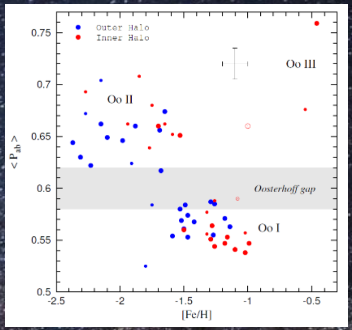
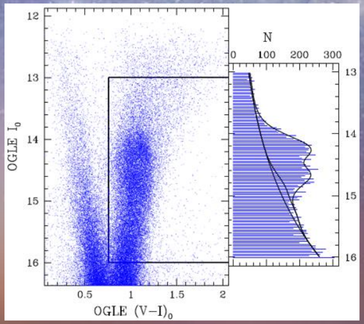
Evolution of Helium-enhanced Stellar Populations

(in Globular Clusters & the Milky Way Bulge)





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Astron. Astrophys. 169, 111–121 (1986)

ASTRONOMY AND ASTROPHYSICS

Spectroscopy of RR Lyrae stars in Baade's Window and in ω Centauri ★

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Summary. New ΔS values (for the definition of S, see Preston, 1959) have been derived for 35 RR Lyrae stars in ω Centauri and Baade's Window. Intensities of a blend of lines near 4300 Å have also been estimated for the ω Centauri variables. Intensities of this blend are correlated with K line intensities in ω Centauri. Our results confirm that ΔS does not correlate with the period shift within ω Centauri, while it does in the galactic centre.

The results have been interpreted with a view to understanding the "Sandage effect" on Population II variables. Our conclusions for ω Centauri, for other globular clusters, and for Baade's window variables may be summarized as follows:

Constraints are found that the less metal rich ($\Delta S > 5$) RR Lyrae variables in ω Centauri are not Zero Age Horizontal Branch (ZAHB) stars but are the evolutionary descendants of blue ZAHB stars. This can account for the observed behaviour of the luminosity of RR Lyrae variables versus metallicity and rules

The Astrophysical Journal, 312:762–777, 1987 January 15

ON THE INTERPRETATION OF THE SANDAGE PERIOD-SHIFT EFFECT AMONG GLOBULAR-CLUSTER RR LYRAE VARIABLES

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Received 1986 April 7; accepted 1986 July 15

ABSTRACT

A new grid of canonical zero-age horizontal-branch (ZAHB) models has been constructed in order to study the Sandage period-shift effect, i.e., the observed shift in the pulsation period of globular-cluster RR Lyrae variables at a given effective temperature with changes in metallicity. These models predict only a negligible period shift and thus fail to explain the Sandage effect when the helium abundance is held constant. This discrepancy between the observed and theoretical period shifts could be resolved within the framework of canonical ZAHB models if the helium abundance and metallicity are anticorrelated in the globular clusters. We derive the required anticorrelation but argue against its existence.

The sensitivity of the theoretical period shift to changes in the input physics used in the stellar models has been explored through several numerical experiments. From a set of red-giant evolutionary sequences we first show that the metallicity dependence of the core mass and hence the theoretical period shift are not sensitive to plausible changes in either the rate of neutrino emission or the conductive opacity, and thus uncertainties in the red-giant input physics cannot be blamed for the period-shift discrepancy. In contrast, test models for the ZAHB phase show that the observed period shift could be explained by an increase by a factor of ~5 in the metal opacity around 10^6 K. However, this possibility would imply a large error in the current Los Alamos opacities.

Our models indicate that CNO enhancements relative to Fe cannot produce the observed period shift when the effects of such enhancements on both the metal opacity and the CNO cycle are taken into account. We have analyzed the effects of evolution away from the ZAHB in the period–effective temperature diagram and have found that the horizontal-branch evolution can only explain part of the observed period shift. Finally, we present several objections against rotation as the cause of the observed period shift. At the present time there is no fully satisfactory explanation for the Sandage effect.

Discovery of Multiple Populations in GCs

letters to nature

Multiple stellar populations in the globular cluster ω Centauri as tracers of a merger event

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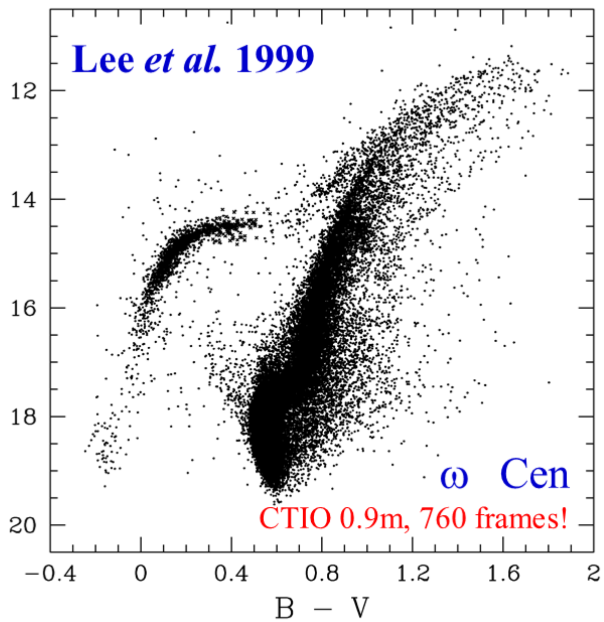
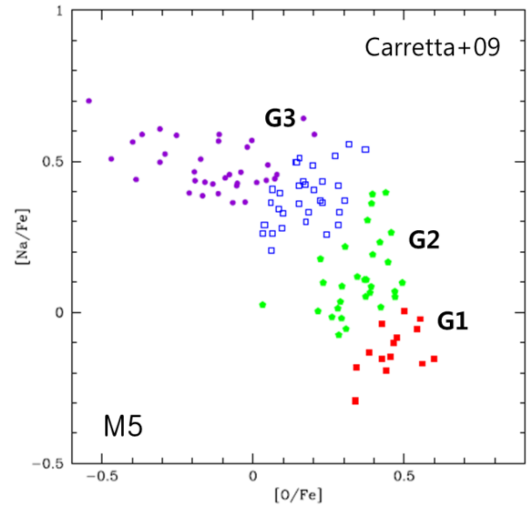
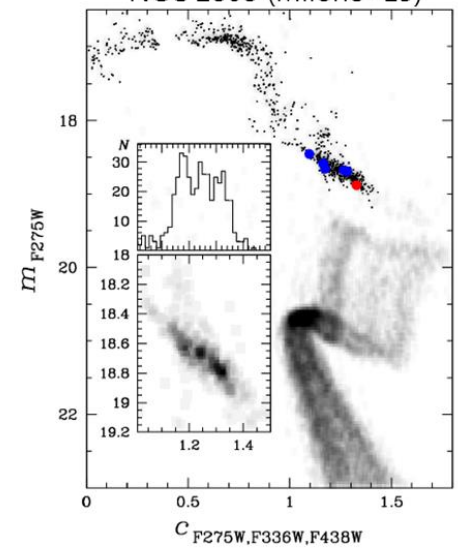




NGC 2808 (Milone+15)



Lee+99; Pancino+00; Rey+04; Bedin+04; Norris 04; D'Antona+04; D'Antona+Caloi 04, 08; Lee+05; Piotto+05; Bekki+06; Decressin+08; D'Ercole+08; Renzini 08; Carretta+09; Ferraro+09; Johnson+Pilachowski+09, 15; Ventura+09; Han+09; JWLee+09; Vesperini+10, 13; Dalessandro+11; Gratton+11, 12, 13; Mucciarelli+12; Joo+Lee 13; Lee+13; Kunder+13; Jang+14; Marino+14; Da Costa+14; Yong+14; Piotto+15; Milone+15; Lim+15; Jang+Lee 15; Han+15... **500+ papers!**

G1: Normal He
G2+G3: He, Na, N.. (Fe, Ca..) enriched
by IMAGB, WMS, (SNe)

Milestones in the discovery of He-enhanced population

Sandage+1981; Sweigart, Renzini, Tornambe 1987: RRL's in metal-poor OoII GCs might be He-rich

Lee+1999; Pancino, Ferraro+2000: discovered MSP from RGB stars in Omega Cen

D'Antona+2002, 2004: suggested He-enhanced pop. from AGB ejecta & HB morphology

Bedin+2004: discovered a MS split from Omega Cen

Norris 2004: suggested He-enhanced pop. from a MS split of Omega Cen

Lee+2005: He-enhanced pop. can explain MS split & EHB simultaneously

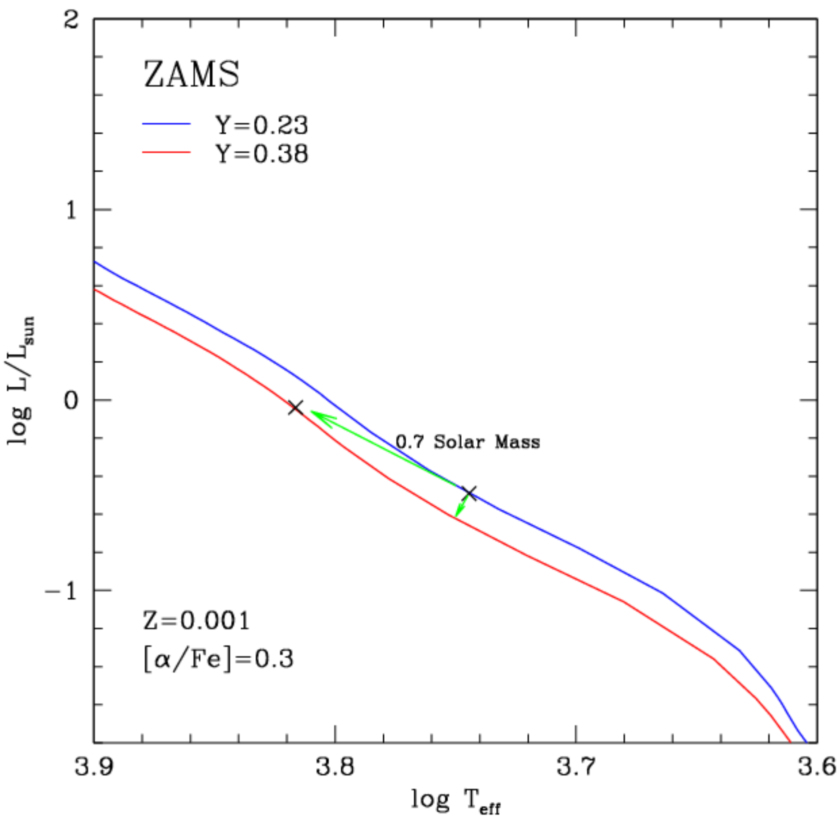
Piotto+2005: indirect evidence for He-enhanced pop. from spectroscopy of MS stars → Blue MS stars are more metal-rich & thus should be He-rich

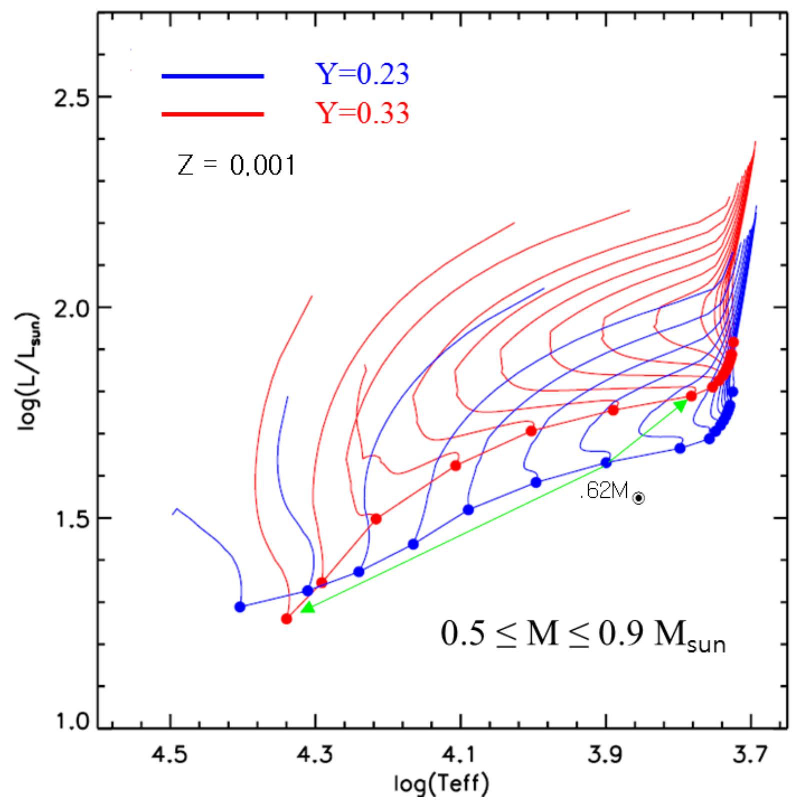
Carretta+2009; Gratton+2012: established Na-O anti-correlation among GCs

→ He-enhanced stars are also enhanced in Na & N

Villanova+2012; Marino, Milone+2014: direct spectroscopic confirmation of He-enhanced stars on bluer HB

Effects of Helium Abundance on HR diagram





He-rich stars (higher T_c & less envelope opacity):

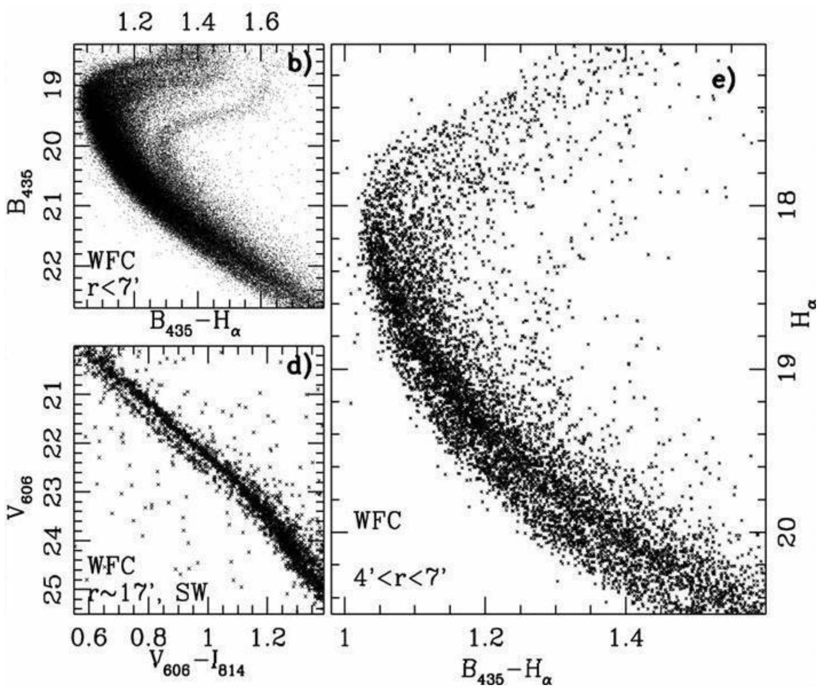
(1) brighter & bluer at a given mass

(2) evolve faster and thus have smaller masses at a given age

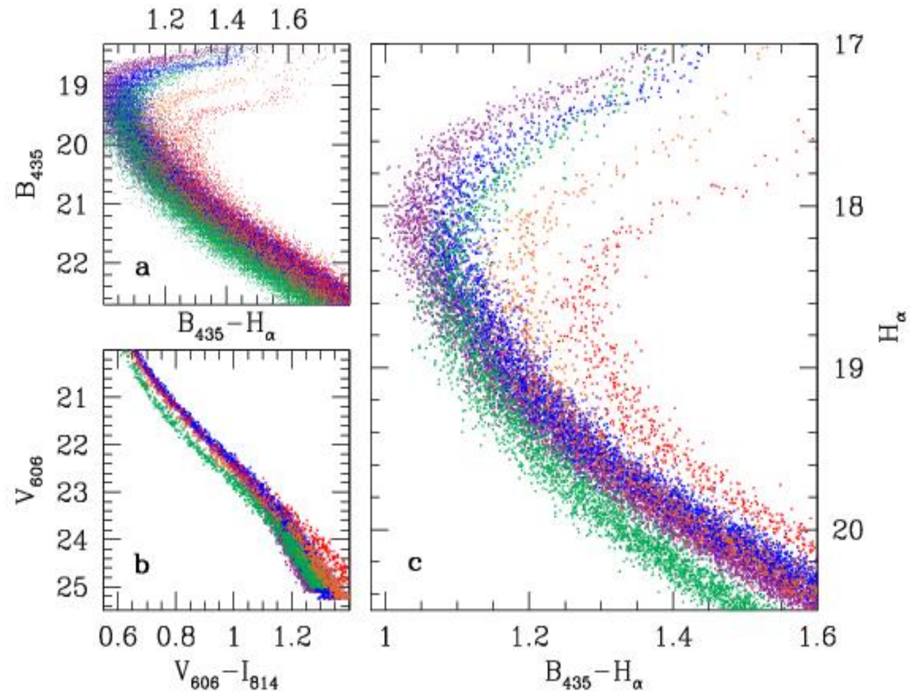
→ fainter & bluer on the MS

(3) bluer color on HB at a given age (for metal-poor GCs)

Effects of He on MS: ω Centauri



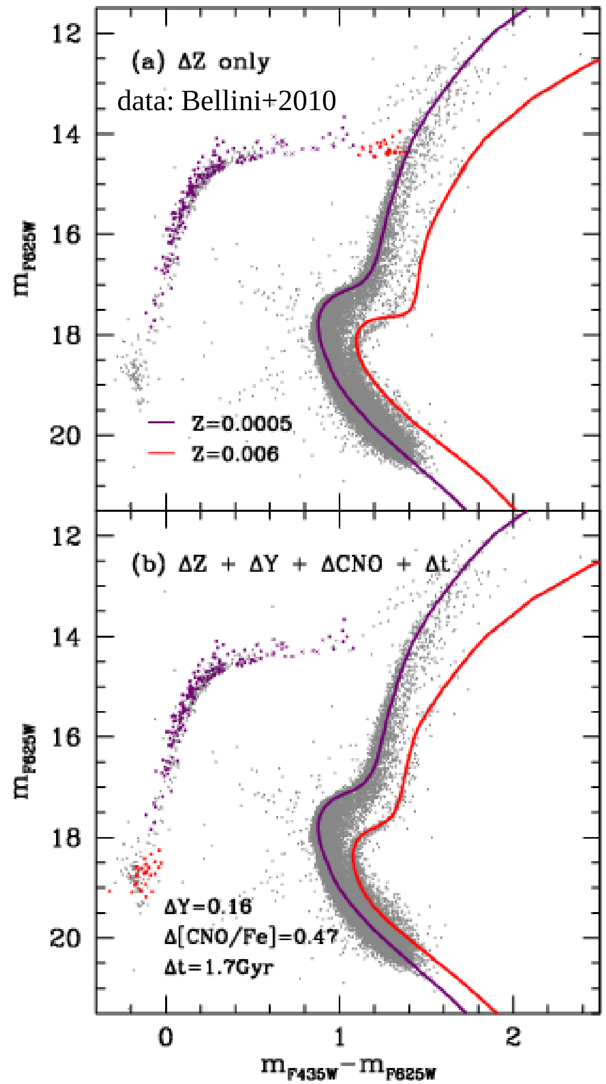
Observation: Bedin+2004

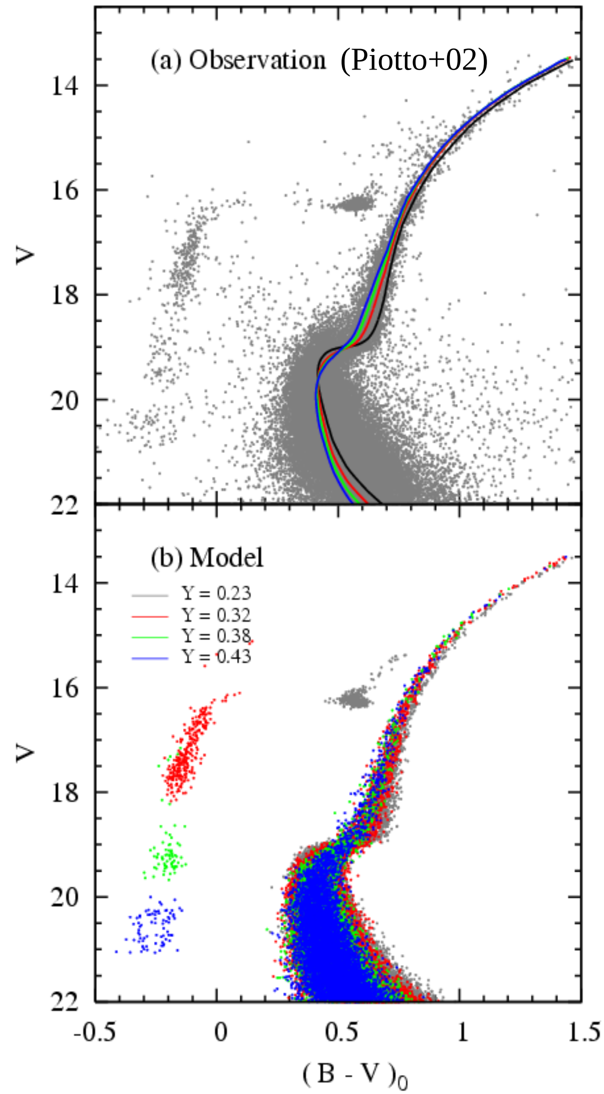


Model: Lee+2005; Joo & Lee 2013

Population	[Fe/H]	Y	Δ[CNO/Fe]	Age [Gyr]	Fraction
G1	-1.81	0.231	0.0	13.1 ±0.3	0.42
G2	-1.55	0.232	0.0	13.0	0.27
G3	-1.31	0.41 ±0.02	0.14	12.0	0.17
G4	-1.01	0.38	0.47	11.4	0.08
G5	-0.62	0.39	0.47	11.4	0.05

Effects of He on HB morphology



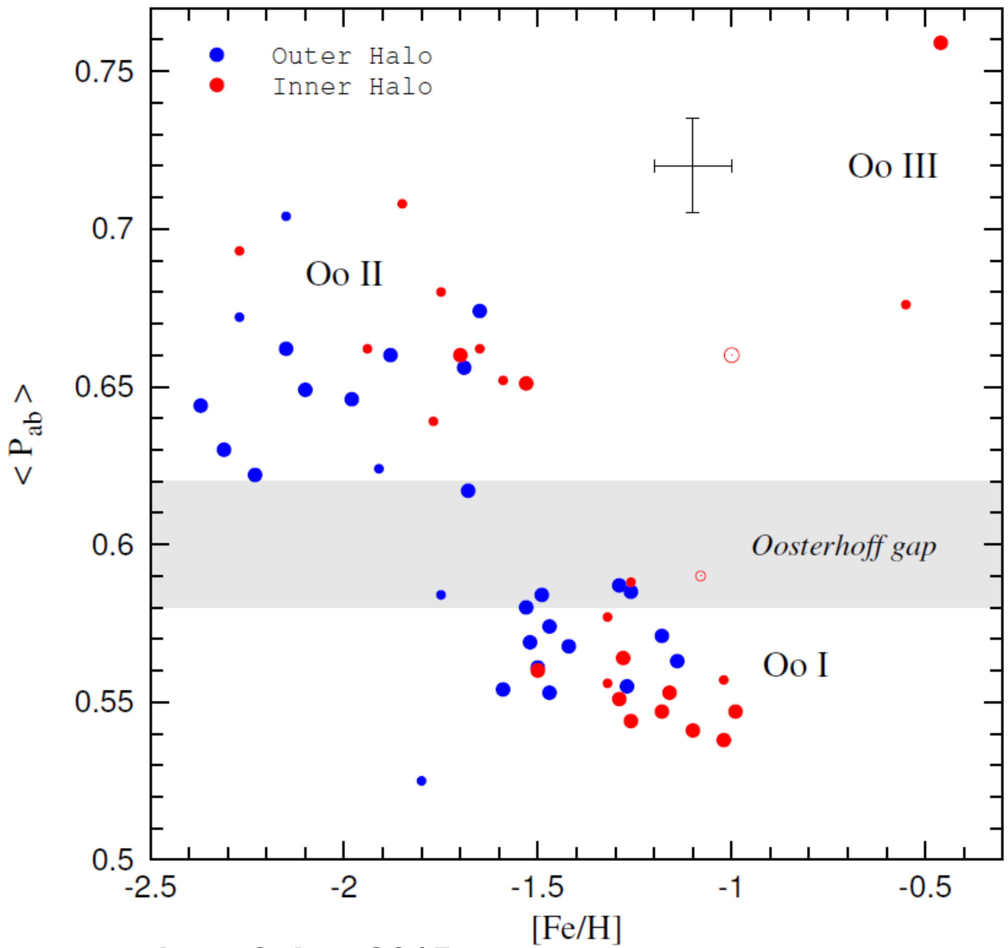


Omega Cen:
Lee+2005; Joo & Lee 2013

NGC 2808:
Lee+2005; D'Antona+2005

The Oosterhoff (1939) Period Groups

According to mean period of type ab RR Lyrae variables in GCs and halo field



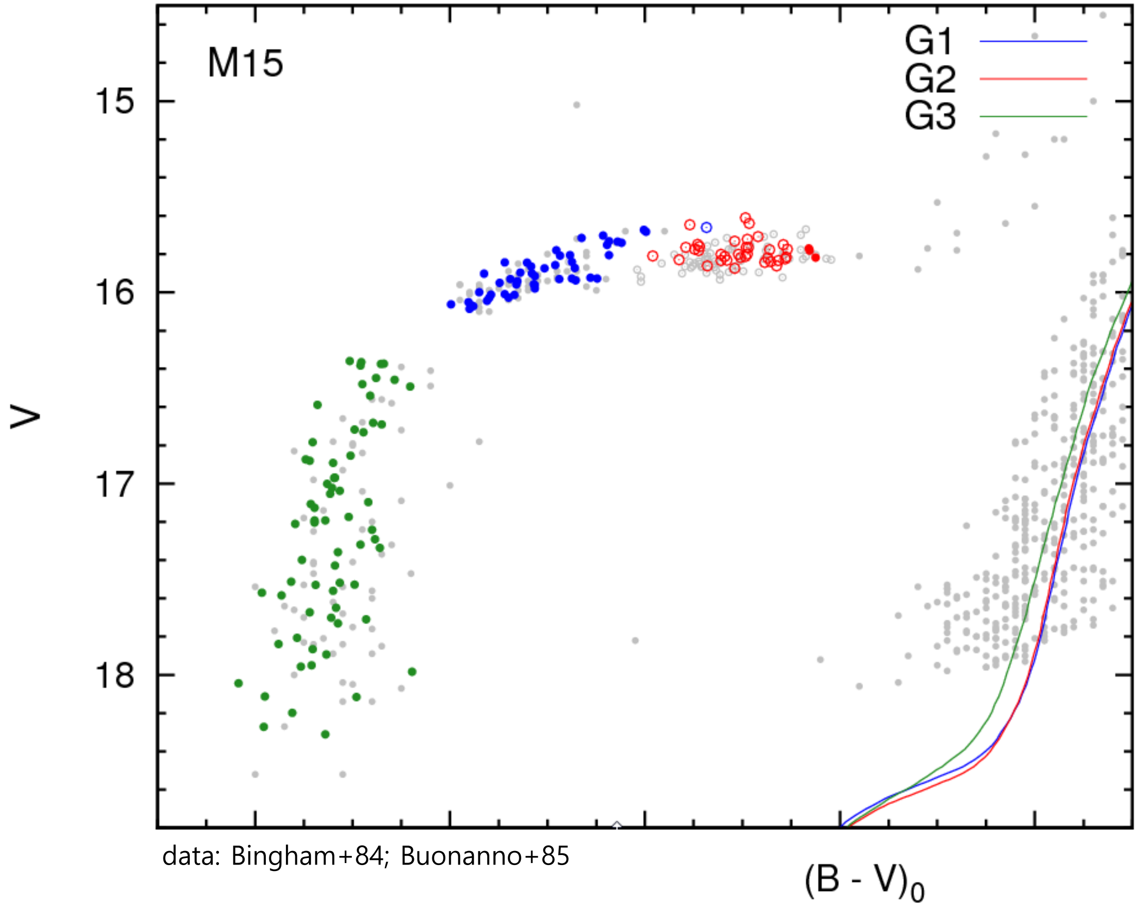
Jang & Lee 2015

Oo group I:
$<P_{ab}>$ ~ 0.55 day, metal-rich

Oo group II:
$<P_{ab}>$ ~ 0.65 day, metal-poor

Oo group III:
$<P_{ab}>$ ~ 0.70 day, very metal-rich

One of the long-standing problems in modern astronomy!
(**~380 papers**, including Sandage+1981, GTO 1986, SRT 1987, LDZ 1990, Sandage 2010)



data: Bingham+84; Buonanno+85

Most RRL's in M15 (Oo II) are from G2, mildly enhanced in He & N

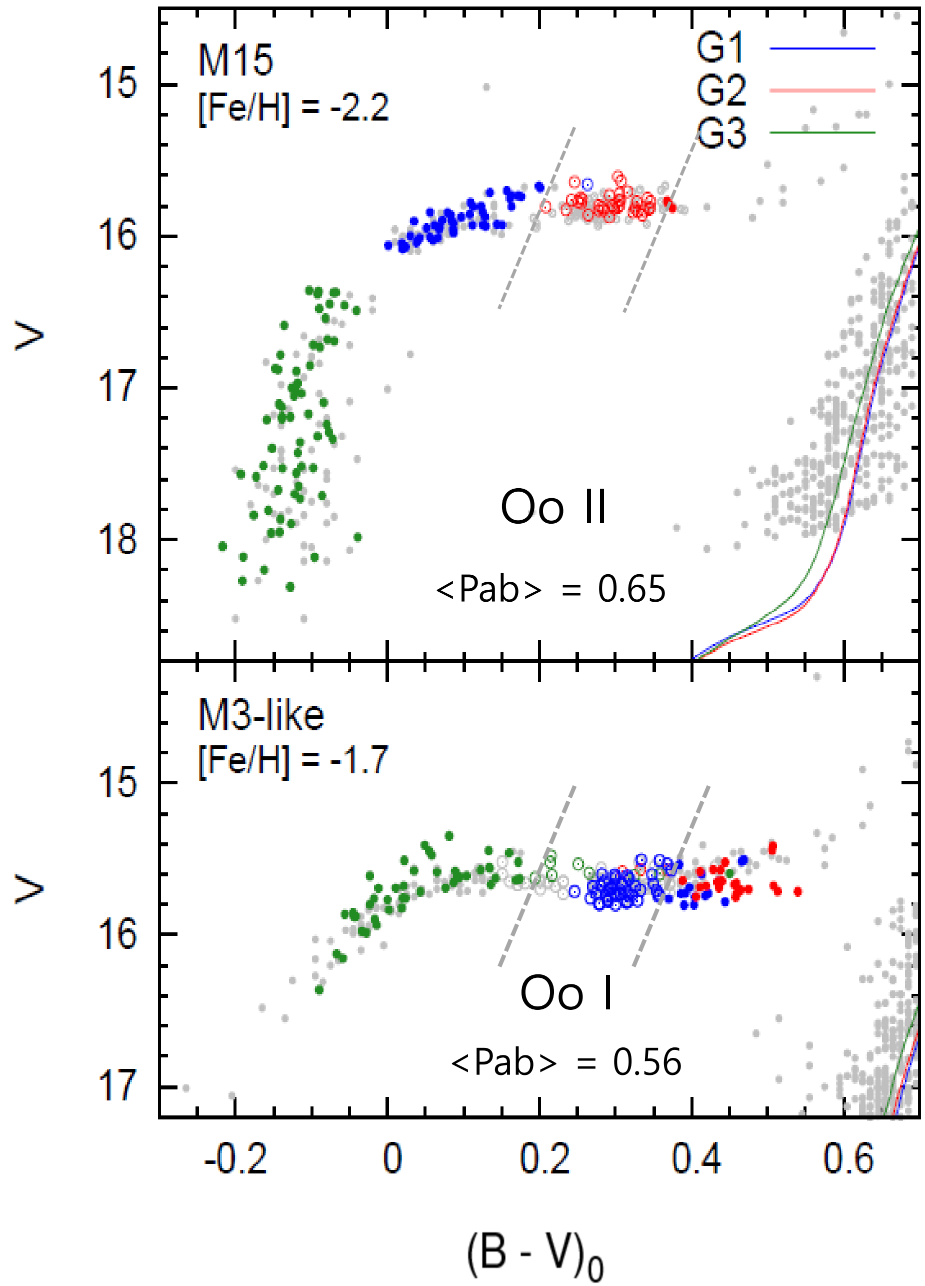
ΔY (G2-G1) = 0.015
ΔZ_{CNO} = 0.0003
Δt = ~1 Gyr

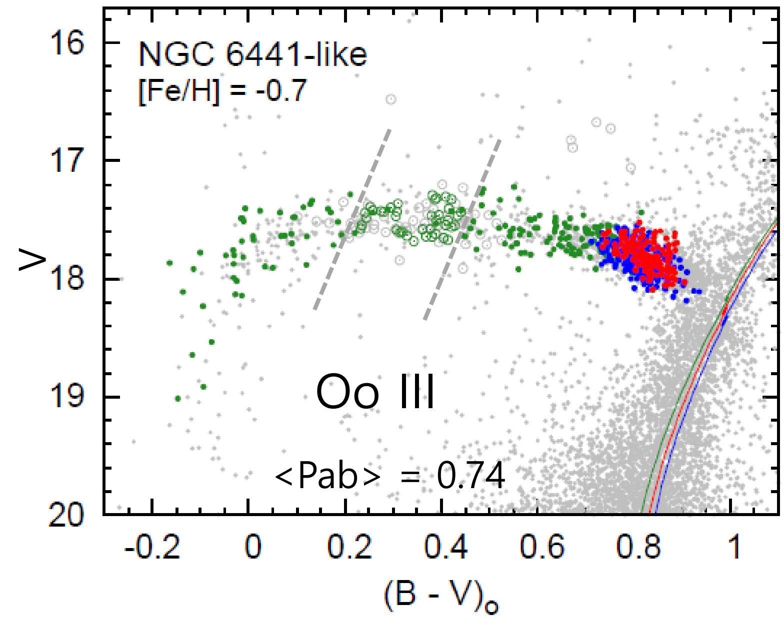
Jang, Lee+2014

(cf. Sandage+81; SRT 87)

Table 1. Parameters from our best-fit simulation of M15.

Population	[Fe/H][a]	$\Delta Z_{\rm CNO}$	Y	Age (Gyr)	Mass Loss[b] ($M_\odot$)	$\langle M_{\rm HB}\rangle$[c] ($M_\odot$)	Fraction	$\Delta \log P'$[d]	$\Delta\langle P_{\rm ab}\rangle$ (day)
G1	-2.2	0	0.230	12.5	0.140	0.686	0.36	-	-
G2	-2.2	0.00026	0.245 ± 0.01	11.4 ± 0.2	0.142	0.684	0.22	0.040	0.087
G3	-2.2	0.00026	0.327 ± 0.01	11.3 ± 0.2	0.129	0.589	0.42	-	-





Period-Shift between Oo groups

→ **"Population-Shift"** within the instability strip (Jang, Lee+2014)

RR Lyraes produced *mostly* by

G1 for Oo I,

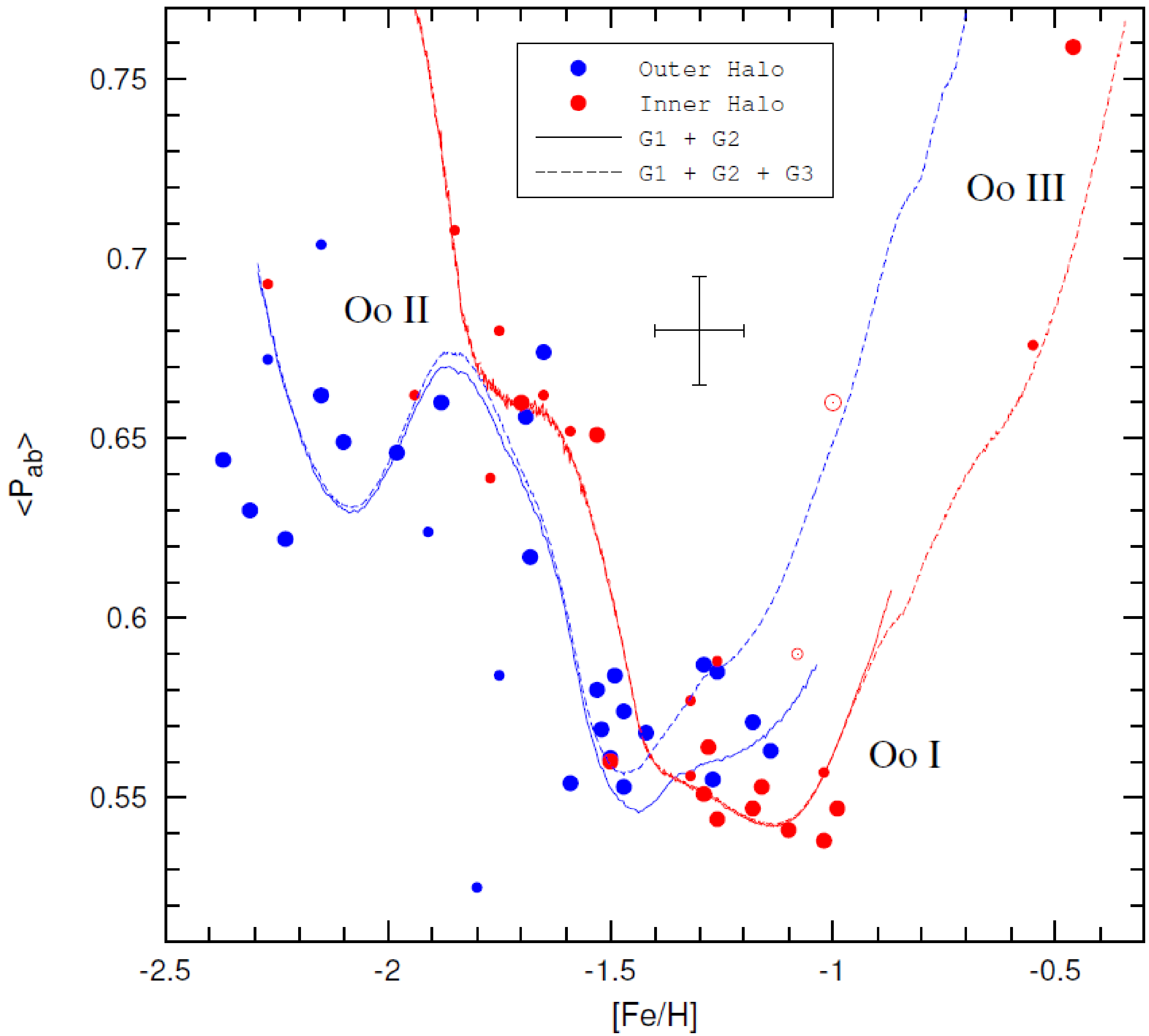
G2 for Oo II,

G3 for Oo III

(G1/G2 overlap if metal-rich or Δt < 0.5 Gyr)

When our models are extended to all metallicity regimes…

The Oosterhoff dichotomy reproduced!



Outer Halo (R > 8kpc):

Δt (G1-G2) = ~1 Gyr

Inner Halo (R < 8kpc):

Δt (G1-G2) = 0.5 Gyr

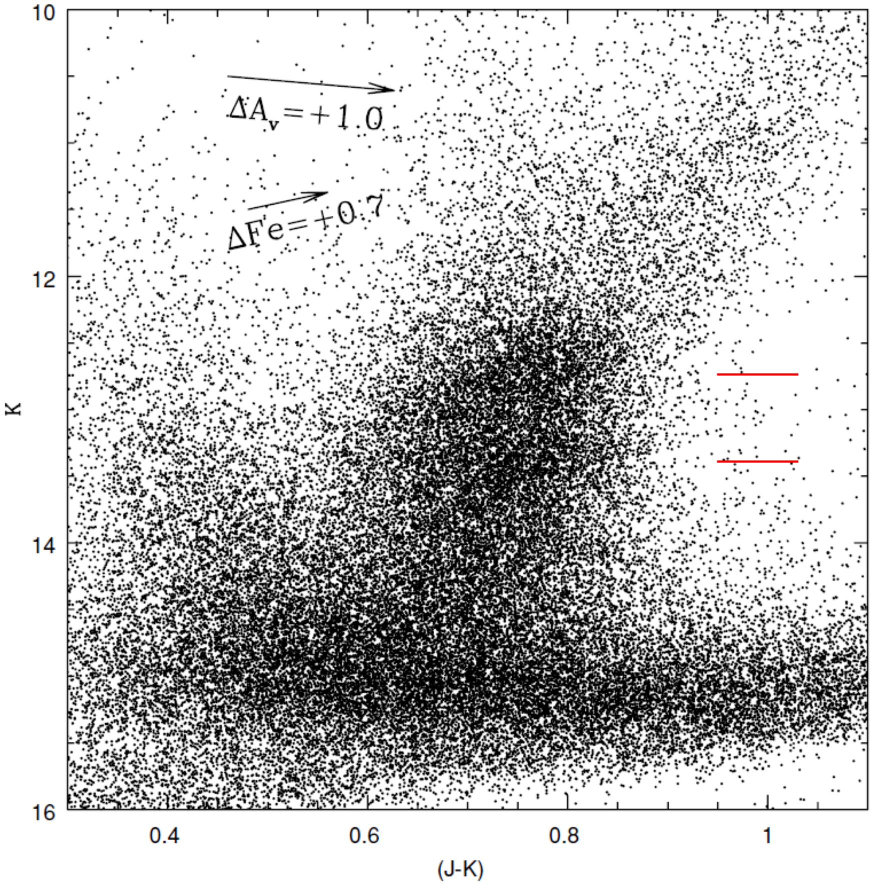
Δt (Inner-Outer) = ~1 Gyr

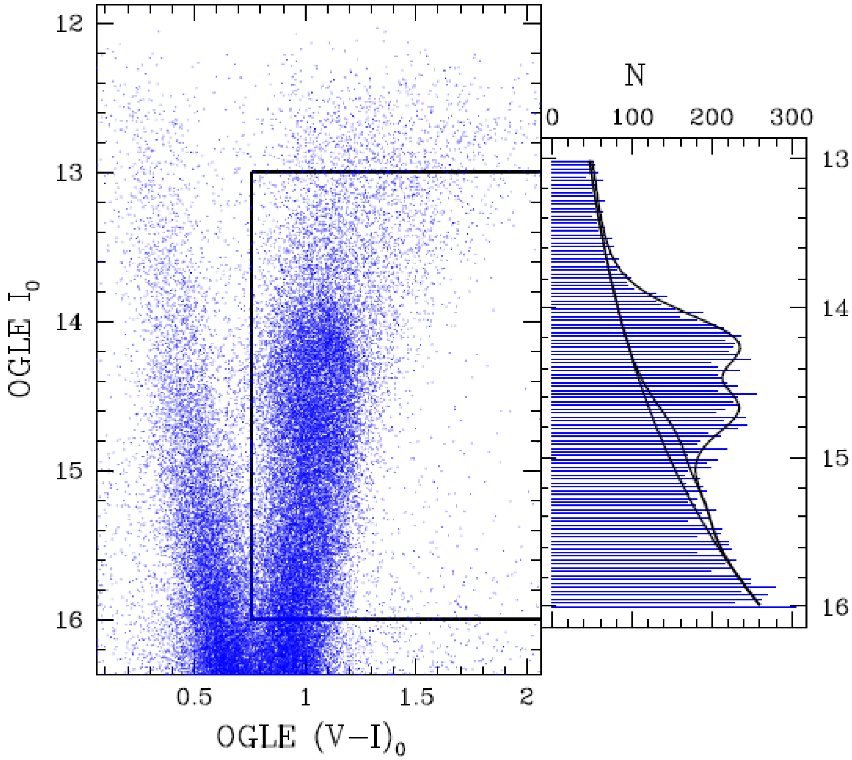
ΔY (G2-G1) = 0.012

Consistent with the dual origin of halo (Zinn 1993; Lee+2007; Carollo+2007)

Jang & Lee 2015

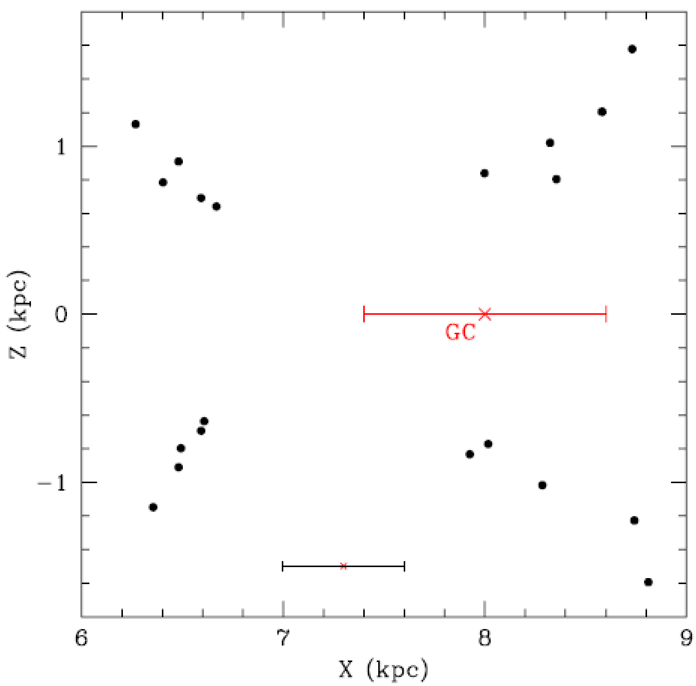
Double Red Clump (RC) in the MW Bulge





Discovery of Two RCs (|b| > 5.5):
McWilliam & Zocalli 2010; Nataf et al. 2010

The X-Shaped Bulge in the Milky Way



X-Shaped Bulge from bar instability:

bright RC (foreground) + faint RC (background)

McWilliam & Zocalli 2010; Nataf+2010, 2015; Saito+2012; Ness, Freeman+2012, 2013; Li & Shen 2012; Uttenthaler+2012; Wegg & Gerhard 2013; Vasquez+2013; Rojas-Arriagada+2014; Gonzalez+2015… **120+ papers**

→ **Even high latitude field of the bulge has "pseudo bulge" characteristic**

But, an alternative interpretation is possible! (Lee+2015)

Hint from Terzan 5: A metal-rich bulge GC with double RC!

The cluster Terzan 5 as a remnant of a primordial building block of the Galactic bulge

F. R. Ferraro[1], E. Dalessandro[1], A. Mucciarelli[1], G. Beccari[2], R. M. Rich[3], L. Origlia[4], B. Lanzoni[1], R. T. Rood[5], E. Valenti[6,7], M. Bellazzini[4], S. M. Ransom[8] & G. Cocozza[4]

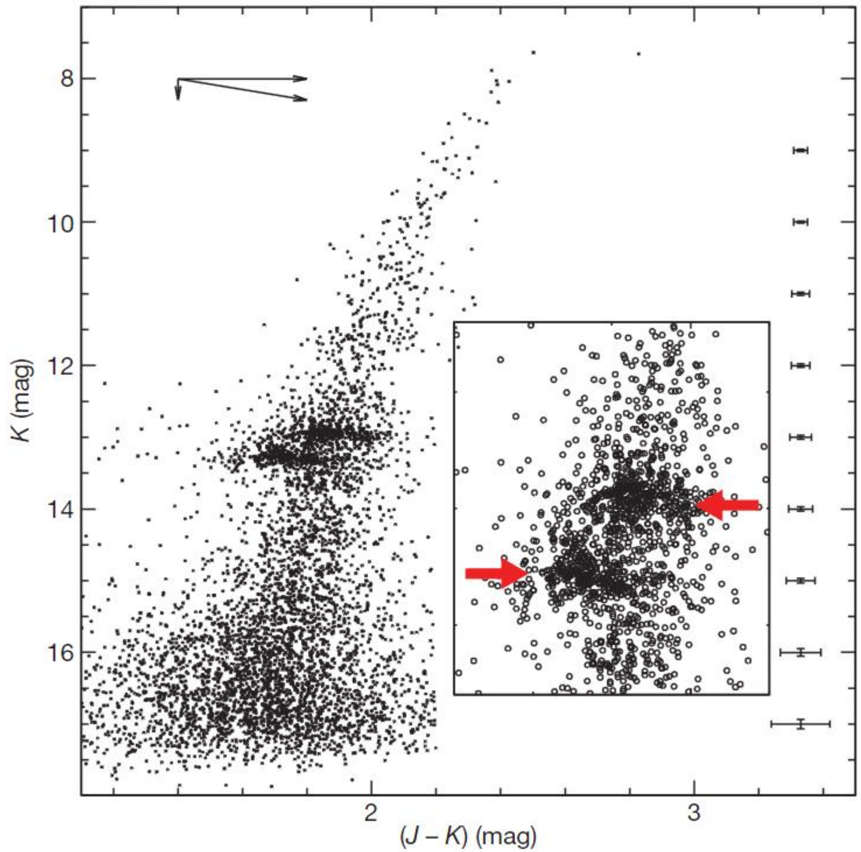


Figure 2 | The two horizontal branch clumps of Terzan 5. Main panel, MAD

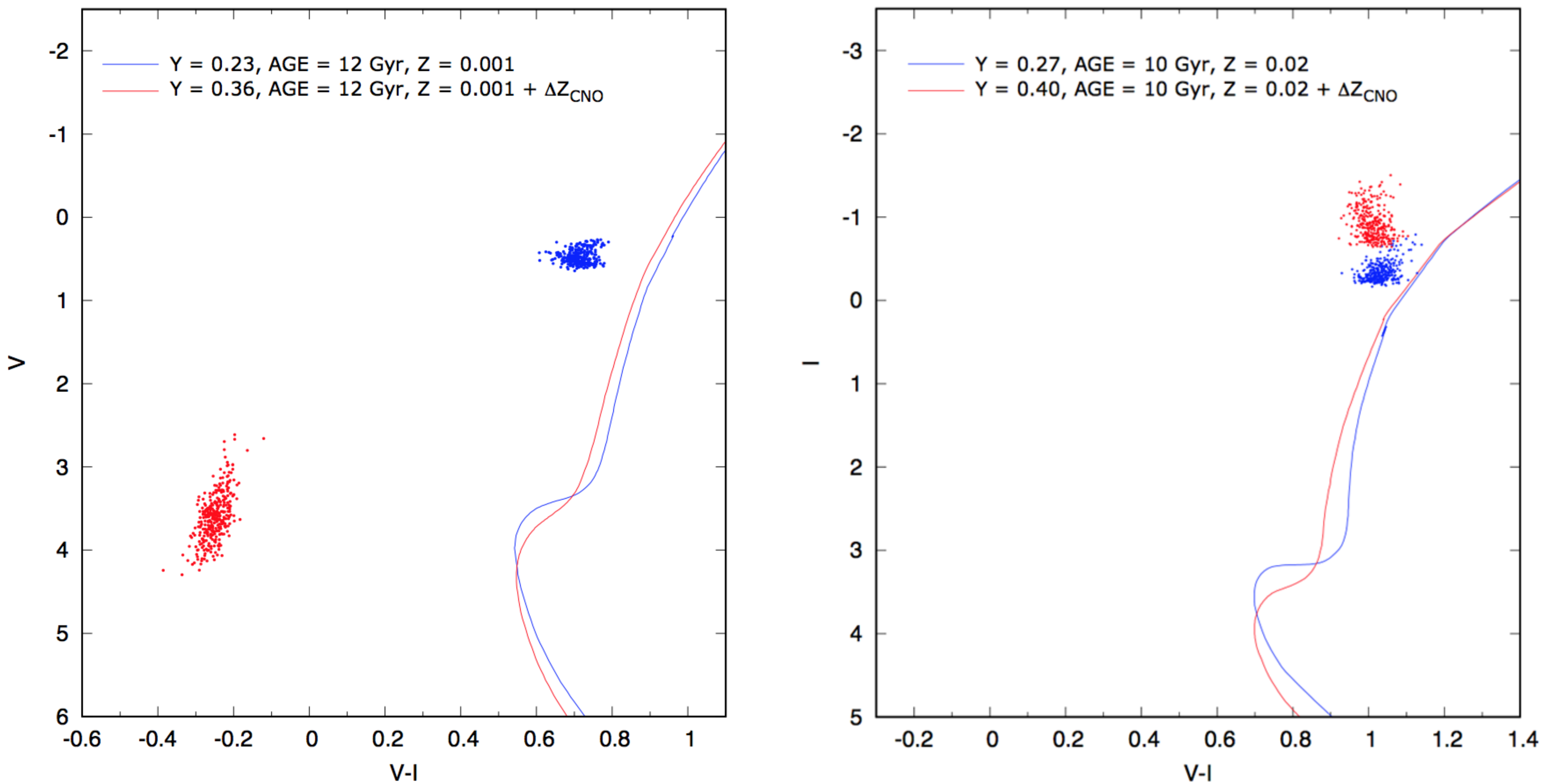
Metal-rich counterpart of ω Cen (Ferraro et al. 2009)

→ Brighter RC is younger (Ferraro+2009; 2016) and super-He-rich (D'Antona+2010; Lee+2015)

→ Very analogous to the double RC in bulge!

In the metal-rich regime..

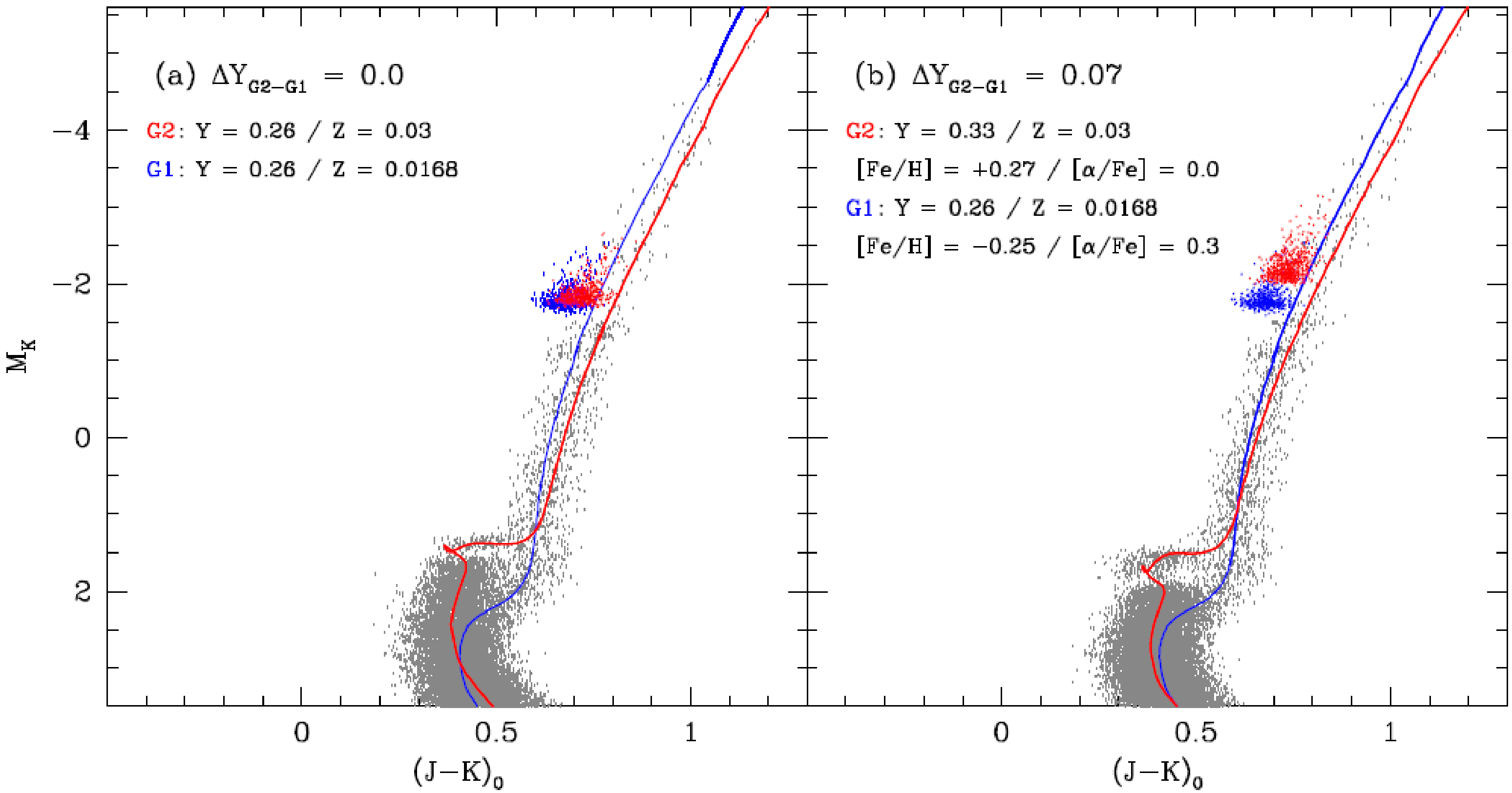
Super-He-rich HB stars are on the brighter RC!



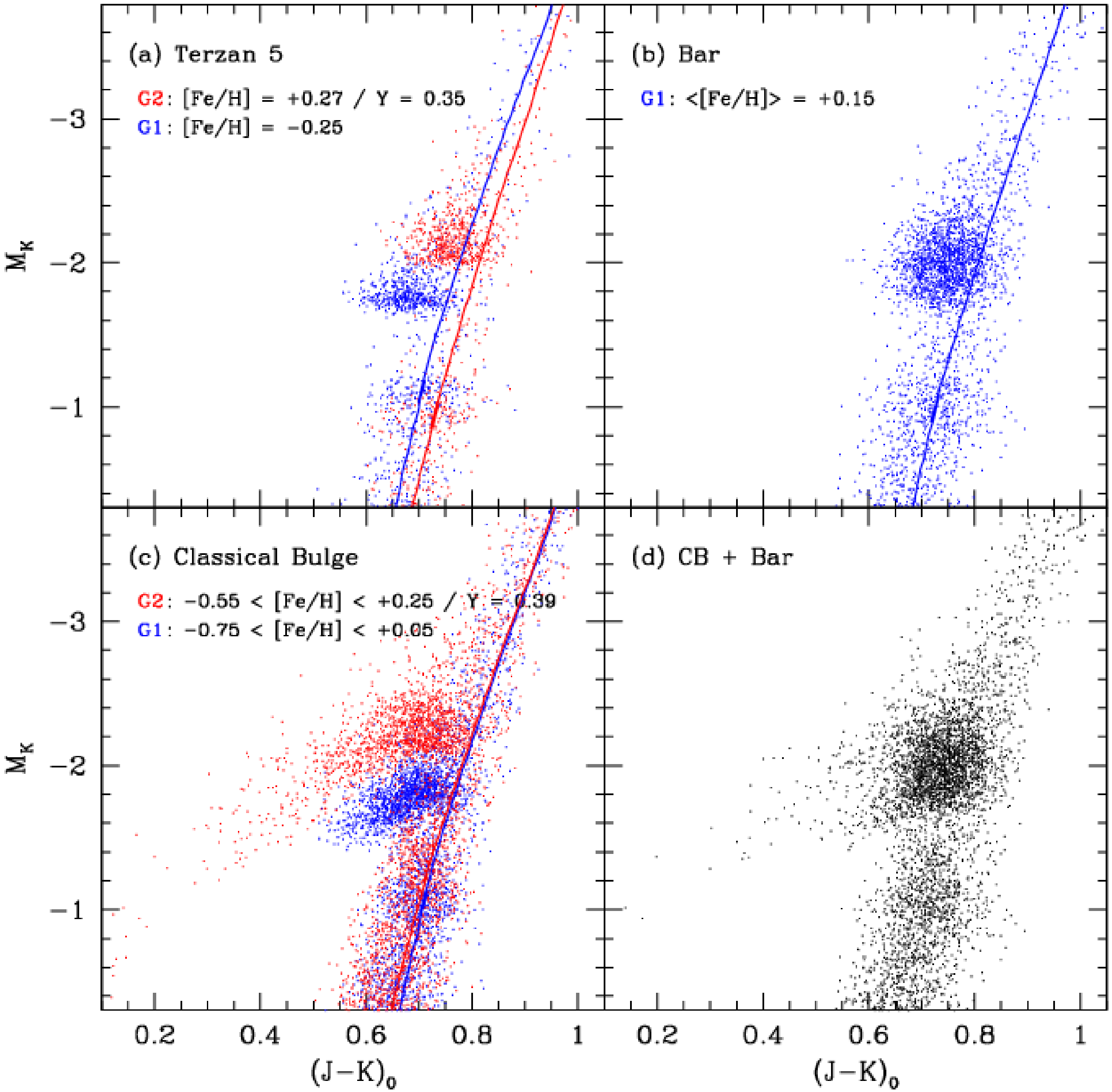
$\Delta Y = 0.13$

Credit: Sohee Jang

Terzan 5



When the observed Δt, Δ[Fe/H] & Δ[α/Fe] (Ferraro+2016; Origlia+2011) are taken into account, we still need a large ΔY ~0.07 (Joo, Lee, & Chung 2017)



Multiple Population Models for the Double RC in Bulge

G1: normal-He
ΔY/ΔZ = 2

G2: enhanced-He
Y = 0.39 (ΔY/ΔZ = 6) at [Fe/H] = -0.1

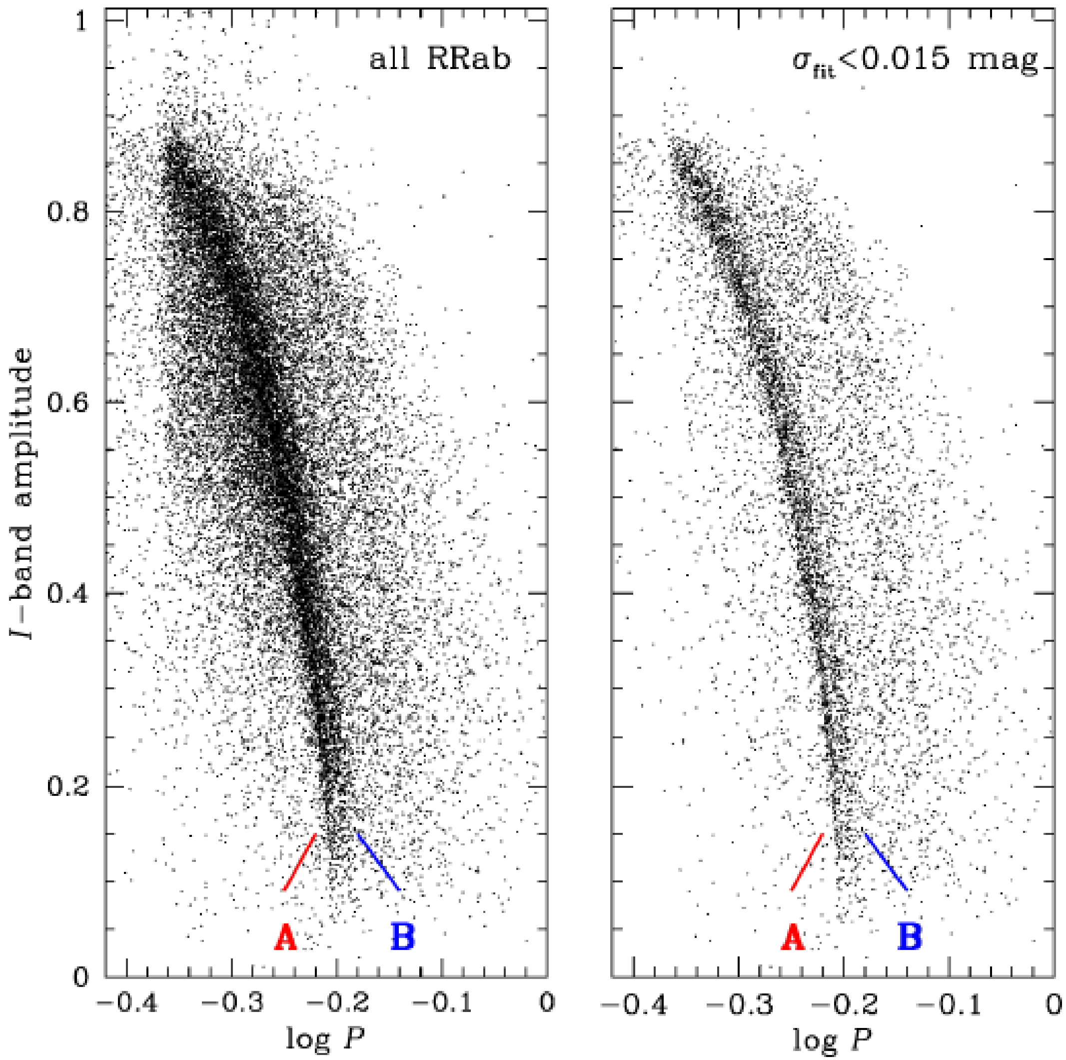
Lee, Joo & Chung 2015

Joo, Lee & Chung 2017

In the metal-poor regime, our models can also reproduce..

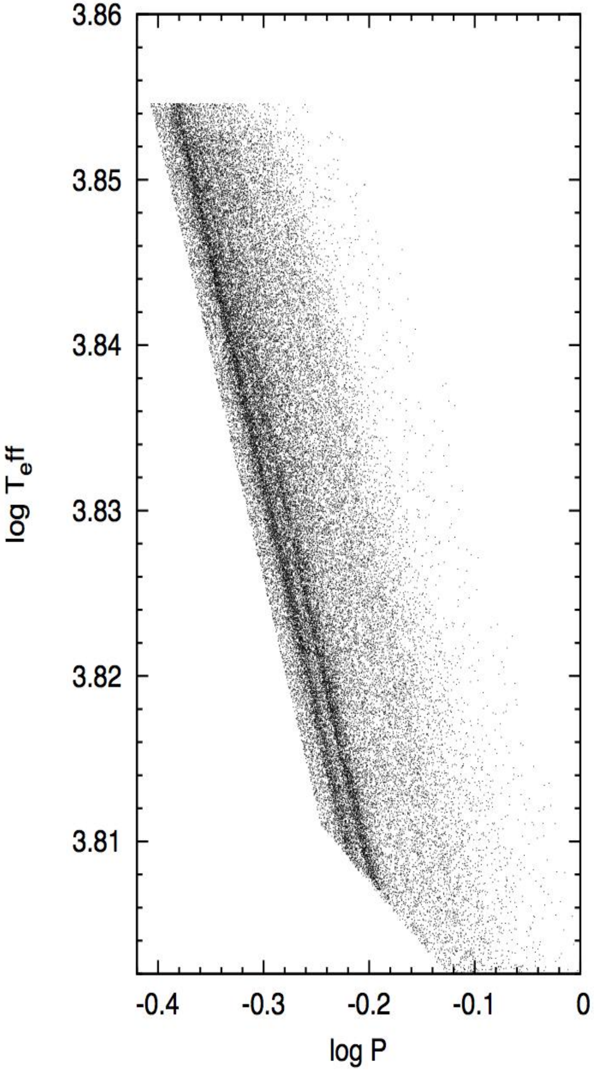
Two populations of RR Lyrae variables in the bulge

(Pietrukowicz et al. 2015)



Our model

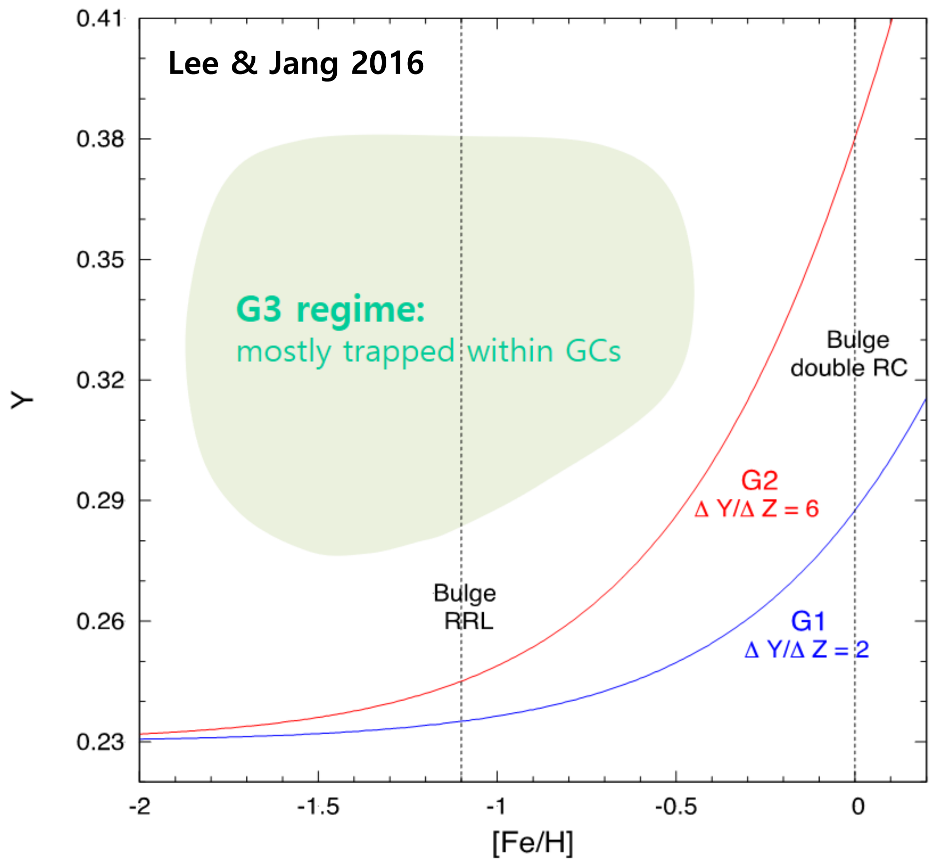
(Lee & Jang 2016)

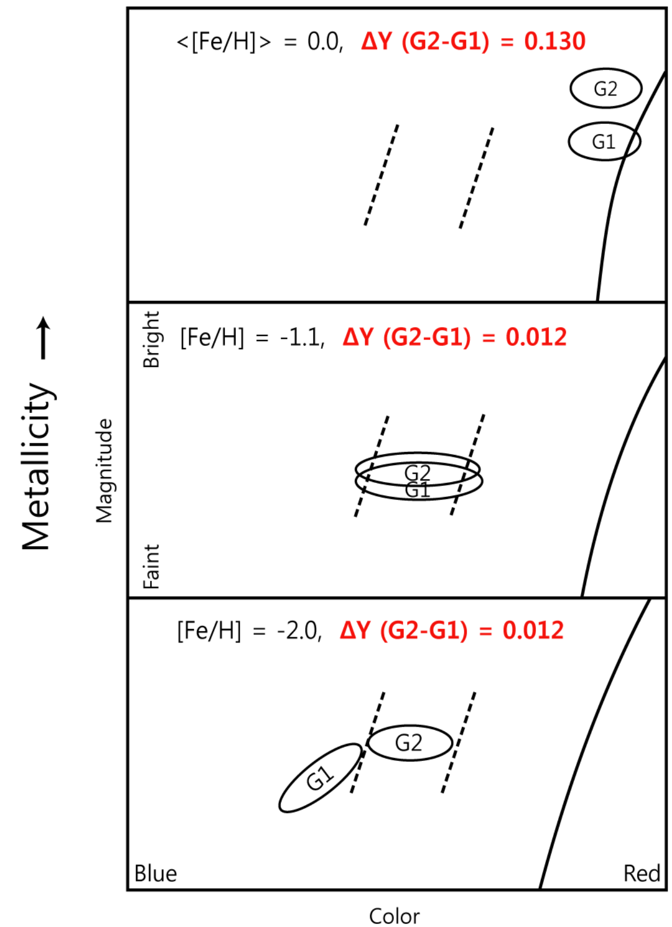


<[Fe/H]> = -1.1

ΔY (G2-G1) = 0.012

Double RC, two bulge RRL populations, & Oosterhoff dichotomy are different manifestations of the same phenomenon !!

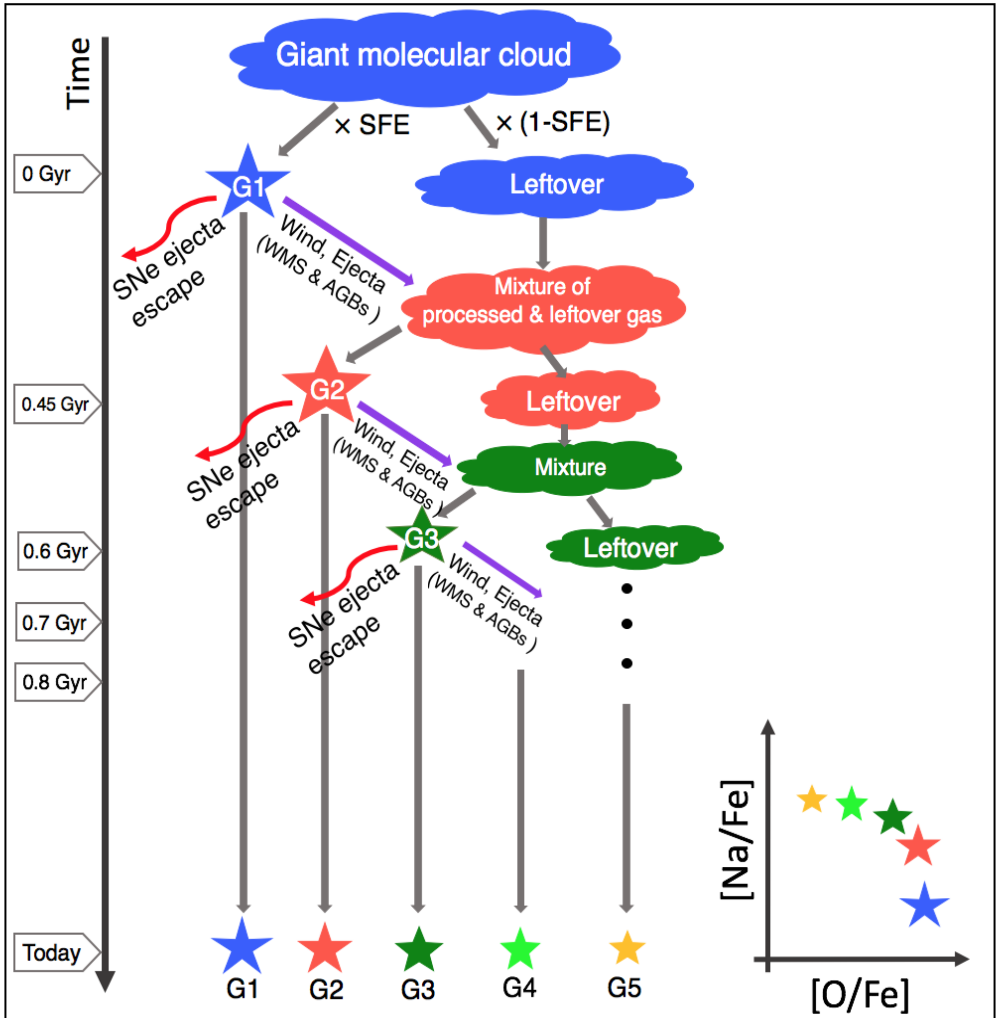




Double RC at solar metallicity is a natural extension of this trend!

Strong metallicity dependence of ΔY(G2-G1) is predicted from our chemical evolution models for proto-GCs

Chemical Evolution Models (Kim & Lee 2017)



Major assumptions/ingredients:

1. SN blast waves undergo blowout without expelling the leftover gas

(Tenorio-Tagle+2015; Silich & Tenorio-Tagle 2017)

→ Chemical evolution is dictated by AGB & WMS (winds of massive stars)!

2. Star formation beyond G2 is allowed to continue, G3, G4…

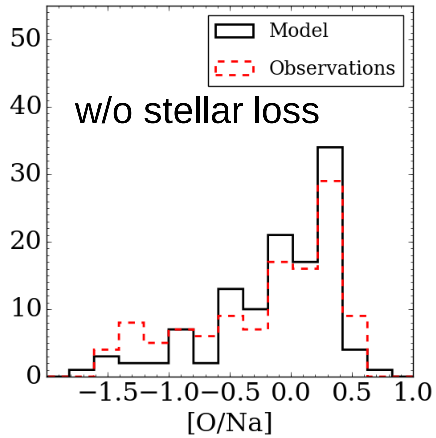
3. IMF slope s ~ 2, SFE ~ 60%

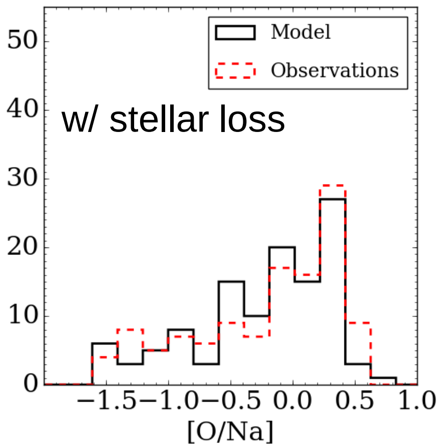
4. Specific star formation history is required ($\Delta t \sim 10^8$ yrs between G1, G2, G3…)

5. Stellar yields from:
Ventura+2013, 2014; Di Criscienzo+2016 (AGB)
Portinari+1998; Hirschi+2005 (WMS)

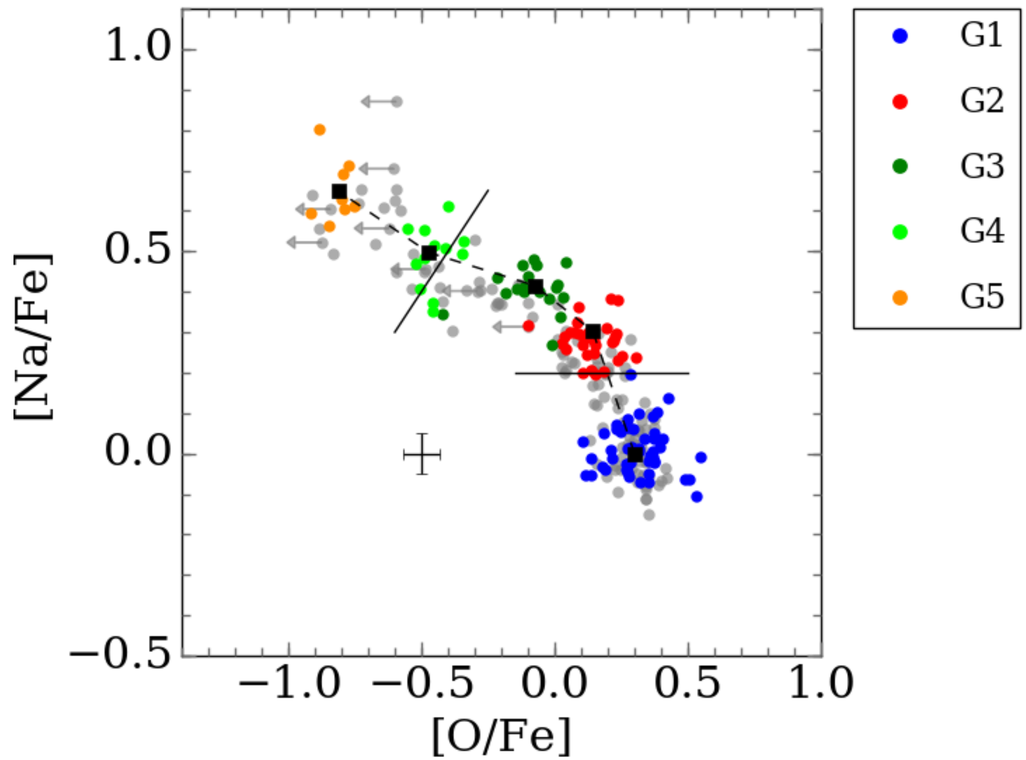
NGC 2808

S = 1.9, SFE= 60%,
[Fe/H] = -1.14





Observation : Carretta et al. 2015

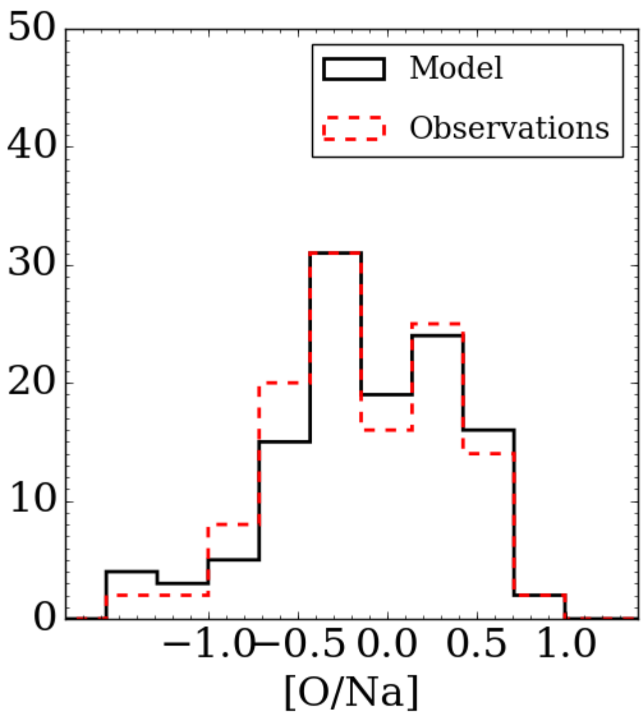


Population	Y	Δ[Na/Fe]	Δ[O/Fe]	Δ[N/Fe]	ΔZ_{CNO}	fraction Original	fraction Remaining	t(Gyr)
G1	0.235	0.0	0.0	0.0	0.0	0.47	0.39	0.0
G2	0.269	0.30	-0.16	0.79	0.00010	0.26	0.26	0.23
G3	0.303	0.42	-0.37	1.00	0.00012	0.14	0.16	0.31
G4	0.335	0.50	-0.77	1.13	0.00014	0.08	0.12	0.36
G5	0.369	0.65	-1.11	1.30	0.00093	0.05	0.08	0.91

M5

s= 2.1, SFE= 60%,
[Fe/H] = -1.3

Observation: Carretta et al. 2009



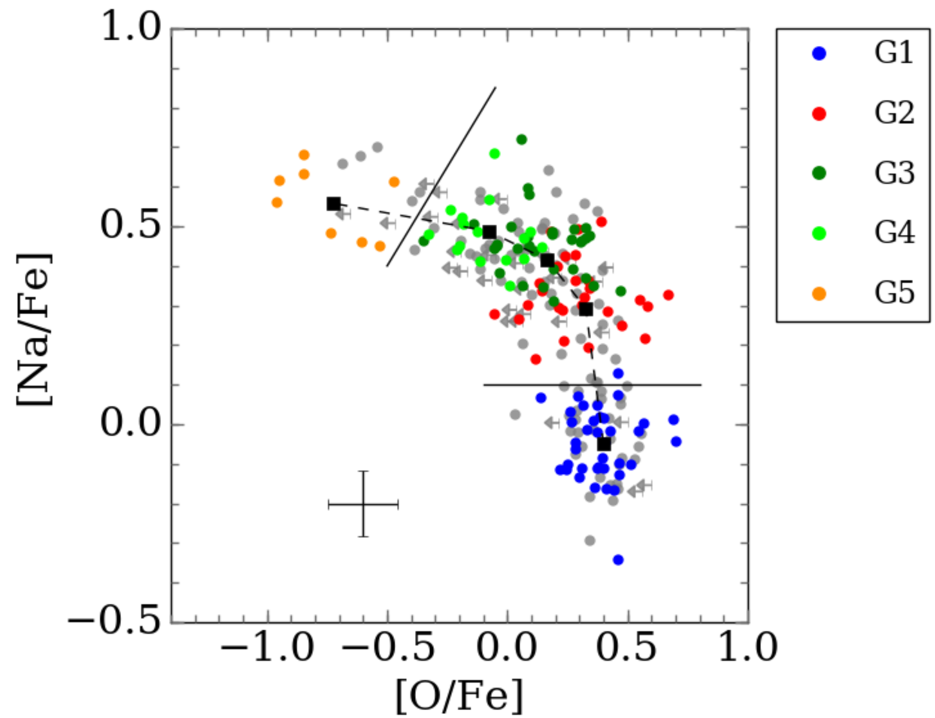
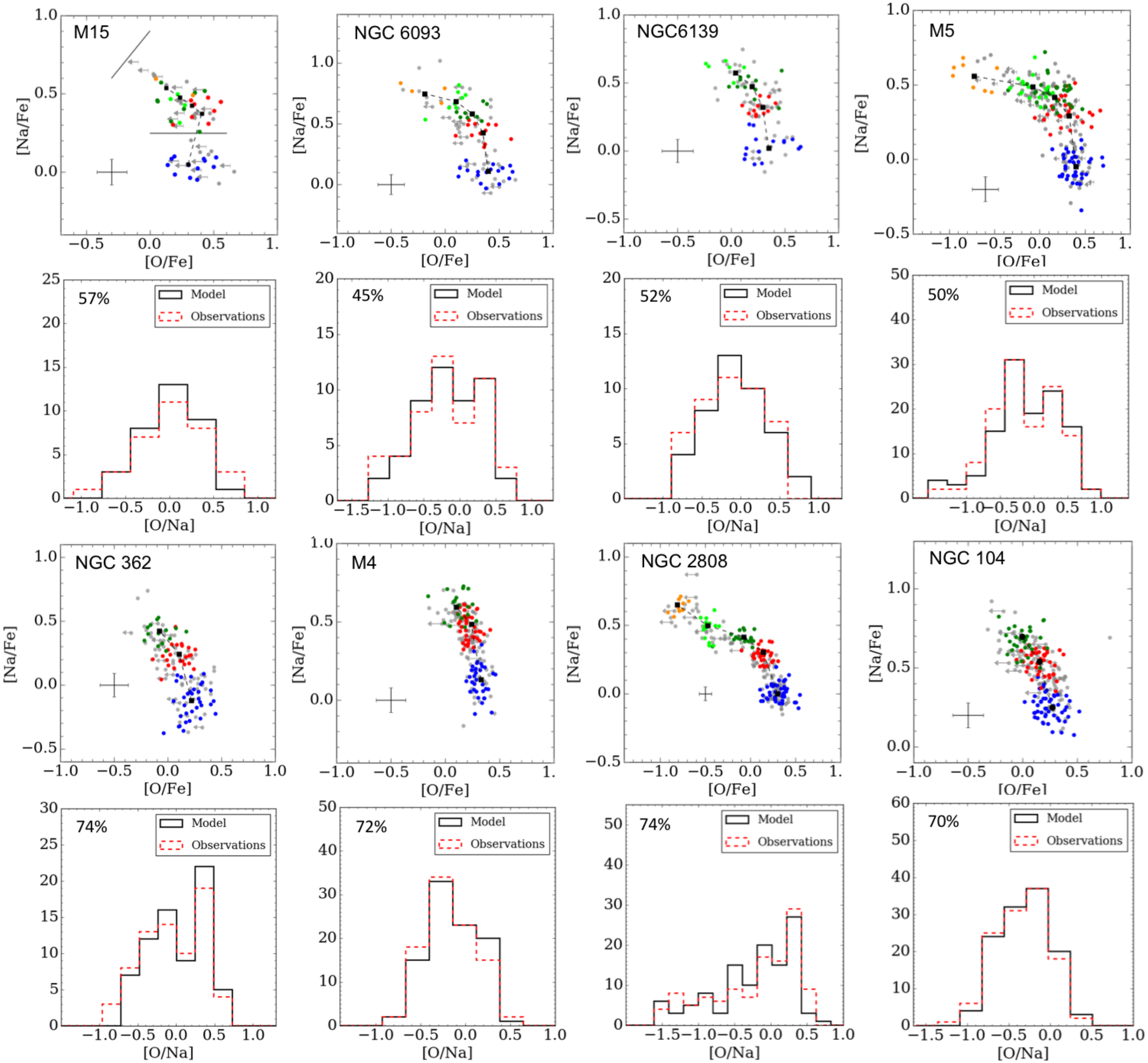


Table 2. Results of our chemical evolution model for the inner halo globular cluster M5.

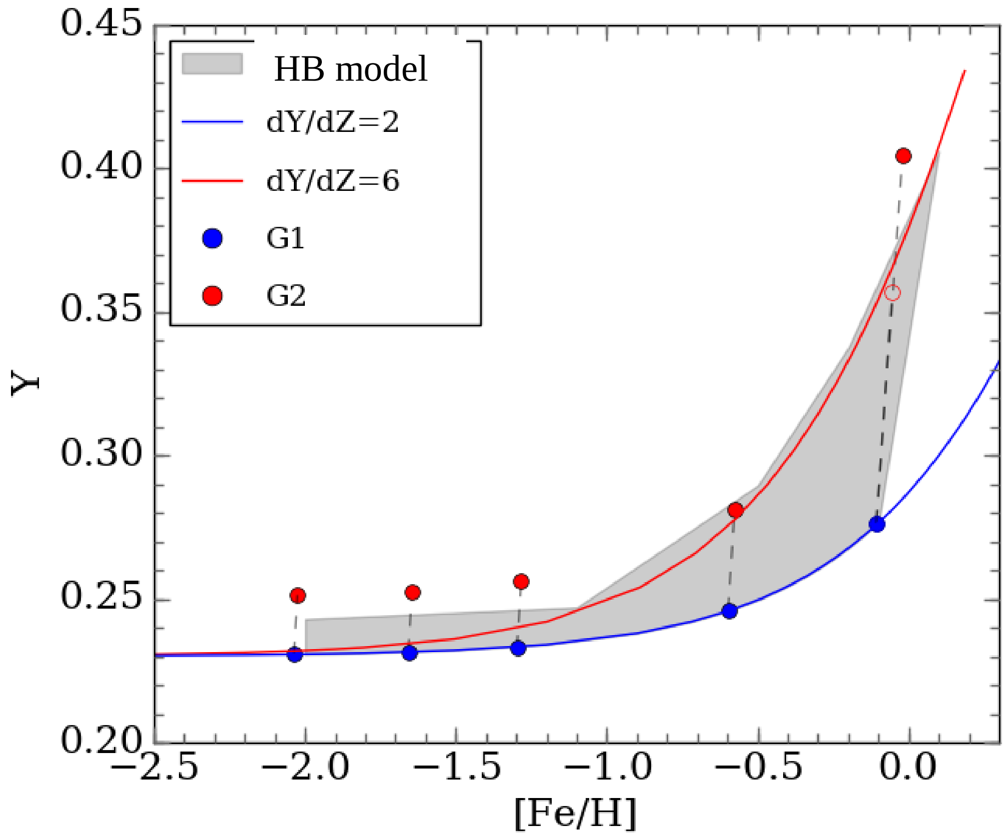
Population	Y	Δ[Na/Fe]	Δ[O/Fe]	Δ[N/Fe]	ΔZ_{CNO}	fraction Original	fraction Remaining	t(Gyr)
G1	0.233	0.0	0.0	0.0	0.0	0.49	0.31	0.0
G2	0.256	0.34	-0.07	0.90	0.00035	0.27	0.23	0.45
G3	0.280	0.47	-0.23	1.09	0.00042	0.13	0.26	0.6
G4	0.303	0.54	-0.48	1.21	0.00044	0.07	0.13	0.7
G5	0.326	0.61	-1.12	1.3	0.00048	0.04	0.07	0.8

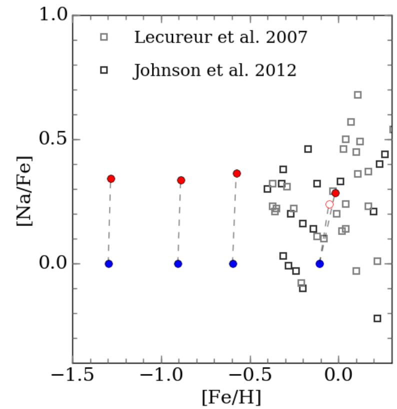
$\Delta t \sim 10^8$ yrs expected from orbital period, MS lifetime of AGB, Lyman & Werner cooling timescale
(see, e.g., Conroy & Spergel 2011)

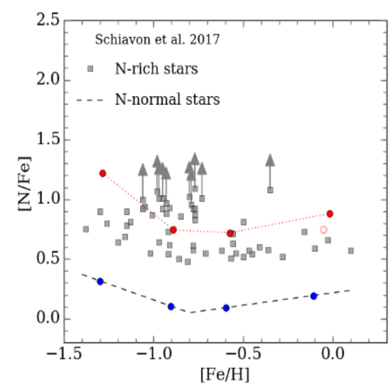


Kim & Lee 2017, in prep.

Our models predict super-He-rich G2 stars in the bulge!



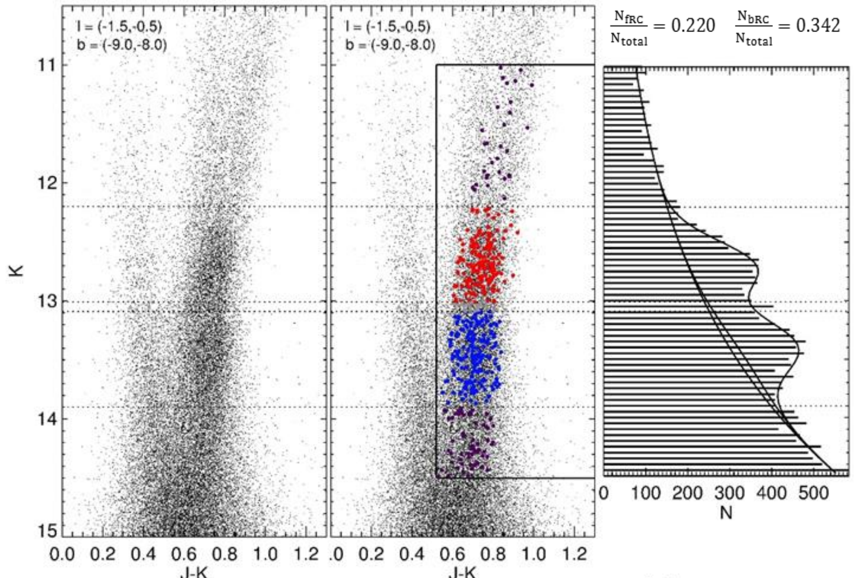




Strong metallicity dependence of ΔY(G2-G1) is mostly due to the winds of metal-rich massive stars (Maeder 1992; Meynet+2008)

Unlike He, main contributor of Na & N is AGBs, without strong Z dependence, and our models are consistent with observed spreads in [Na/Fe] & [N/Fe] in MW bulge! (Johnson+2012; Schiavon+2017)

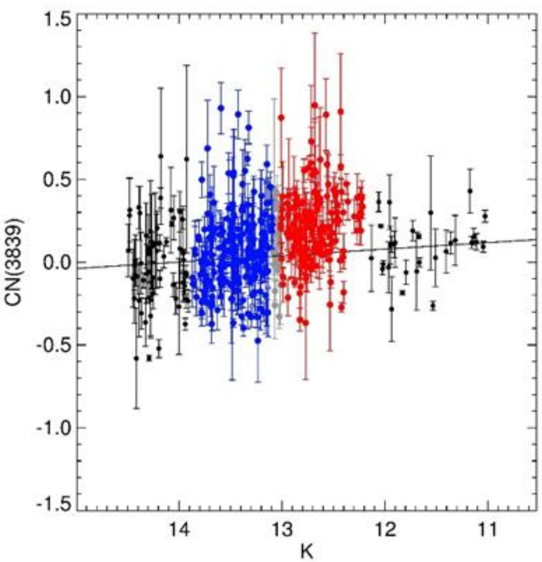
Bright RC stars are enhanced in CN (& He)!

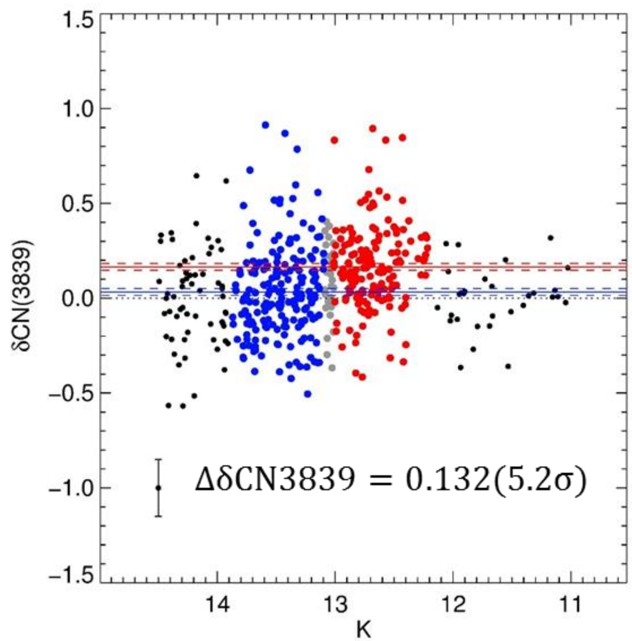


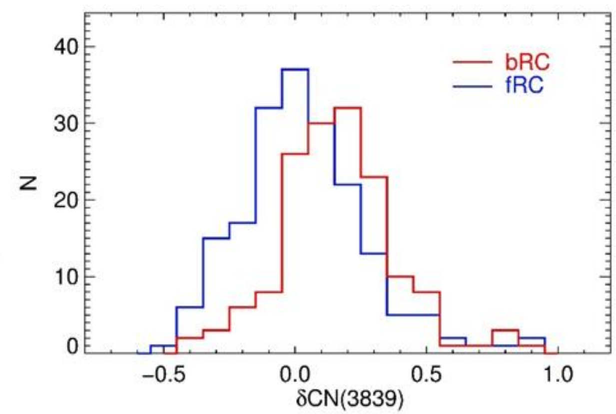
du Pont 2.5m low-resolution spectroscopy for 462 RC & RGB stars in the bulge (b = -8.5):

Direct evidence that (1) double RC is due to multiple population phenomenon, & (2) bulge stars have GC origin!!

See poster by Hong, Lim & Lee







$\Delta\delta\mathrm{CN} = 0.132\ (5.2\sigma)$

$\Delta\delta$CN(G2-G1) = 0.43

(similar to GCs: Lim+15, 16, 17)

The double red clump of the Milky Way bulge has nothing to do with an X-shaped structure !

1. It is another manifestation of helium-enhanced multiple population phenomenon (Lee+2015).

2. In the metal-poor regime of the bulge, the same phenomenon is observed as two sequences of RR Lyrae stars on the period-amplitude diagram (Lee & Jang 2016).

3. The required helium enhancement ($\Delta Y/\Delta Z$ = 6) for the second generation stars is naturally predicted by our chemical evolution models (Kim & Lee 2017).

4. The bright RC stars are enhanced in CN, which traces N, Na, & He! The ΔCN(bRC-fRC) is consistent with ΔCN(G2-G1) observed in GCs! (see poster by Hong, Lim, & Lee)

5. The observed spread in [Na/Fe] among bulge RGB stars is 2-3 times larger than that of the disk (bar) population, and is consistent with our chemical evolution models.

6. Our models can reproduce key observations: double RC = f ([Fe/H], b, l) (Lee+2015; Joo+2017)

7. Our models are not inconsistent with observed kinematics (see Lee+2015).

8. The claimed X-shaped structure from WISE residual map (Ness & Lang 2016) is most likely an artifact or exaggeration. Even if it is real, the stellar density in the faint X-shaped structure is way too low to be observed as the double RC (Han & Lee 2017).

9. The observed difference in I magnitude between the RR Lyrae stars and the RC (~0.55 mag) is consistent with our multiple population models.

10. There is also no evidence for the X-shaped structure from main sequence stars & Mira variables (Lopez-Corredoira 2016, 2017).

Summary & Implications

1. He-enhanced G2 can naturally explain the Oosterhoff dichotomy in the halo & the two populations of RR Lyraes in the bulge (Jang & Lee 2015; Lee & Jang 2016).

2. Double RC in MW bulge is another manifestation of He-enhanced multiple populations in metal-rich regime, and has nothing to do with an X-shaped structure (Lee+2015; Joo, Lee, Chung 2017).

3. This is supported by our chemical evolution models and CN observations.

4. MW has a composite bulge (bar + classical bulge).

5. Proto-GCs were the major building blocks in the classical bulge formation!

6. Early-type galaxies would be similarly prevailed by super-helium-rich population!
→ Na-enhanced gE's (van Dokkum & Conroy 2010) are explained w/o bottom heavy IMF (see Lee+2015): They are also CN-enhanced!! (e.g., Worthey 1998)

7. Gaia distances can provide a further test!

In order to understand galaxies and their formation, you need to first understand ***the amazing life of He-enhanced stars*** *in GCs!*