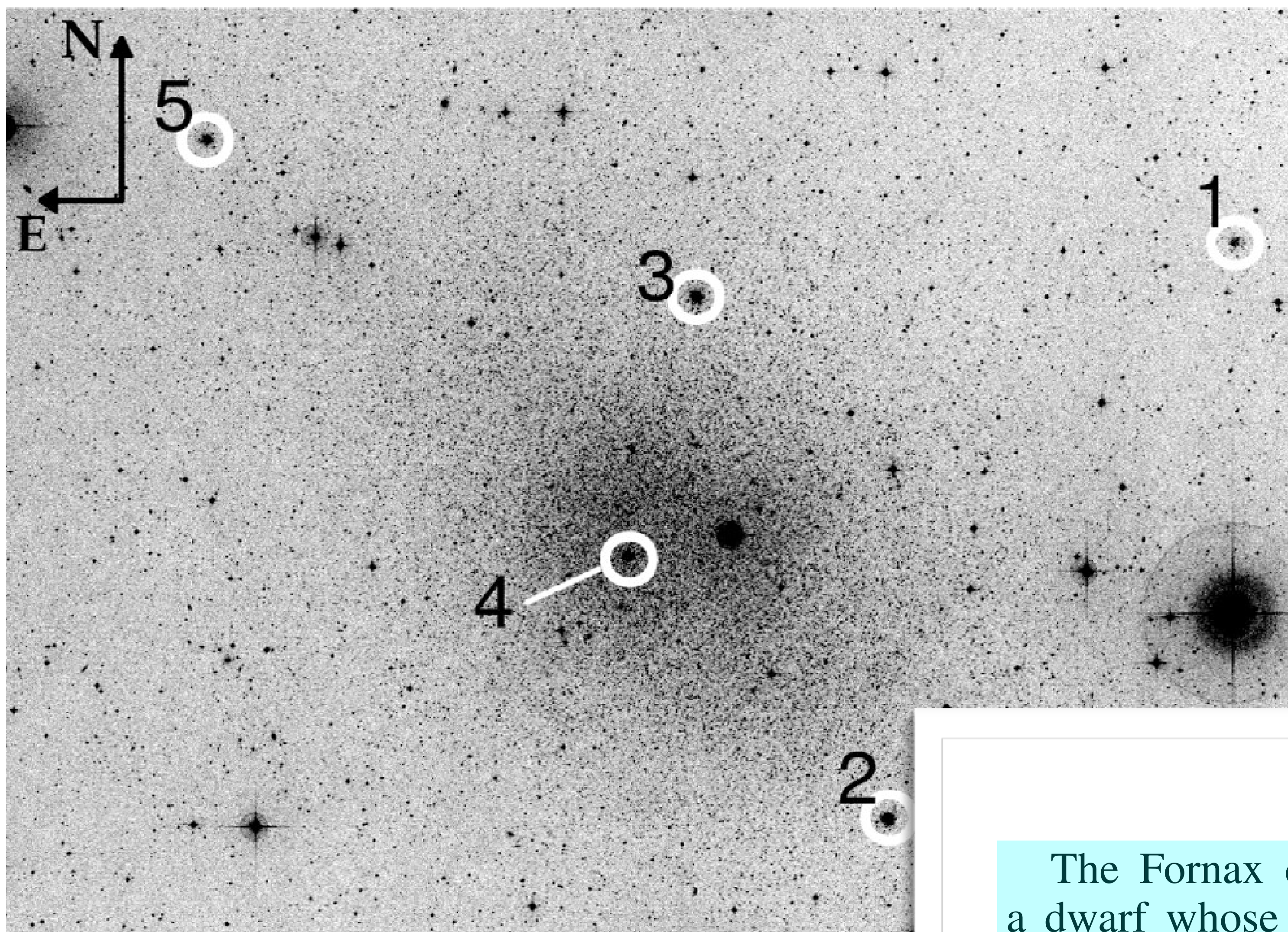
$$S_N = N_{\rm GC} \times 10^{0.4(M_V+15)}$$



Georgiev et al. (2010)

The Fornax dSph

1°



(image from Letarte et al. 2006)

5 GCs, $M_V \sim -13.1$
(Hodge 1961; Mateo 1998)

Total stellar mass
$M^* \sim 6\times10^7\ M_\odot$
(Coleman & de Jong 2008).

Mass of GCs ~ $10^6\ M_\odot$
(~1.7% of M*)

4.2.1. Fornax

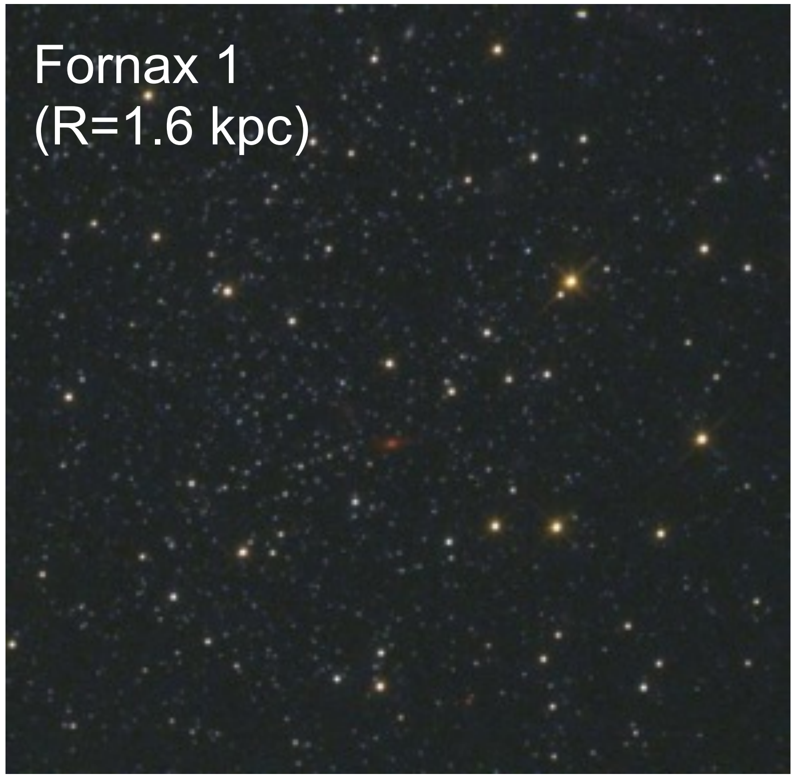
The Fornax dwarf provides probably the clearest case of a dwarf whose stellar component has *not* been disturbed by Galactic tides. Not only is the tidal radius clearly well outside the luminous radius, but also there is no evidence for distensions in the outer profile that may be ascribed to the past effect of tides. A $c_k = 4$ King model fits the surface density profile of Fornax extremely well, down to the last measured point.

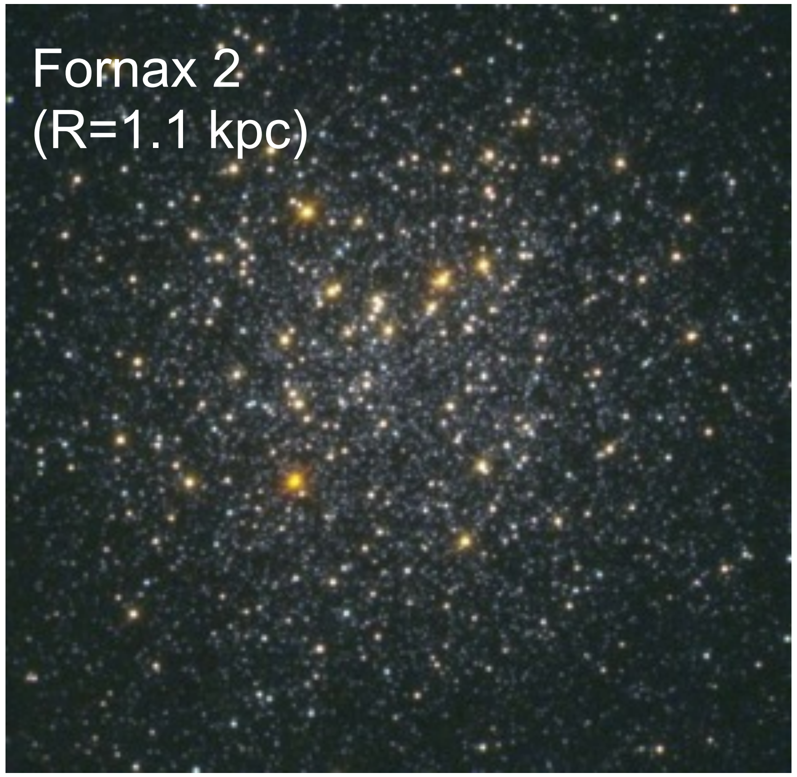
Peñarrubia et al. 2009

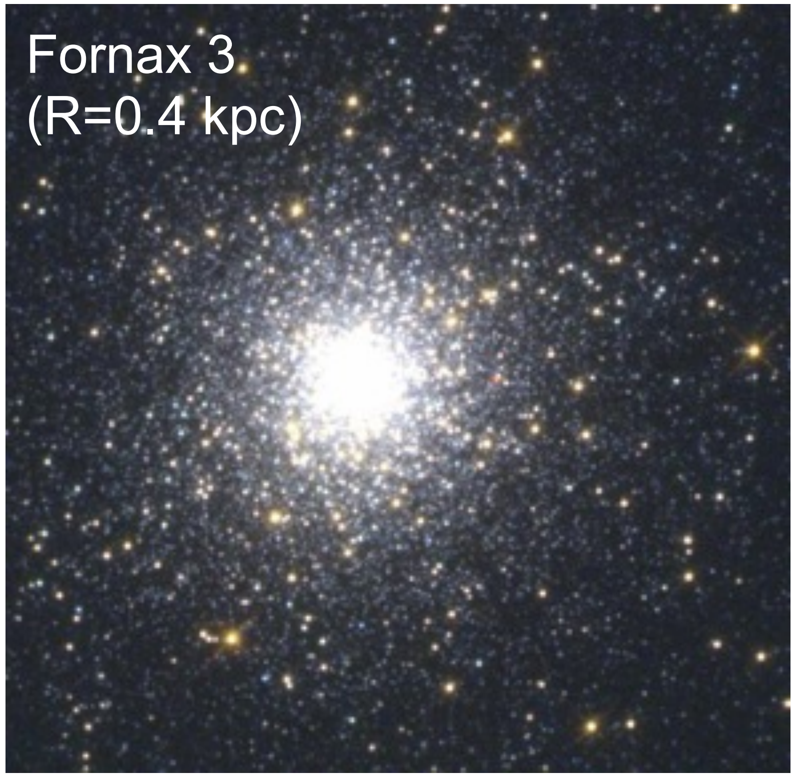
The Fornax GCs

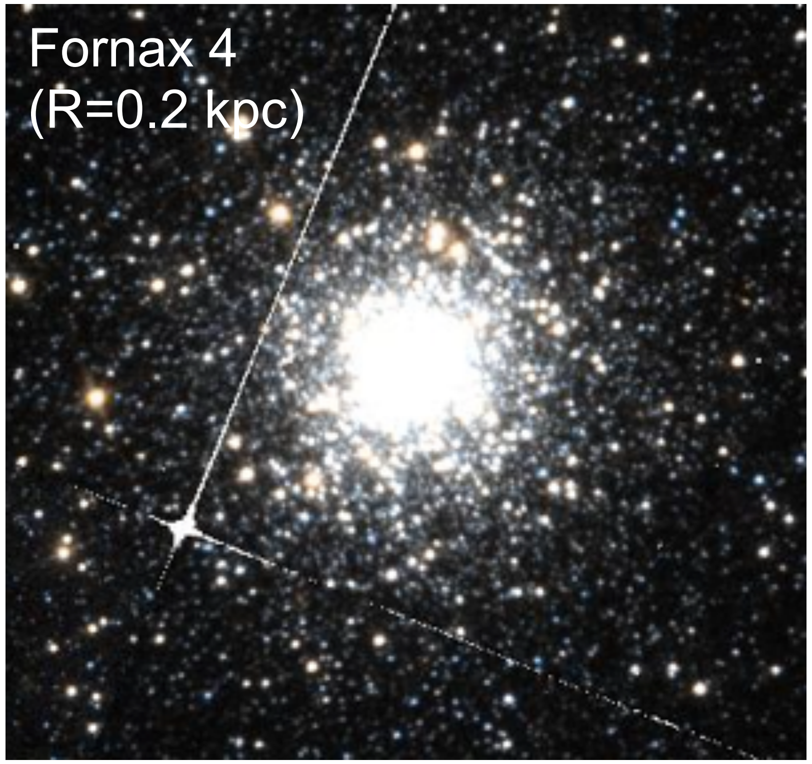
HST WFPC2+WFC3
F343N/F555W/F814W

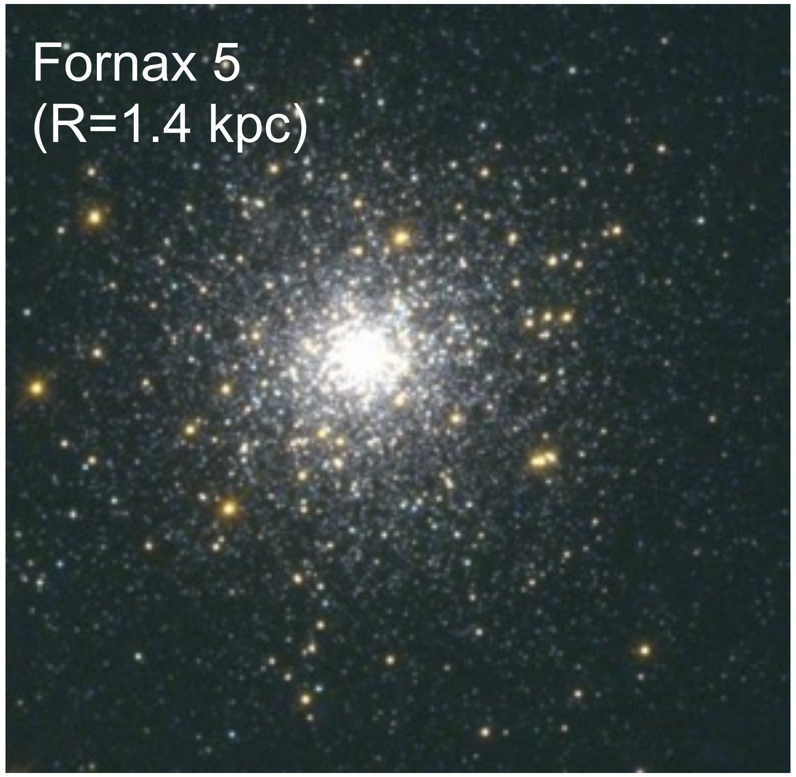
~24 pc











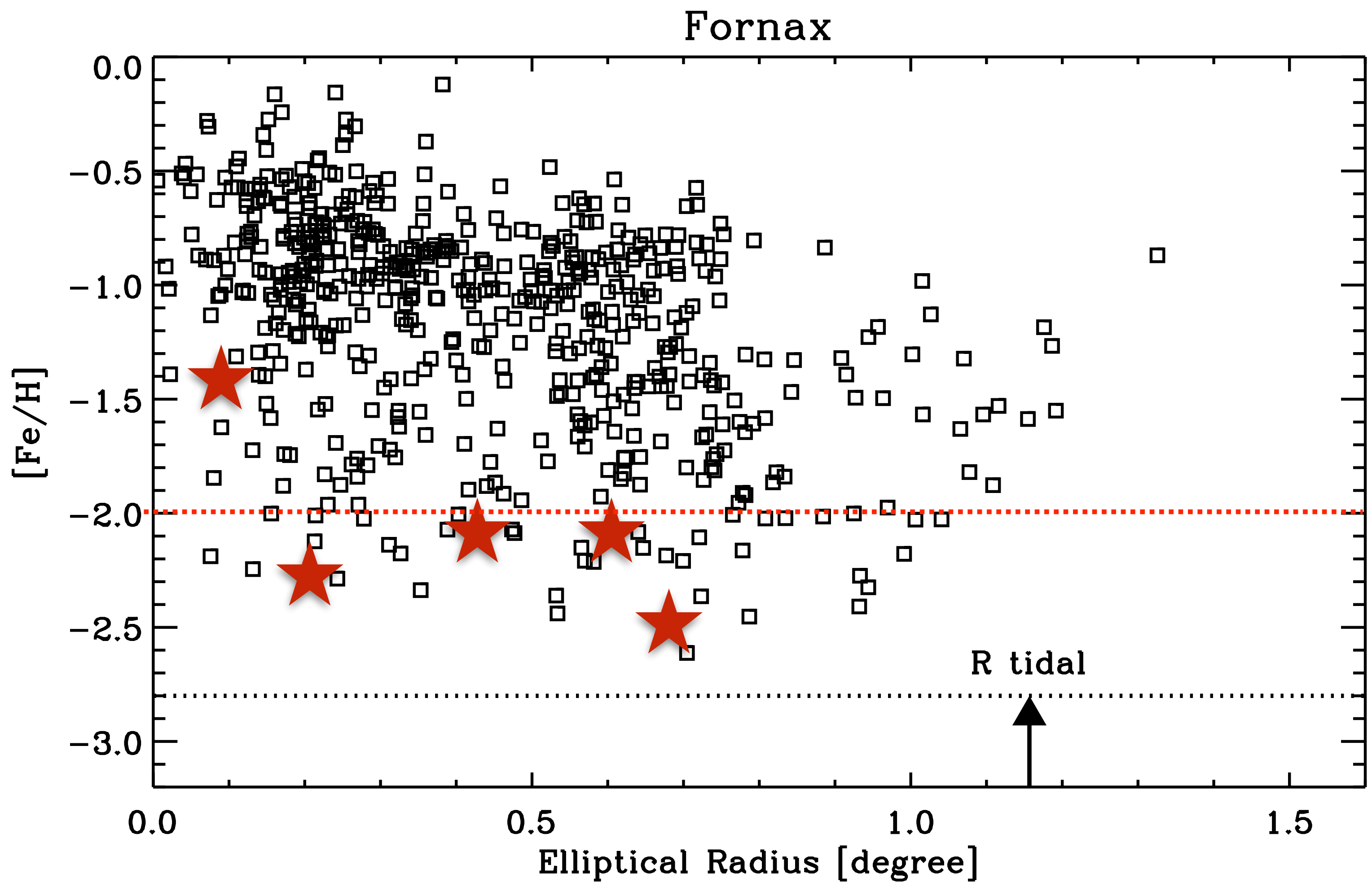
Metallicities from high-dispersion spectroscopy

	[Fe/H]	[Ca/Fe]	v_r (km s^{-1})	Source	
Fornax 1	−2.5 ± 0.1	+0.15 ± 0.04	59 ± 1	Letarte et al. 2006	Indiv. stars
Fornax 2	−2.1 ± 0.1	+0.20 ± 0.03	64 ± 1	Letarte et al. 2006	Indiv. stars
Fornax 3	−2.3 ± 0.1	+0.25 ± 0.08	60.4 ± 0.2	This work	Integr. light
Fornax 4	−1.4 ± 0.1	+0.13 ± 0.07	47.2 ± 0.1	This work	Integr. light
Fornax 5	−2.1 ± 0.1	+0.27 ± 0.09	60.6 ± 0.2	This work	Integr. light

- Fornax 1, 2, 3, 5 all have [Fe/H] < -2
- Field star metallicities peak near [Fe/H] = -1
  (Battaglia et al. 2006; Kirby et al. 2011).

Larsen et al. (2012)

GCs and field stars in Fornax

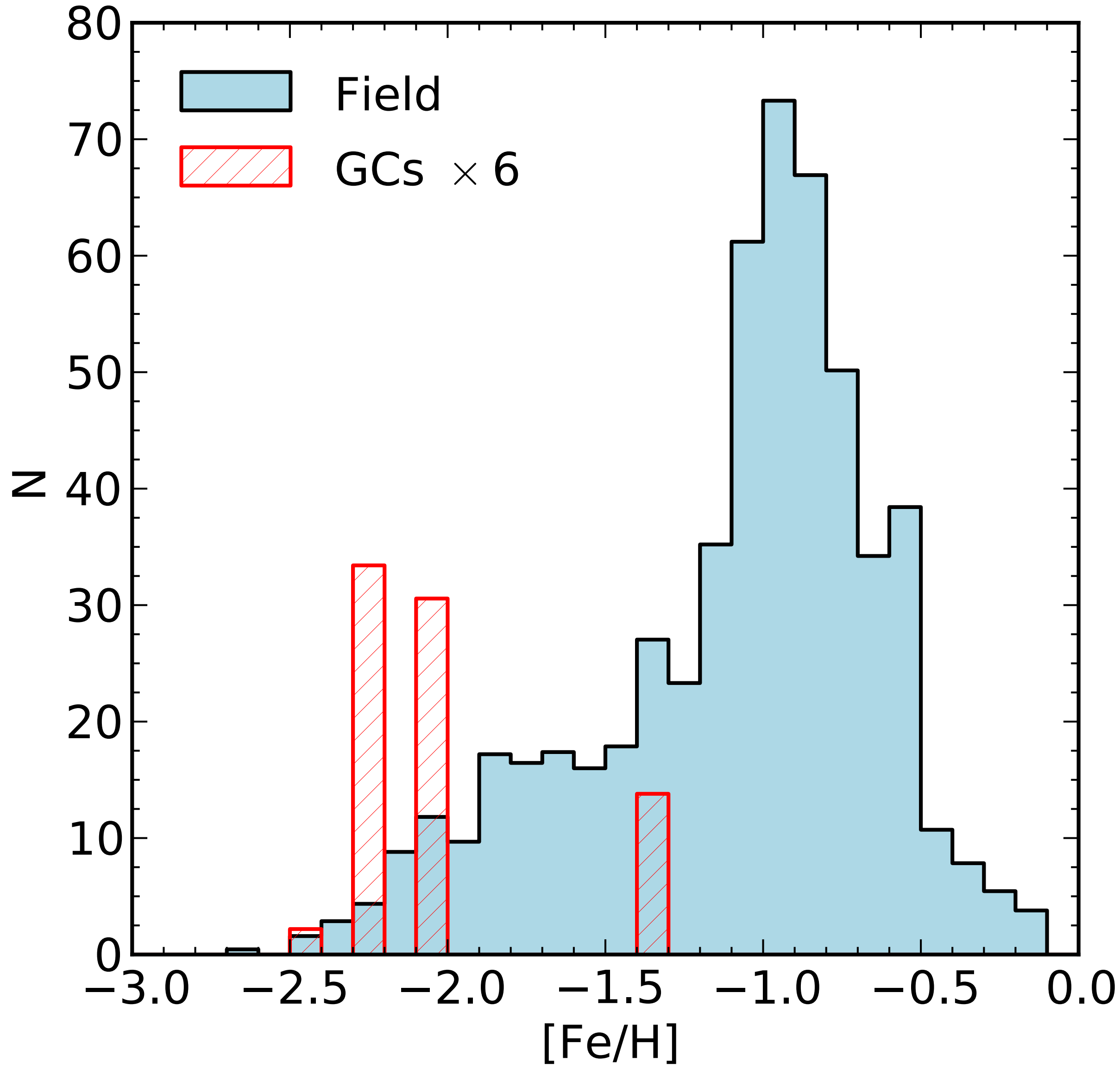


GCs much more metal-poor than most field stars.

Few field stars at [Fe/H]<-2

Field stars: Battaglia et al. (2006), Ca II triplet spectroscopy.
GCs: Letarte et al. (2006); Larsen et al. (2012)

Field stars and GCs in Fornax: Metallicity distributions



Larsen et al. (2012, A&A 544, L14)
Field stars: Battaglia et al. (2006), corrected for spatial coverage.
GCs: Letarte et al. (2006), Larsen et al. (2012)

For [Fe/H] < -2:
Mass in field stars ~ 3×10^6 $M_\odot$
Mass in GCs ~ 1×10^6 $M_\odot$

About 1/5-1/4 of all metal-poor stars in Fornax dSph belong to F1+F2+F3+F5.

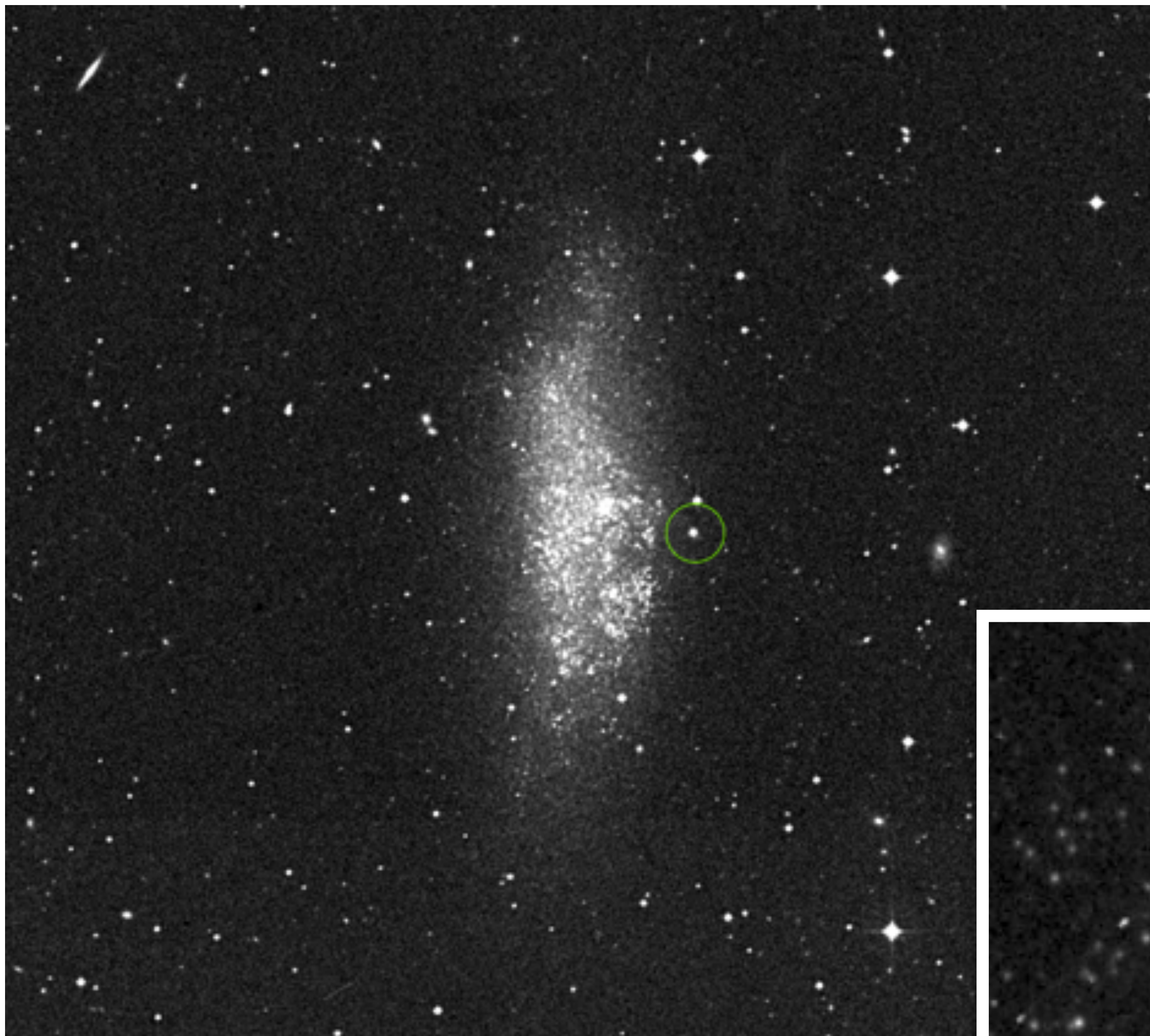
Clusters could at most have been ~4-5 times more massive initially!

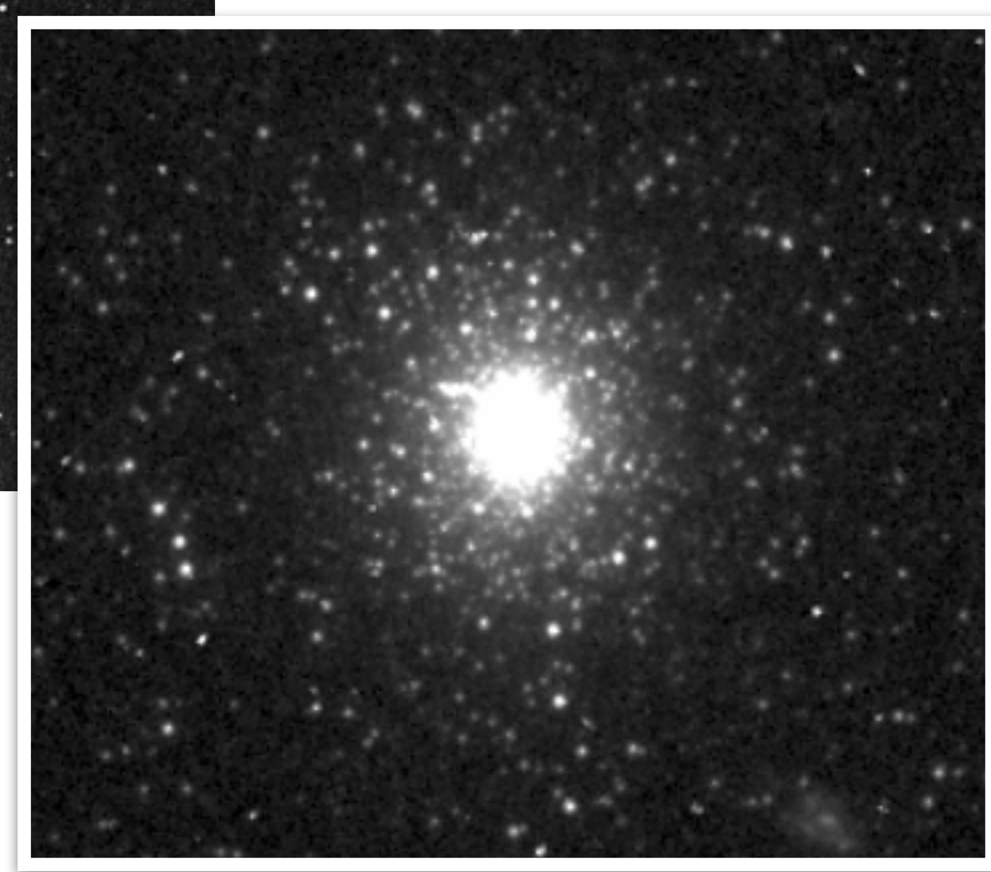
This assumes no other clusters or field stars formed with similar metallicity, no “infant mortality”.

The WLM dIrr

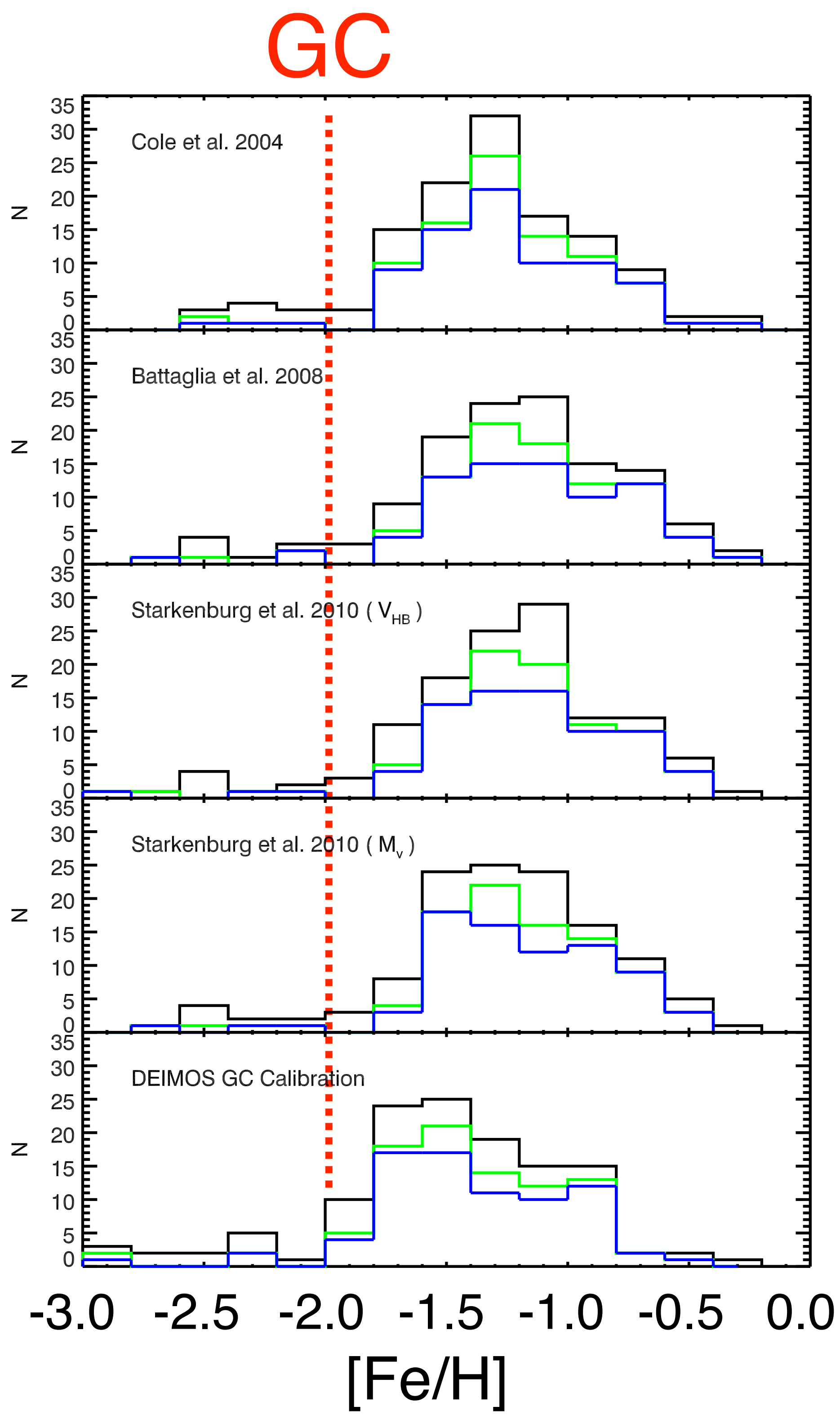
D(WLM-Milky Way)~925 kpc
D(WLM-M31) ~ 950 kpc
Near edge of Local Group
M_V ~ -14.5

1 old GC: M_V=-9.0, M~6×10^5 $M_\odot$
(Humason et al. 1956; Ables & Ables 1977; Sandage & Carlson 1985; Larsen et al. 2014a)





WLM: field stars vs GC



Leaman et al. (2013)

Field stars:

Stellar mass M* ~ $1.6\times10^7\ M_\odot$

(Zhang et al. 2012)

<[Fe/H]> = -1.28

(Leaman et al. 2013, Ca II IR triplet spectroscopy of RGB stars)

Globular cluster:

M ~ $6\times10^5\ M_\odot$

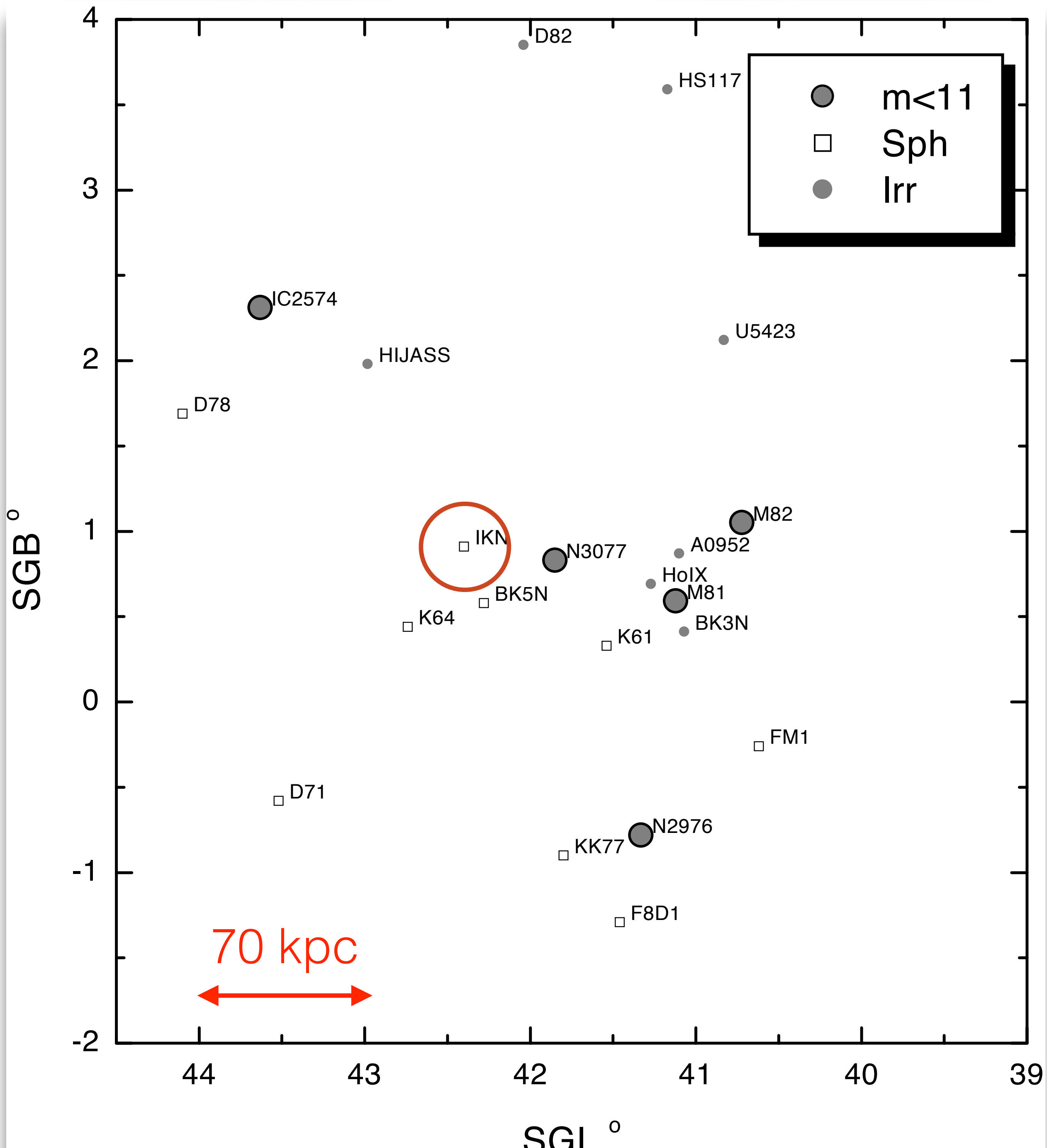
Metal-poor ([Fe/H]~-2.0)

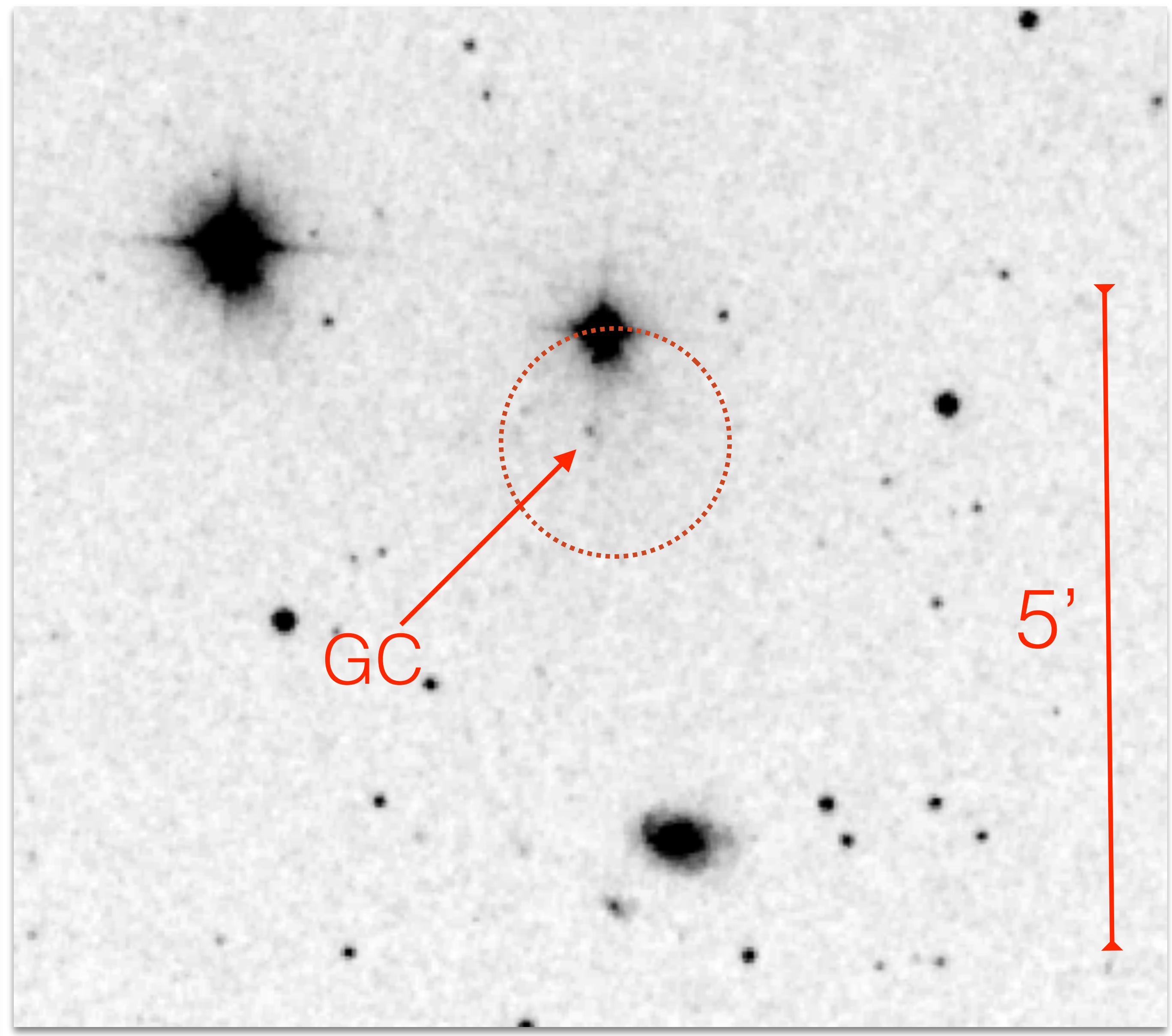
GC accounts for 17%-31% of metal-poor stars

(Larsen et al. 2014a)

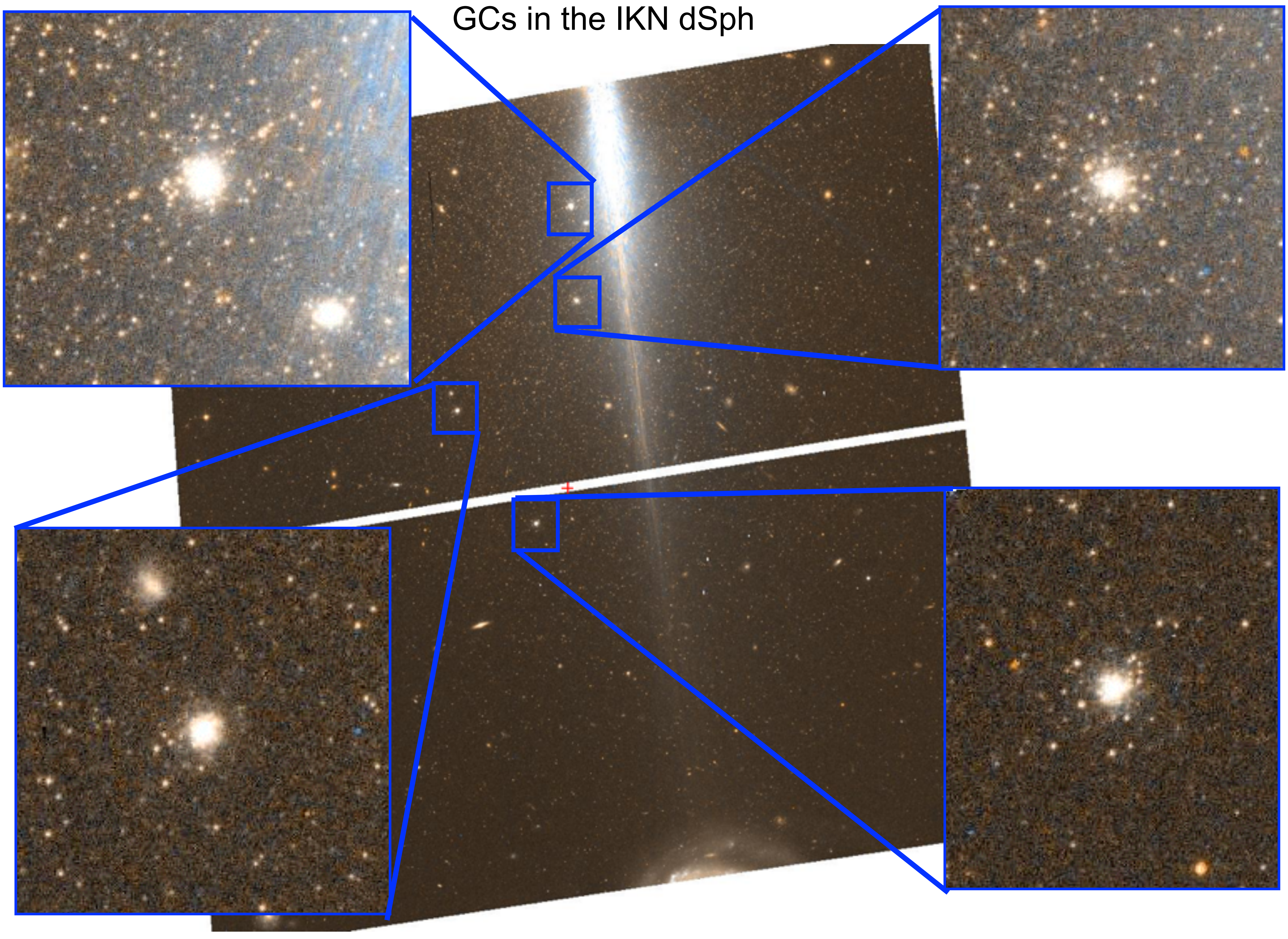
The IKN dSph

Karachentsev et al. (2002)

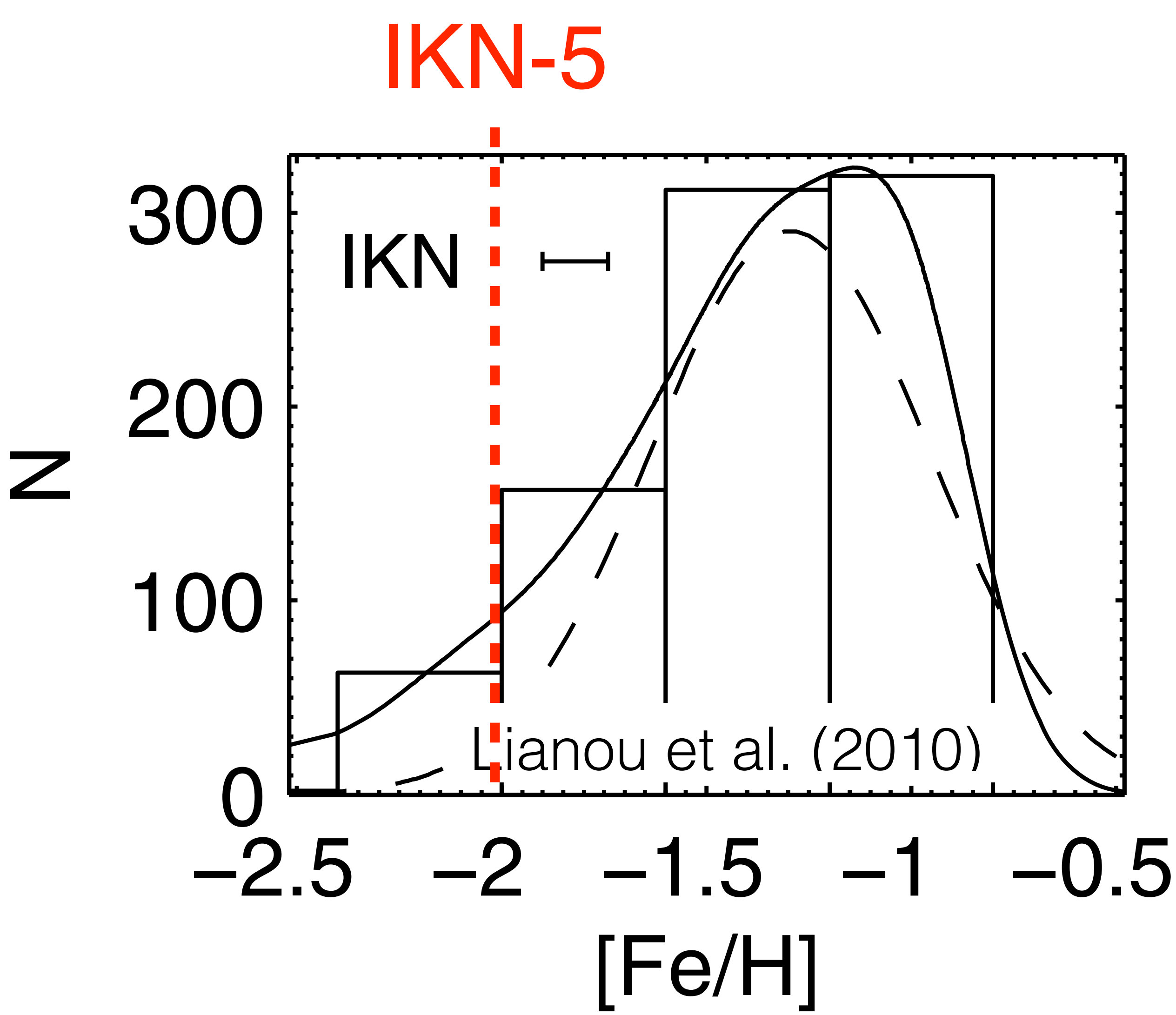




DSS image: brightest GC marked (IKN dSph itself practically invisible)


GCs in the IKN dSph

IKN: Field stars vs GCs



$L_{\rm GC}/L_{\rm tot} \approx 13\%$

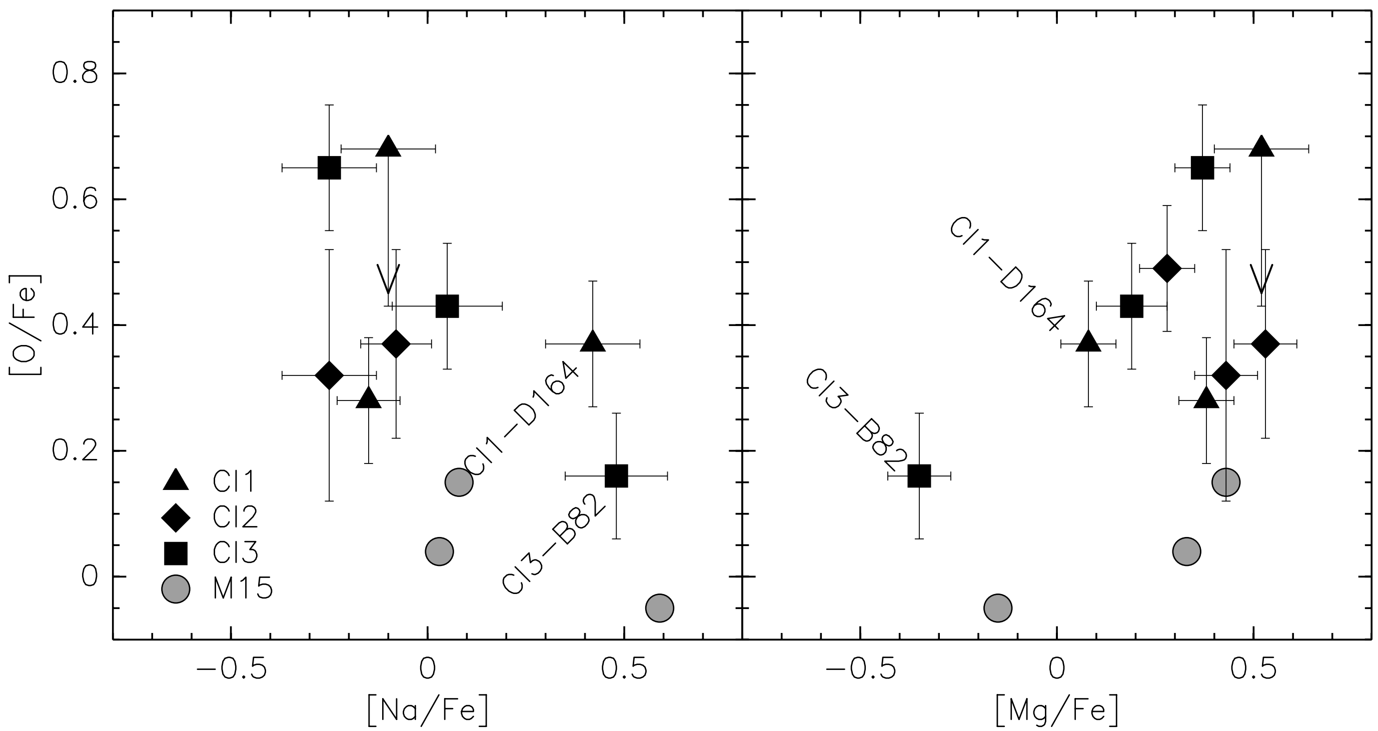
Field star metallicities from photometry of RGB
(Lianou et al. 2010)

1 GC (IKN-5) has [Fe/H] ~ -2.0

Field:GC ratio about 1:1 at [Fe/H] = -2

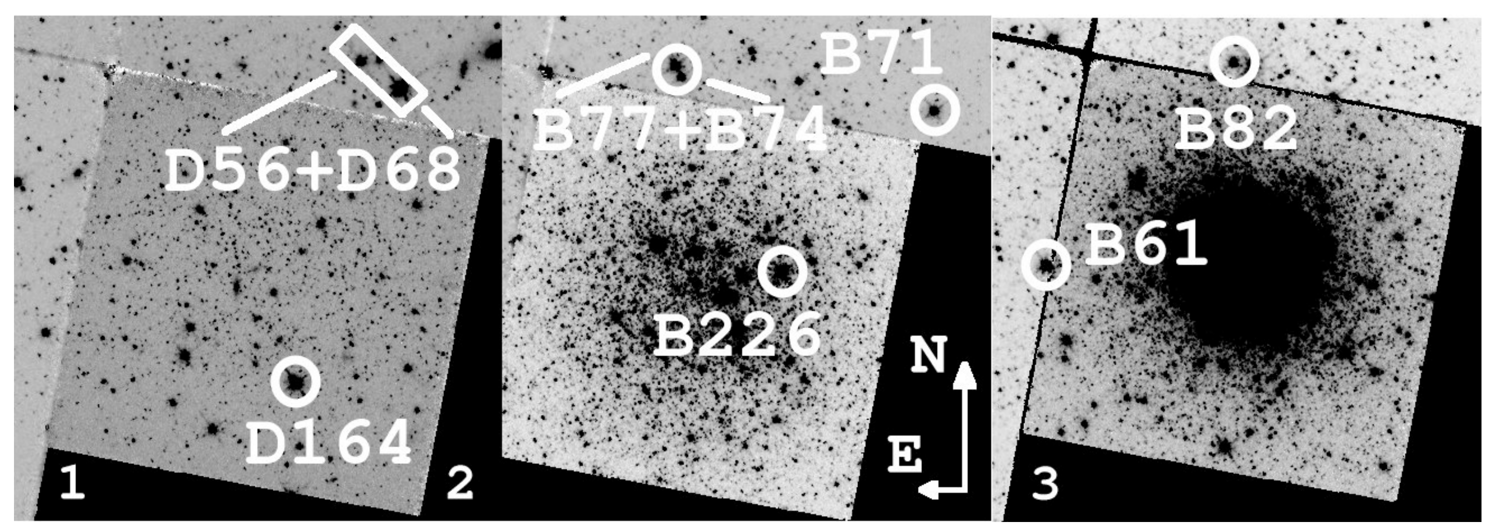
(Larsen et al. 2014a)

Light elements in Fornax GCs: Individual stars



Tentative hints at the Na/O anti-correlation

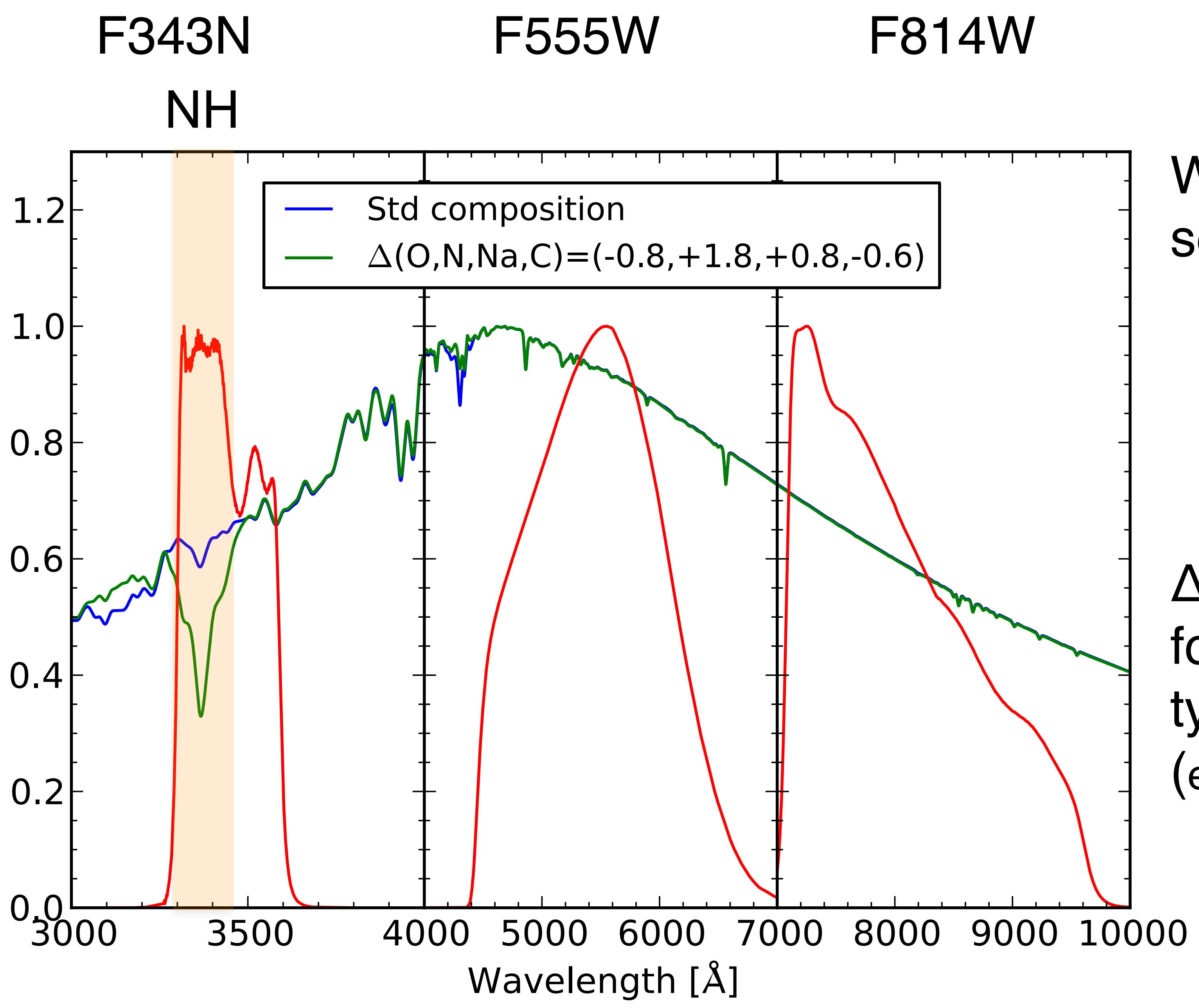
(also integrated light; Larsen et al. 2012; 2014a).



Letarte et al. 2006

Fig. 2. The finding charts for our observations of the Fornax GCs, from 1 (*left*) to 3 (*right*). North is up and East is left, as indicated. Note that star Cl3-B59 is outside of the cluster 3 HST field, to the west.

Constraining abundances with photometry



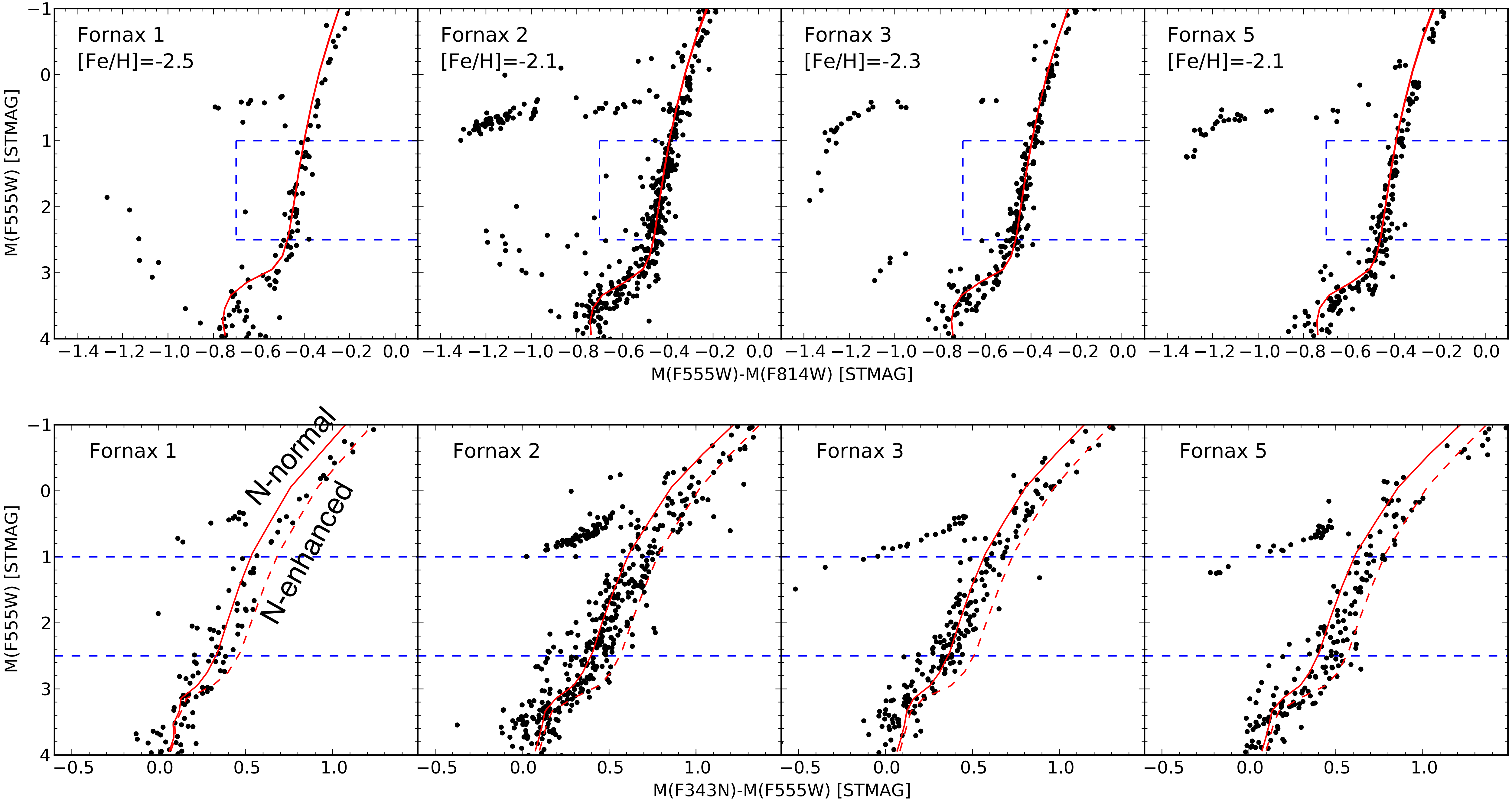
WFC3/F343N band sensitive to N abundance

$\Delta(m_{F343N}-m_{F555W}) \sim 0.2$ mag for Δ[N/Fe]~2; typical range seen in GCs (e.g. Yong et al. 2008)

N spreads in Fornax GCs

F555W-F814W: Insensitive to [N/Fe], spread consistent with errors

F343N-F555W: Spread larger than errors, Δ[N/Fe]~2 dex, similar to M15



Isochrones from Dotter et al. 2007

Synthetic colours based on ATLAS12/SYNTHE model spectra.

Larsen et al. (2014b)

Bottom line:

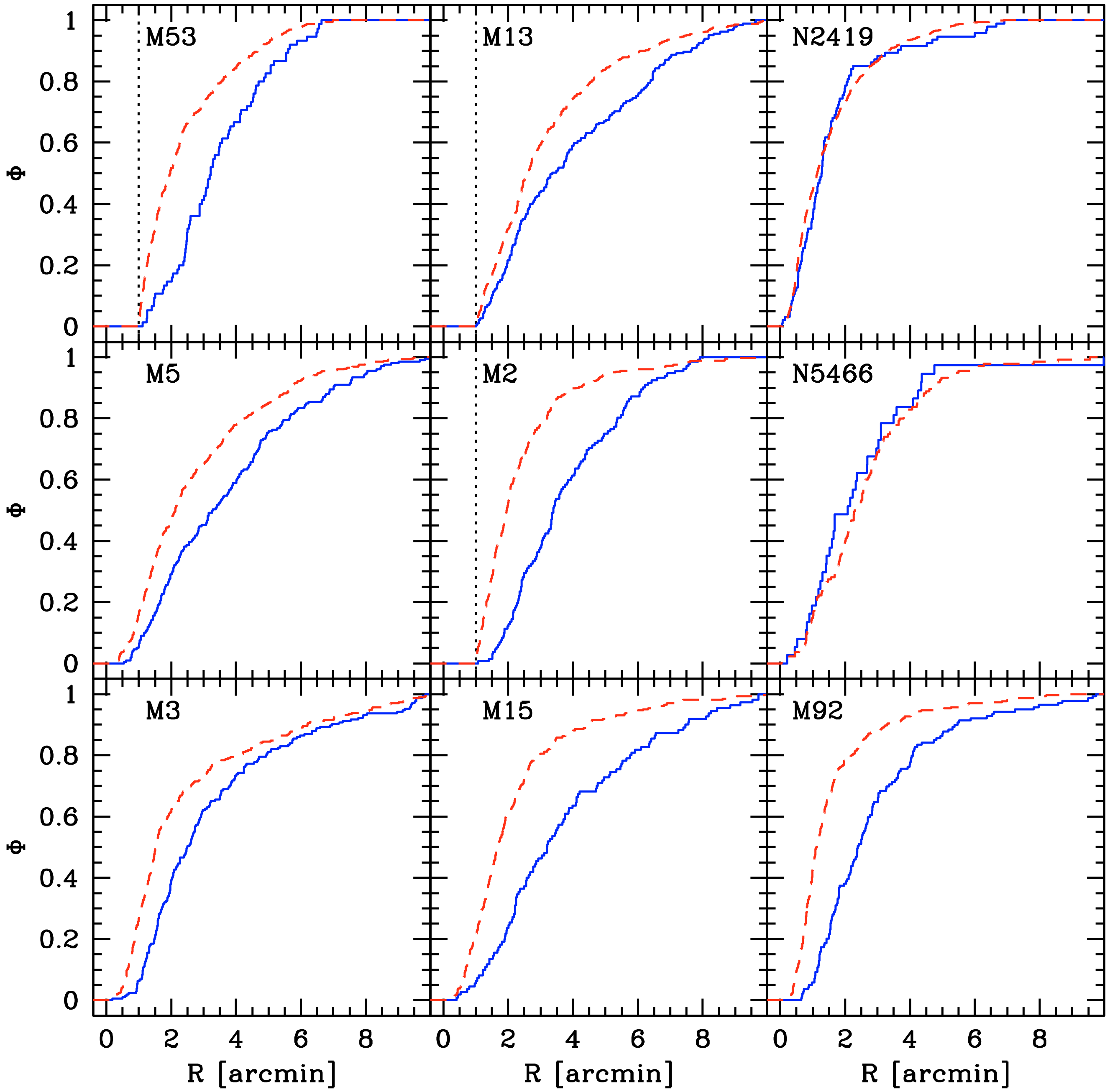
The GCs in the Fornax dSph (and probably other dwarfs) are similar to their Milky Way counterparts in terms of multiple stellar populations.

GC formation models must account for both
"*internal*" (large number of polluted stars)
and
"*external*" (high ratio of GC/field stars in dwarf galaxies)
mass budget problems.

Radial distributions

- All scenarios: enriched population should be more centrally concentrated
  - AGB: Formation from cooling flow
  - Massive stars: enriched population forms near mass-segregated massive stars
  - Early disc accretion: Accretion most effective in central regions, where density is high.

Radial distributions of sub-populations



Lardo et al. (2011)

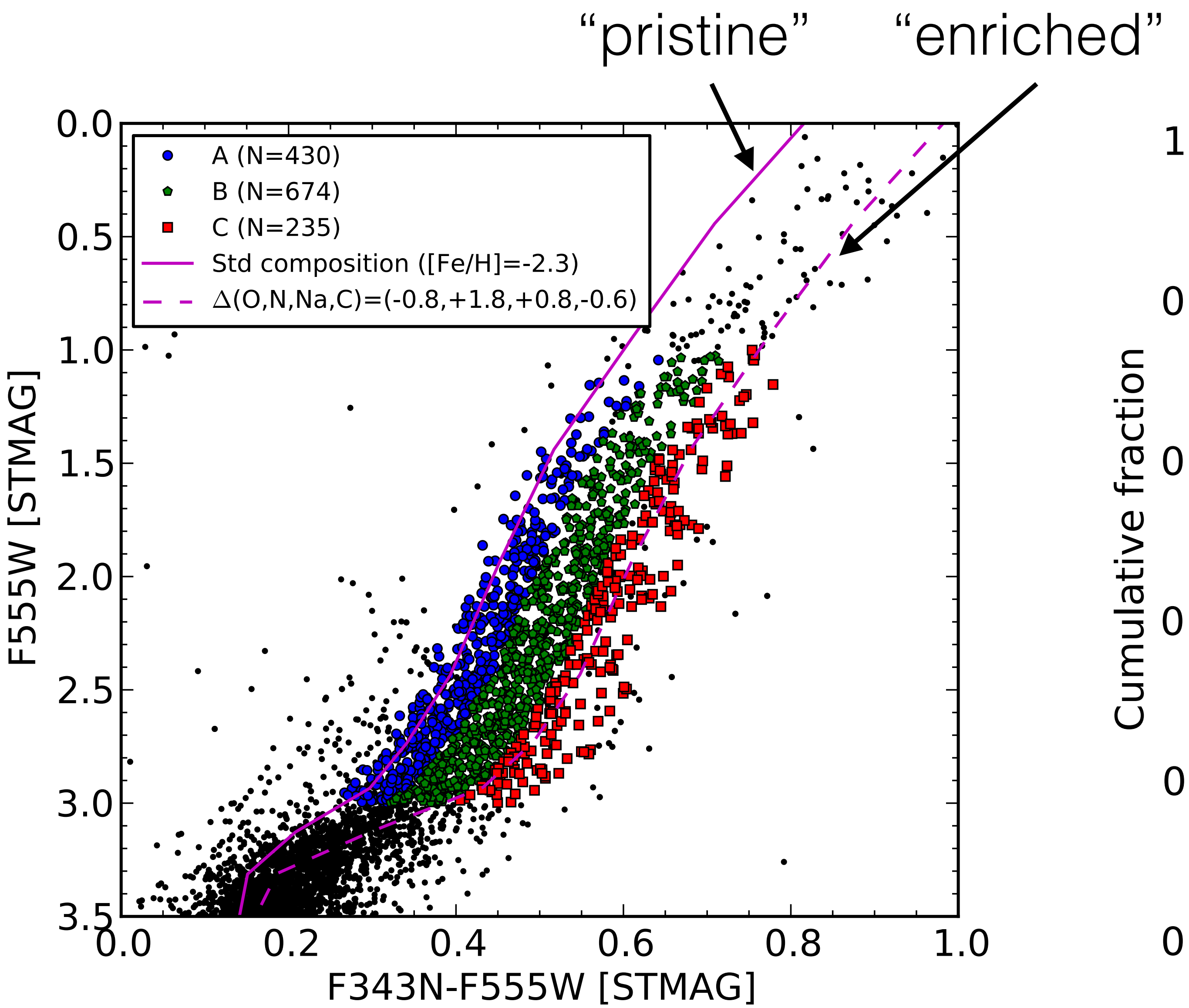
SDSS data, $r > 0.5\ r_h$:

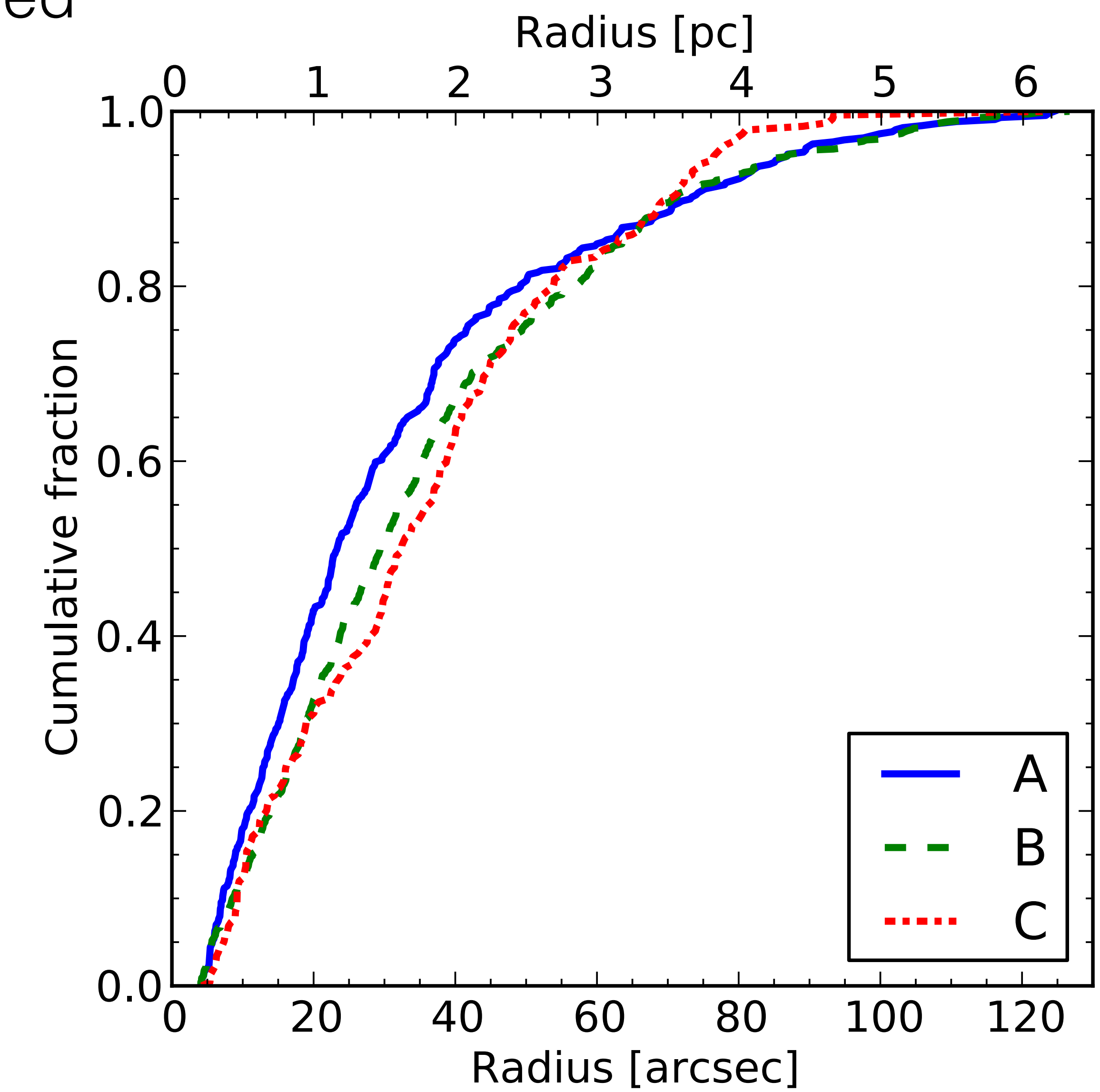
Enriched stars generally the most centrally concentrated.

Expected in all scenarios

- AGB scenario (cooling flow)
- Massive stars (mass segr.)
- Disc accretion (most efficient near centre)

Radial distributions in M15

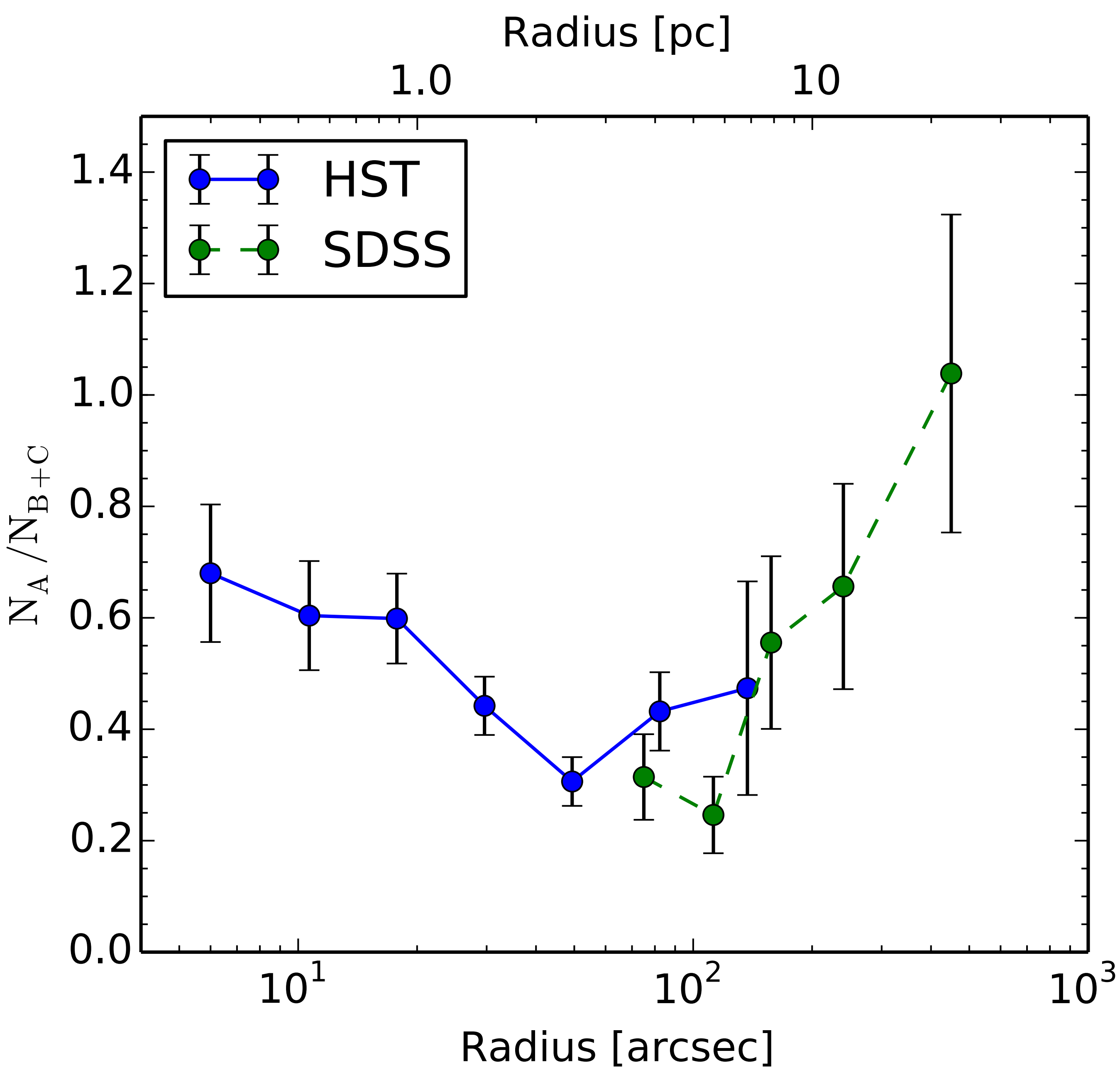




Group A (“pristine”) stars *most* centrally concentrated.

K-S test for radial distr. of A vs (B,C): $P = 3{\times}10^{-5}$.

Combining HST and SDSS data



"U"-shaped trend of normal vs. "enriched" stars.

Enriched stars are preferentially located near the half-mass radius.

Not expected in any of the current scenarios.

Larsen et al., ApJ, subm.

Mass segregation?

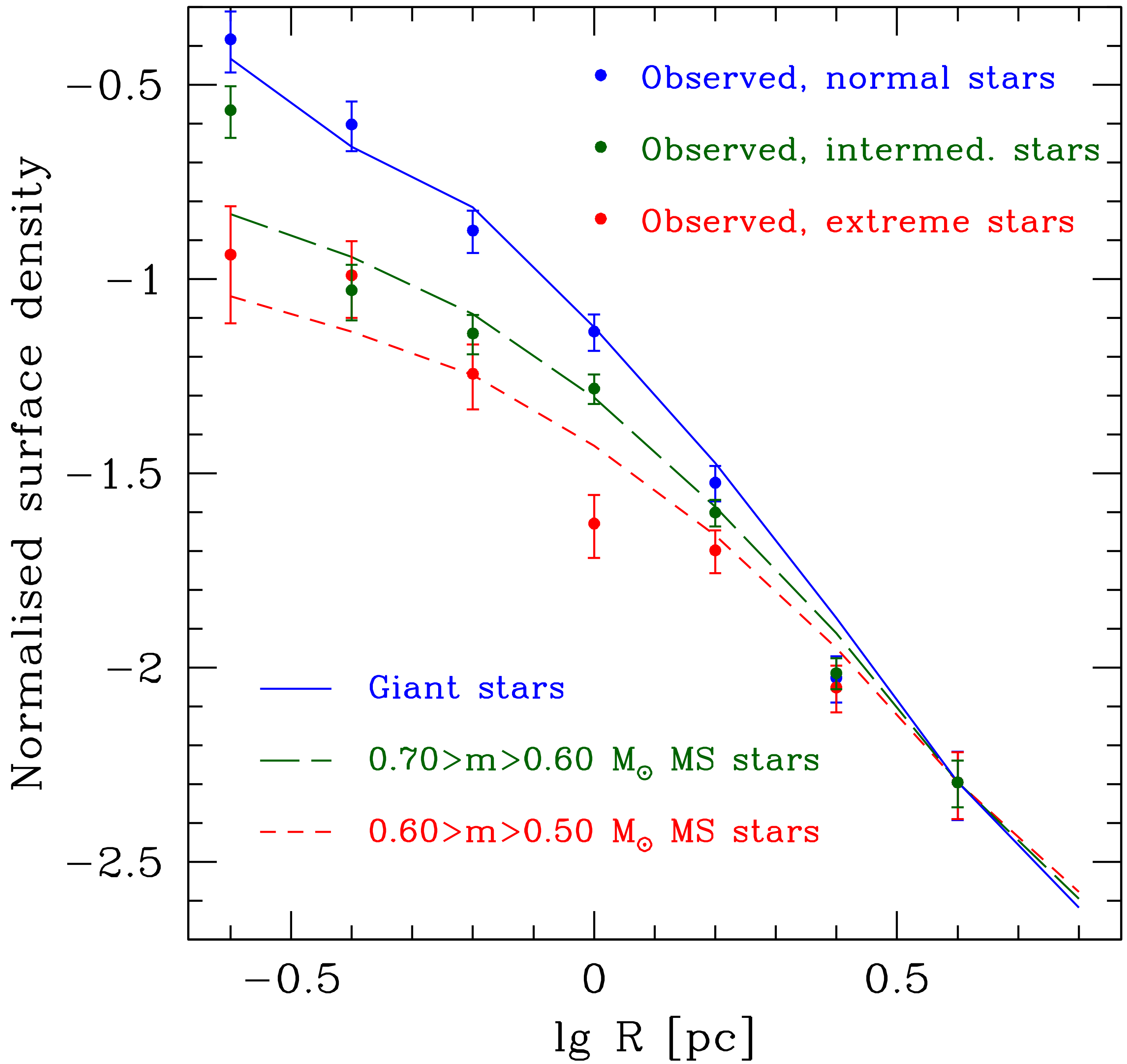
- If enriched stars are strongly He-enriched ($Y \sim 0.40$), then $M_{TO} \sim 0.6\ M_{\odot}$ instead of $0.8\ M_{\odot}$ at 13 Gyr

- Mass segregation might then “push” enriched RGB stars outwards from the centre

- In outer regions, primordial trends would be preserved because of long relaxation time.

- Does this work?

N-body simulations



Larsen et al., ApJ, subm.

NBODY6 simulations for stars of

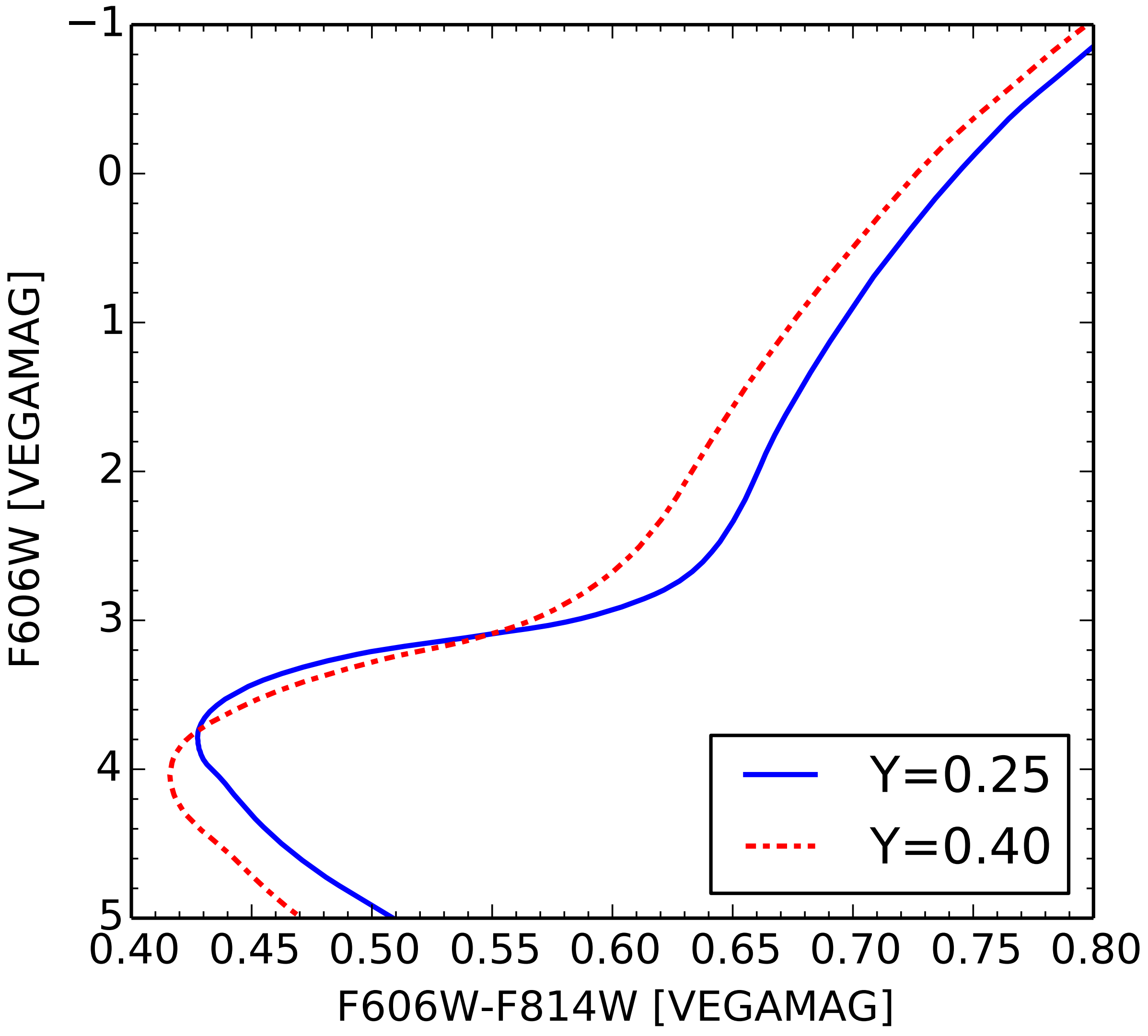
- different masses
- same initial distrib.

Evolved to 11.5 Gyr

(Lützgendorf et al. 2013; McNamara et al. 2012)

It might just work!
But…

Effect of Y on isochrones

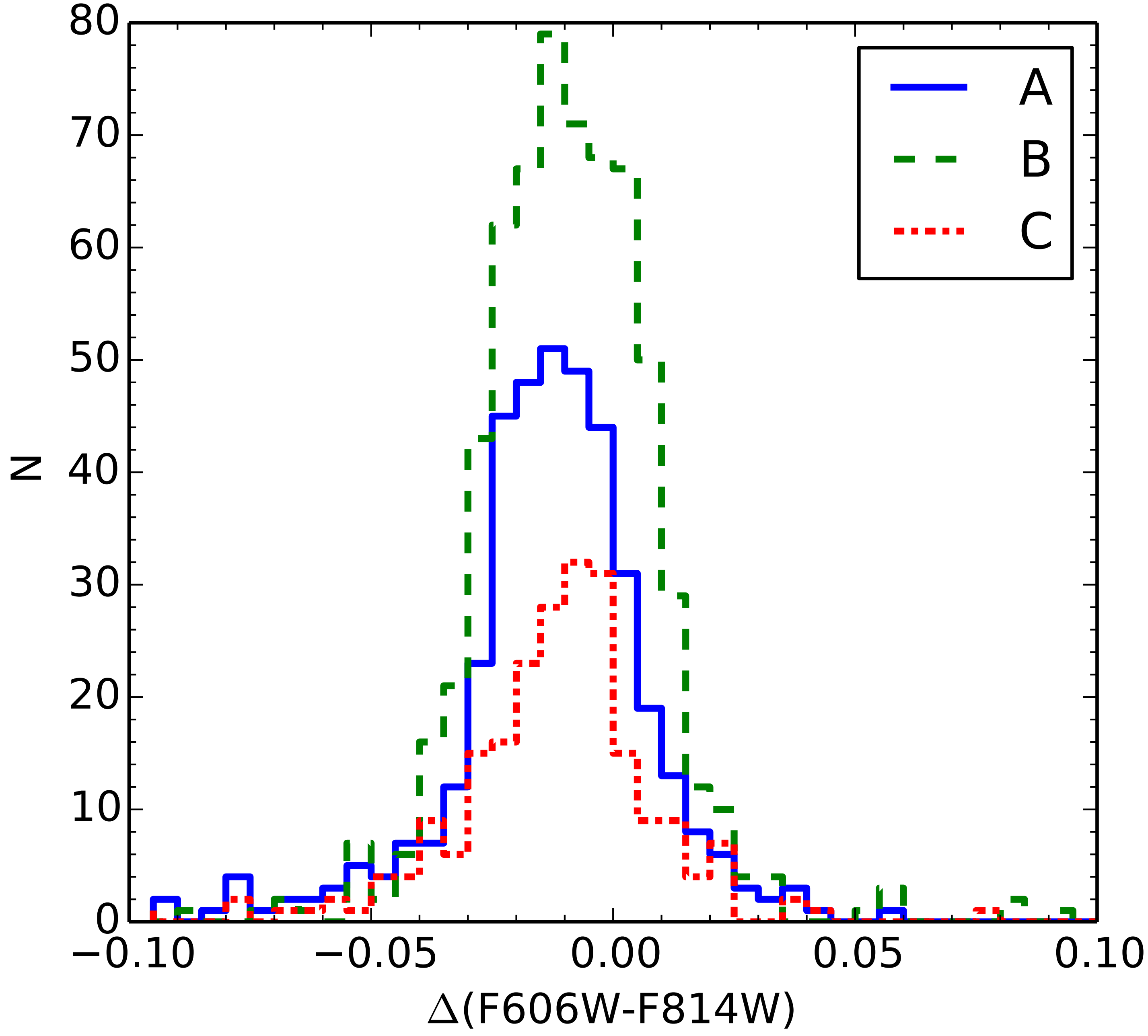


$\Delta_{F606W\text{-}F814W}$ ~ 0.03 mag for Y=0.25 vs Y=0.40

Measurable.

Dartmouth isochrones
(Dotter et al. 2007)

No colour difference!



Mean colours of all (normal, interm., extreme) stars identical to within 0.001 mag in F606W-F814W.

$\Delta Y < 0.005$ and $\Delta M < 0.01\ M_{\odot}$.

Mass segregation will not work!

Summary

- Young massive clusters are very gas-poor very early on.
- High ratio of metal-poor GCs to field stars in dwarf galaxies is a challenge to AGB and FRMS scenarios.
- Radial distribution of subpopulations in M15 is a challenge to all scenarios.