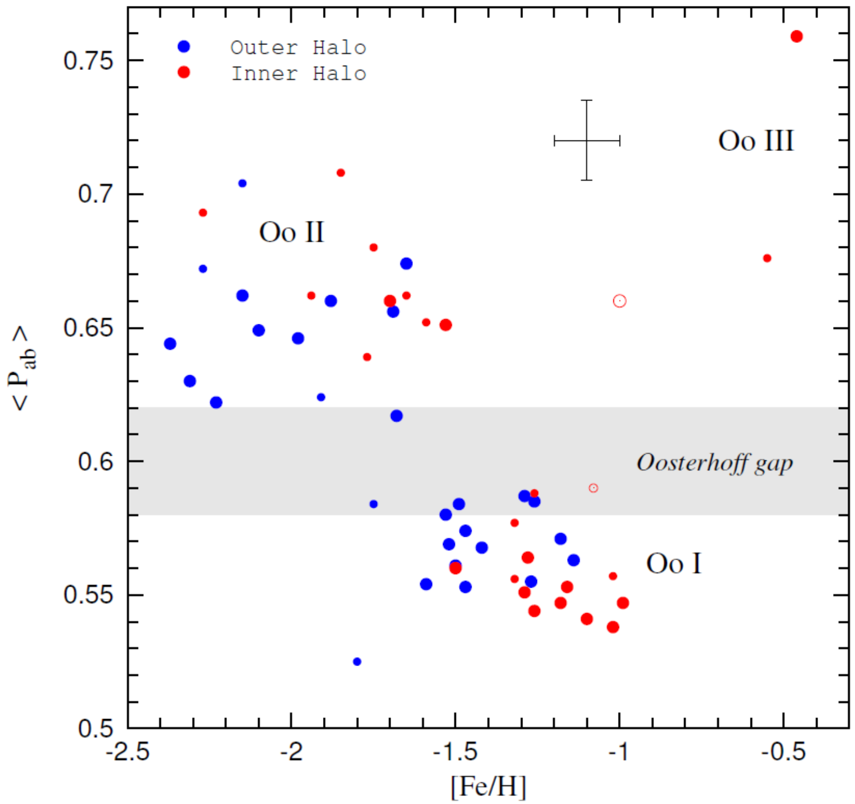
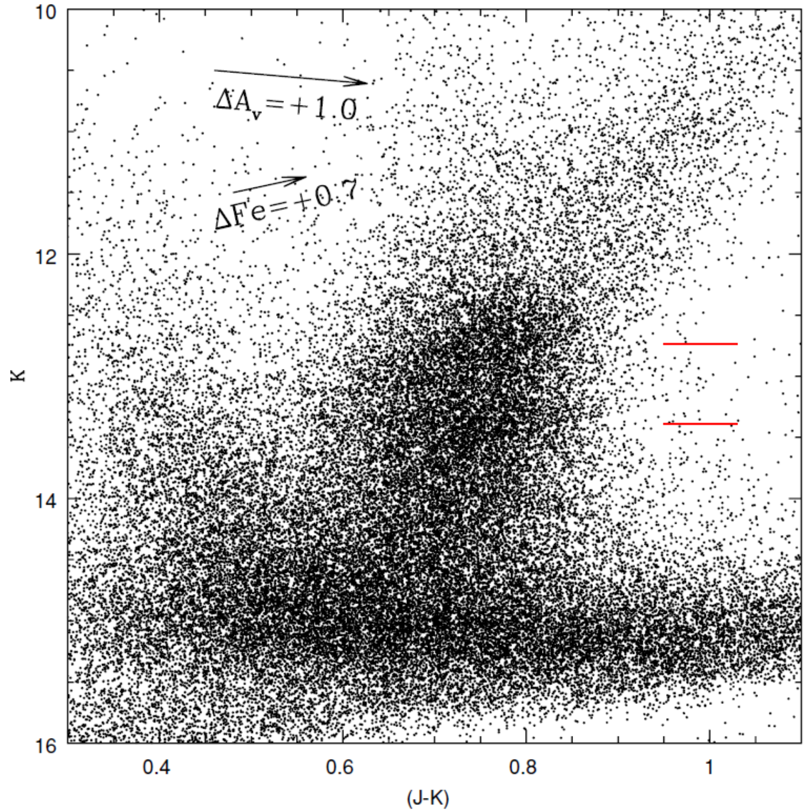
The Origin of the Oosterhoff Dichotomy & the Double Red Clump in the Halo & Bulge of the Milky Way



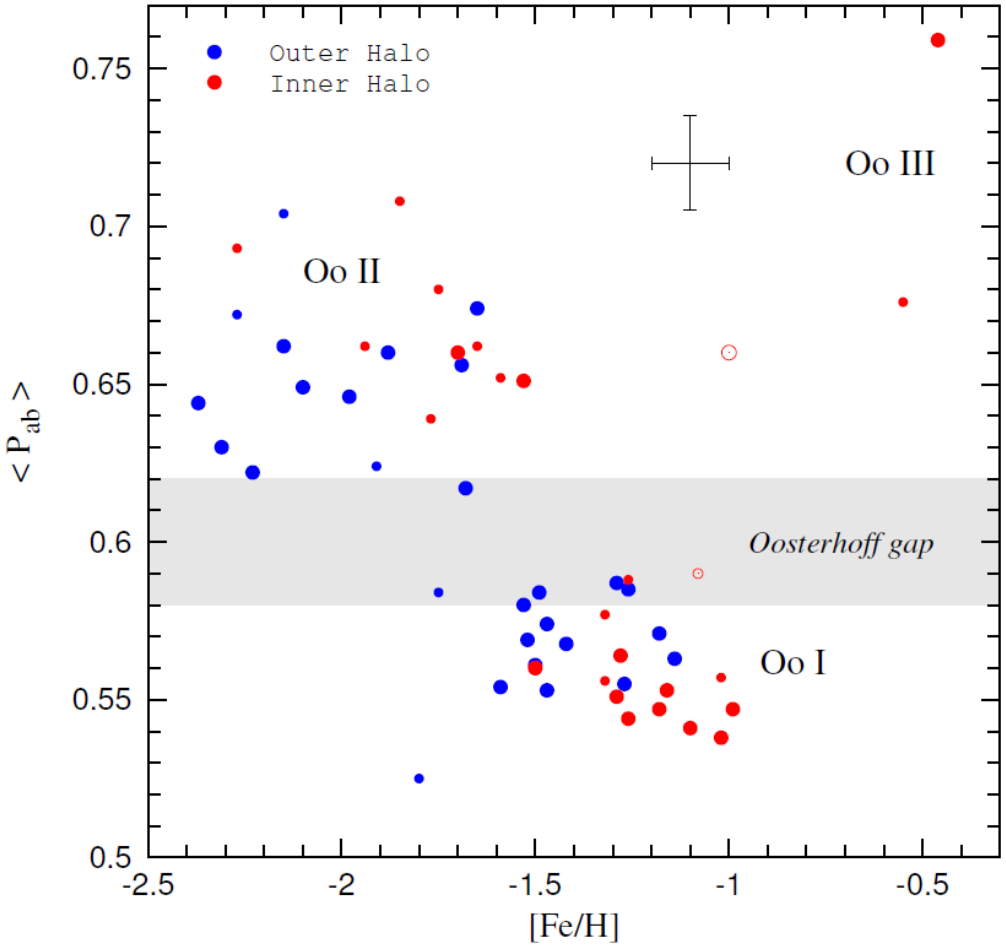


Young-Wook Lee, Sohee Jang, Seok-Joo Joo, & Chul Chung

Yonsei University, Seoul, South Korea

The Oosterhoff (1939) Period Groups

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



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 m odern astronomy!
(**~370 papers**, including Sandage 2010)

Pulsation theory (e.g., van Albada & Baker 1971):

P – Mean density relation, $P_{RR} = f(L, M, T_{eff})$

$$\log P_f = 0.84 \log L - 0.68 \log M - 3.48 \log T_{eff} + 11.497,$$

where P is in days and L and M are in solar units

Suggested origin for the Oosterhoff dichotomy (among ~370 papers)

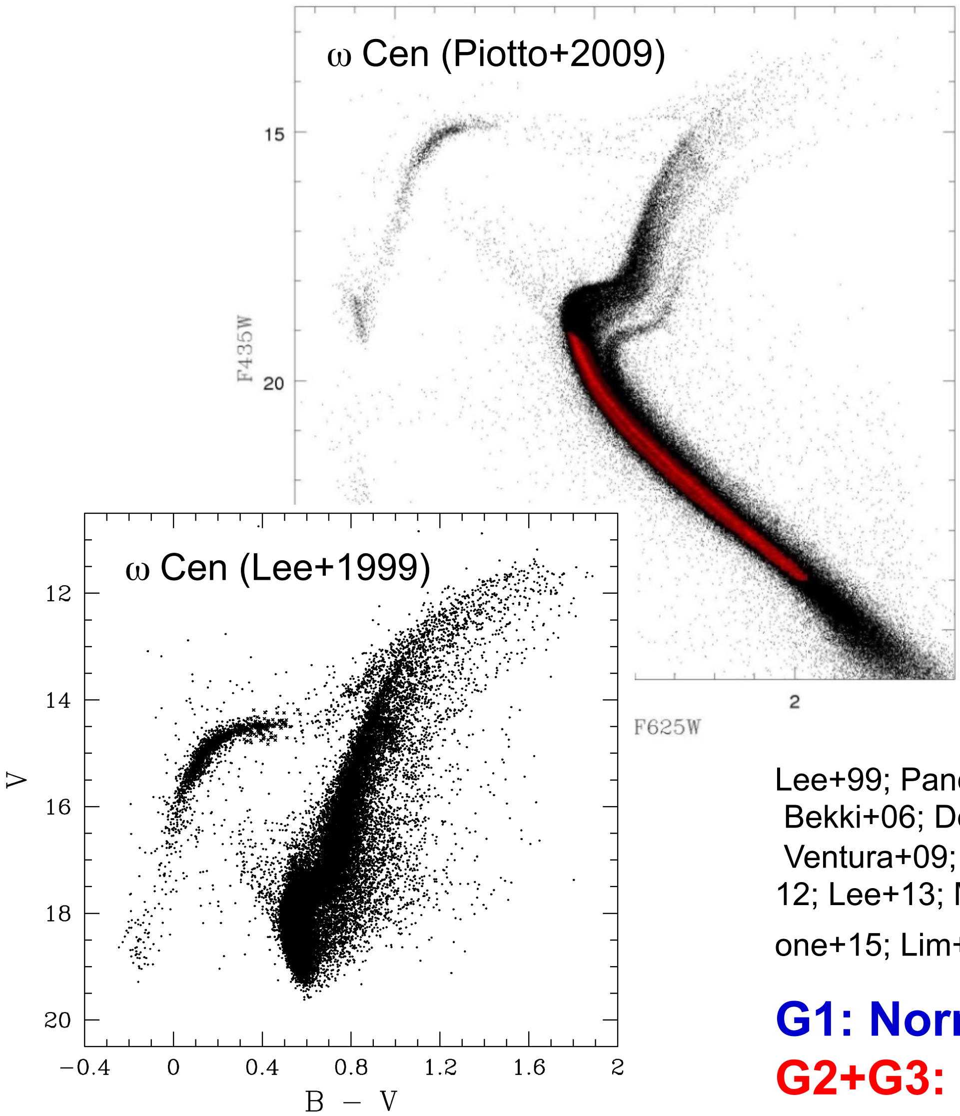
van Albada & Baker 1973: "Hysteresis effect" → T_{eff} difference

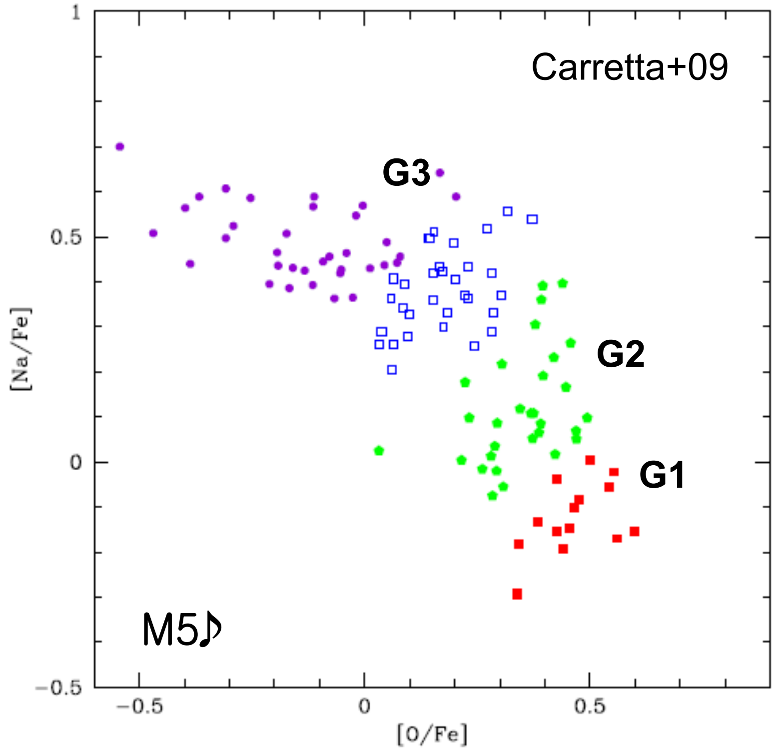
Sandage 1981: "P-shift" at fixed T_{eff} → L difference

Lee, Demarque, & Zinn 1990: L difference → Post-ZAHB evolution from blue HB

Yoon & Lee 2002: Metal-poor Oo II GCs were accreted from a satellite galaxy

Discovery of Multiple Stellar Populations in GCs





Lee+99; Pancino+00; Bedin+04; Norris 04; D'Antona+04; Lee+05; Piotto+05; Bekki+06; Decressin+08; D'Ercole+08; Renzini 08; Carretta+09; Ferraro+09; Ventura+09; Han+09; JWLee+09; Dalessandro+11; Gratton+12; Mucciarelli+12; Lee+13; Marino+14; Da Costa+14; Yong+14; Piotto+15; Nardiello+15; Milone+15; Lim+15; Han+15… **300+ papers!**

G1: Normal He

G2+G3: He, Na, N.. (Fe, Ca..) enriched

by IMAGB, FRMS, (SNe)

Synthetic HB models with multiple populations

(Jang, Lee+2014; Jang & Lee 2015; Lee+2015)

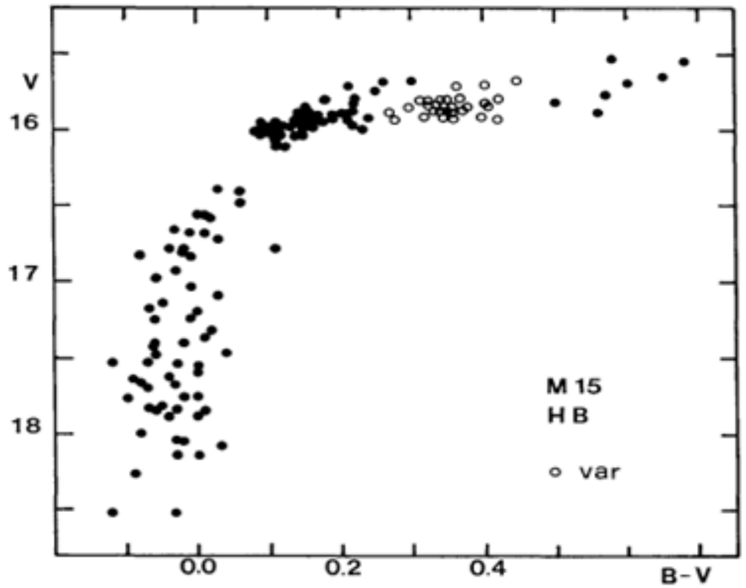
- **Stellar Libraries & Synthetic HB**
  - Lee, Demarque, & Zinn 1990, 94; **Joo & Lee 2013**
  - Yonsei-Yale (Y^2) isochrones & HB evolutionary tracks with He & CNO enhancements

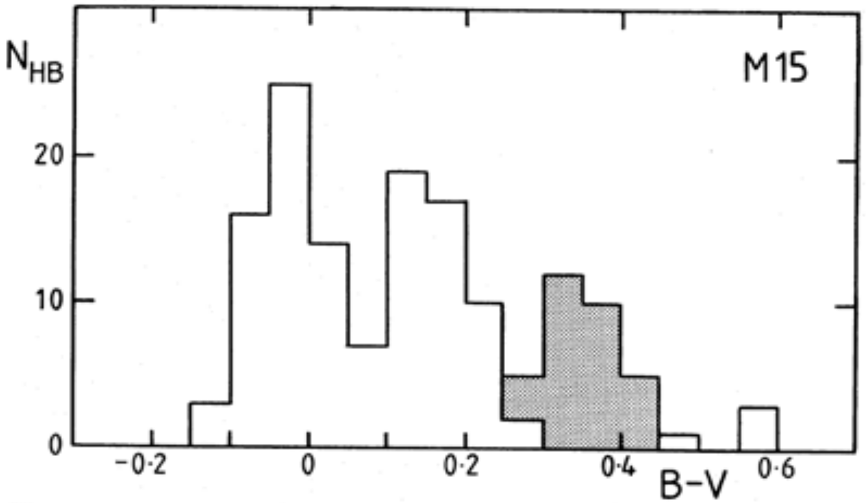
[Fe/H]	-3.51, -2.51, -1.90, -1.51, -0.90, -0.65, -0.49, -0.17, 0.17, 0.39, 0.56
[α/Fe]	0.0, 0.3, 0.6
Y	0.23, 0.28, 0.33, 0.38, 0.43
[N/Fe] ([CNO/Fe])	0.0, 0.8, 1.6 (0.21, 0.31, 0.67)

- **Mass-Loss on RGB**
  - Reimers' mass-loss parameter η calibrated to the HB morphologies of inner halo GCs ($\eta \sim 0.4$)

- **Stellar Pulsation**
  - The blue edge of the instability strip : Tuggle & Iben 1972; Bono et al. 1995
  - P_{ab} and P_c : van Albada & Baker 1971; Bono et al. 1997
  - Transition T_{eff} between c and ab type RRL: Sandage's (2006) empirical formula

Three distinct subgroups on the HB of M15





M15 (Oo II)

Buonanno+1985; Bingham+1984

3 distinct subgroups on HB:
RR Lyraes, blue HB, & blue tail (extr eme BHB).

Assume that they were originated fr om 3 distinct subpopulations (G1, G 2, & G3) in this GC.

Other Oo II GCs, NGC 5466 & 4590, also show gaps between RR Lyraes & blue HB.

Placements of G1, G2, & G3 on the HB of M15

G1: Normal Blue HB ([Fe/H] = -2.2, t = 12.5 Gyr)

G2: RR Lyraes (somewhat enhanced in Helium & CNO, ~ 1 Gyr Y ounger)

G3: "Blue tail" or Extreme Blue HB (Super-He-rich)

Some evidence for He and CNO enhancements in G2:
Theory (IMAGB/FRMS): Fenner+2004; Ventura & D'Antona 2009; Karaka s 2010; Decressin+2009
Observations: Sneden+1997; Cohen et al. 2005; Alves-Brito+2012; Marino+ 2012, 2014; Gratton+2011, 2012, 2013; Yong+2014
→ Need more observations for CNO sum

Both helium and CNO enhancements play a role in increasing the period of RR Lyrae variables!

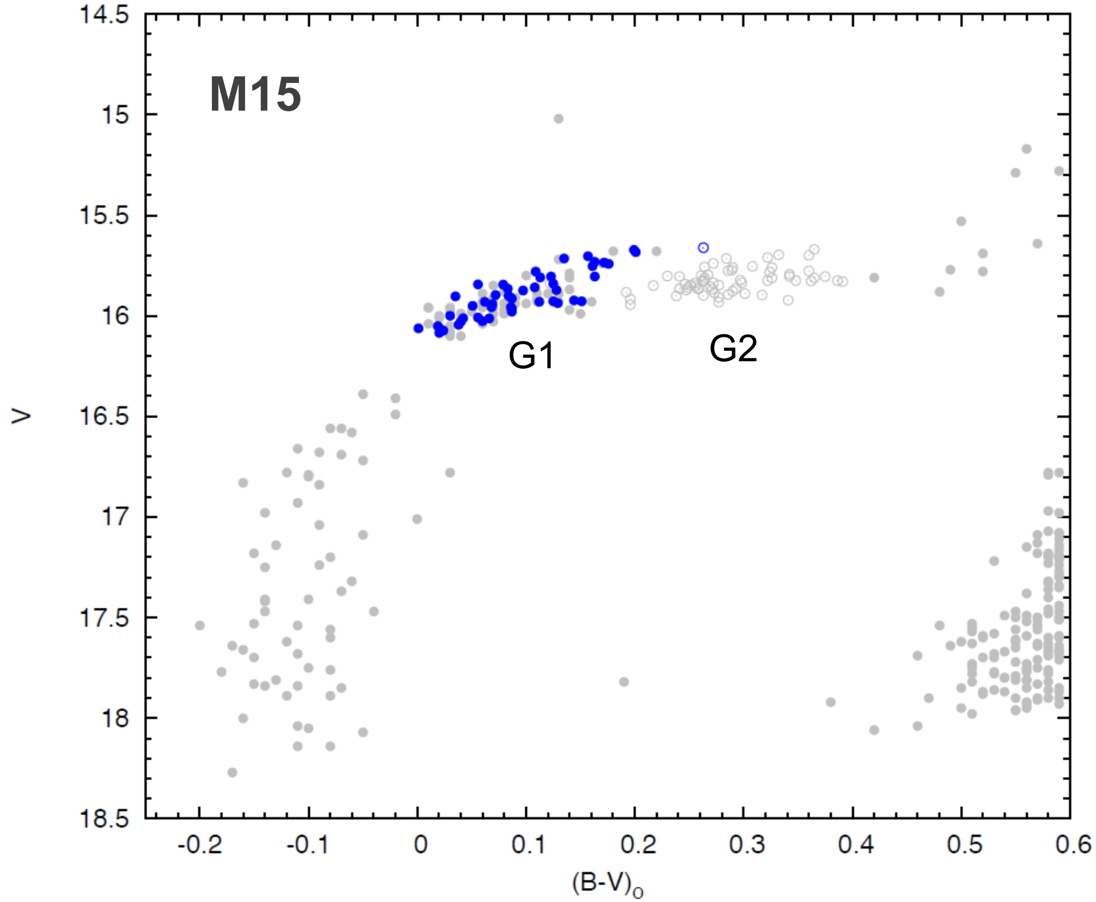
Effects of Y, Age, and Z_{CNO} on the HB of G2

[Fe/H] = -2.2
t = 12.5 Gyr
Y = 0.23

ΔY = + 0.015

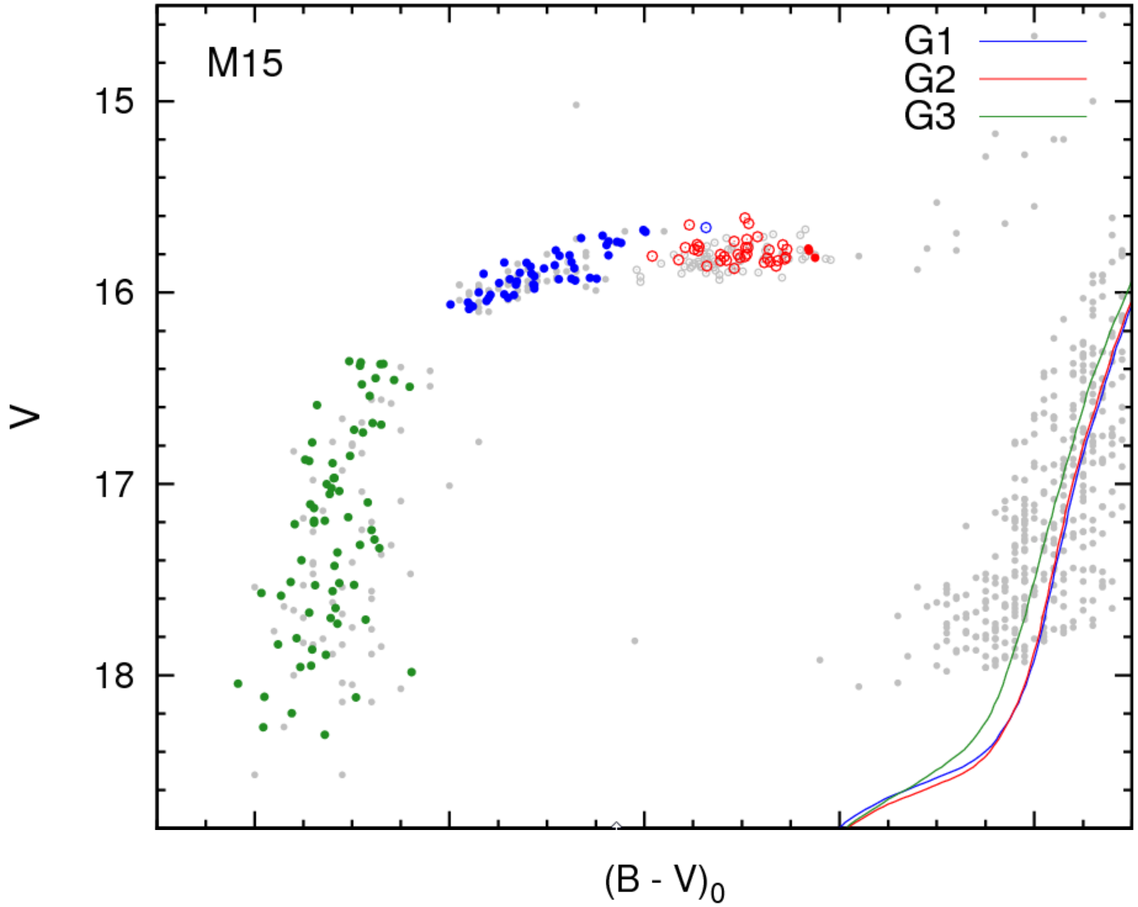
ΔY = + 0.015
Δt = - 1.1 Gyr

ΔY = + 0.015
Δt = - 1.1 Gyr
ΔZ_{CNO} = + 0.00026



Data: Buonanno+1985

Open Circles: RR Lyraes

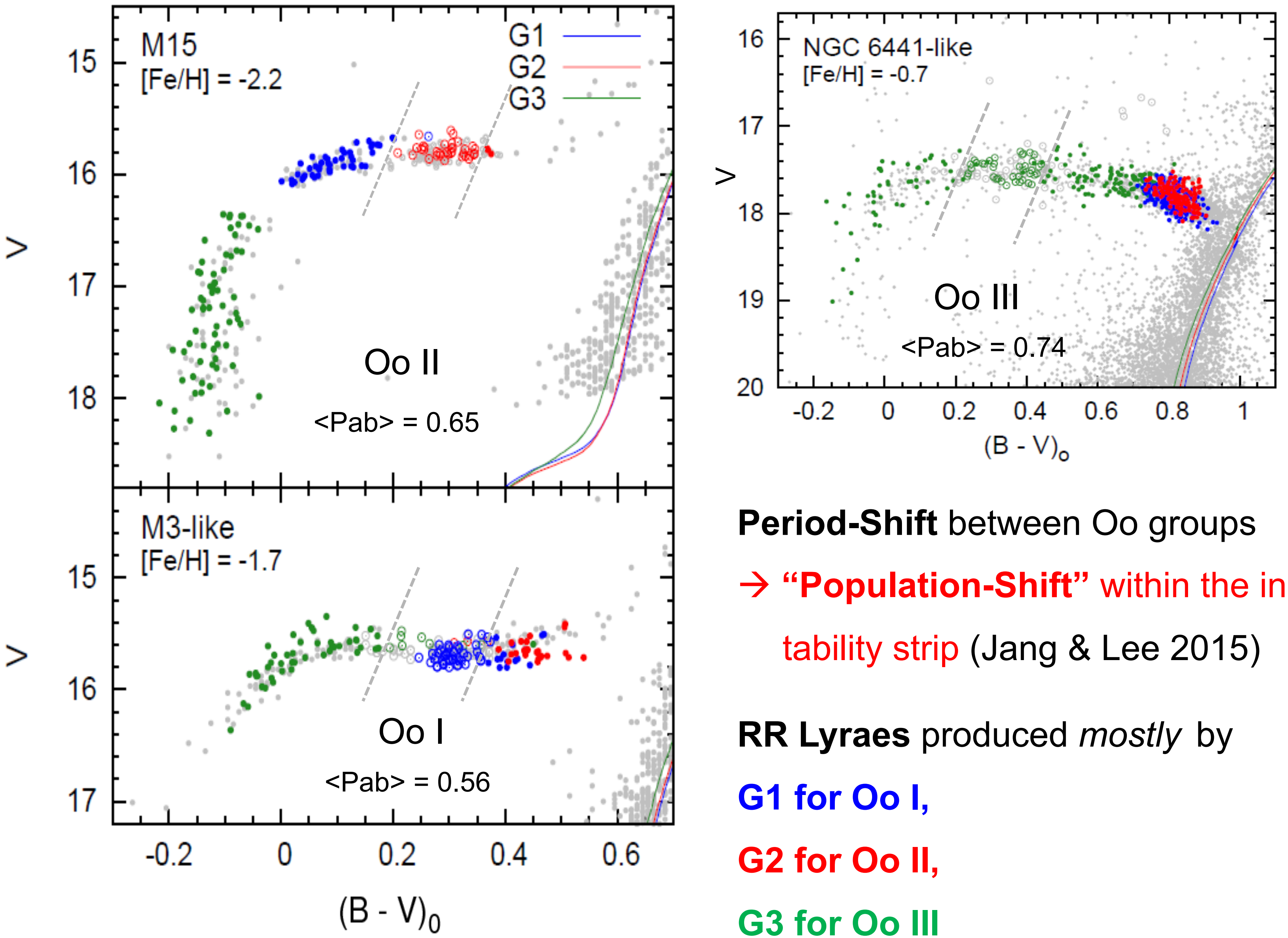


Jang, Lee+2014

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

Population	[Fe/H][a]	ΔZ_{CNO}	Y	Age (Gyr)	Mass Loss[b] ($M_\odot$)	$\langle M_{HB}\rangle$[c] ($M_\odot$)	Fraction	$\Delta\log P'$[d]	$\Delta\langle P_{ab}\rangle$ (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	0.327 ± 0.01	11.3 ± 0.2	0.129	0.589	0.42	-	-

[a] $[\alpha/Fe] = 0.3$ for G1 & G2, 0.5 for G3.



Period-Shift between Oo groups

→ **“Population-Shift”** within the ins tability strip (Jang & Lee 2015)

RR Lyraes produced *mostly* by

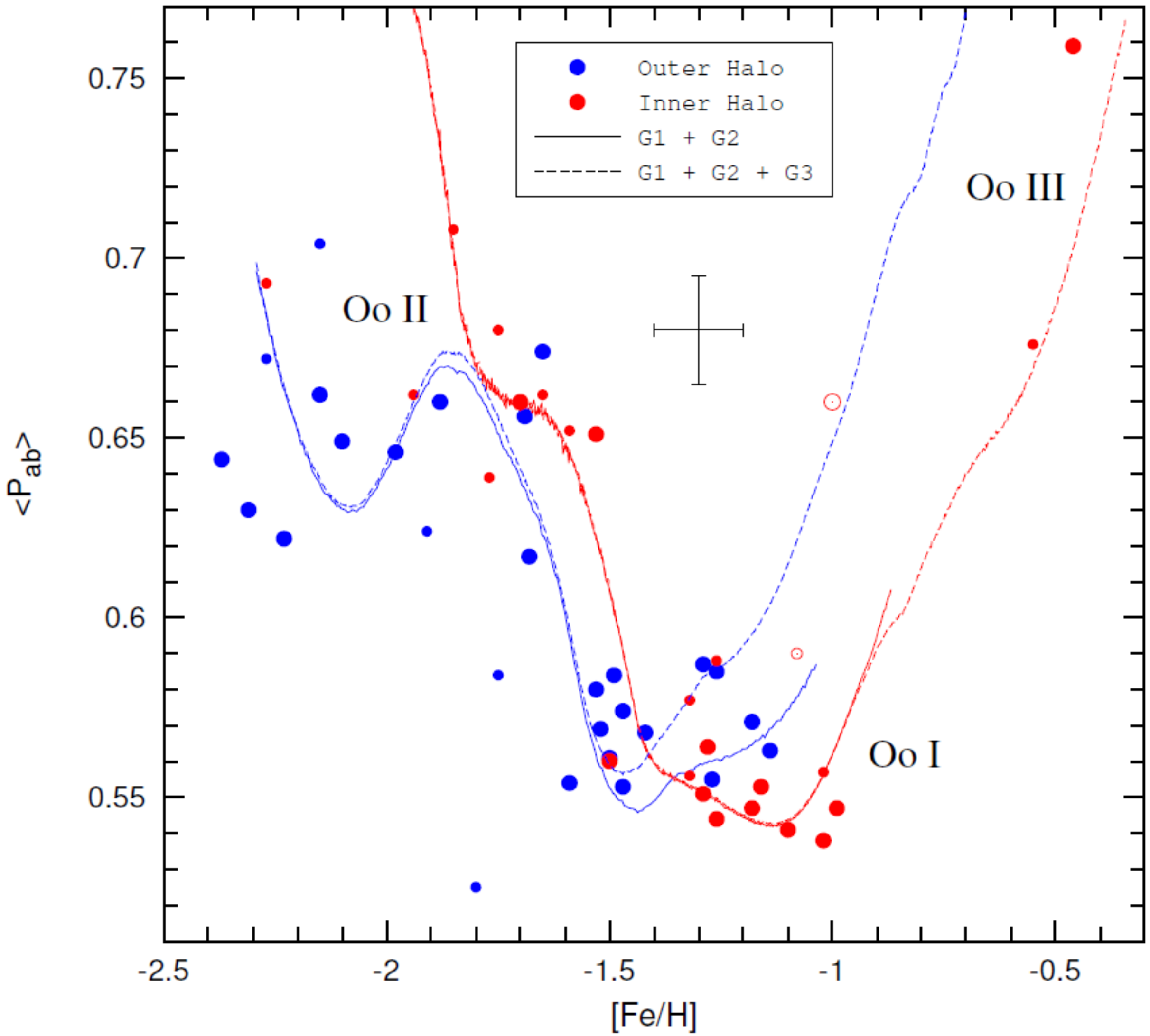
G1 for Oo I,

G2 for Oo II,

G3 for Oo III

When our models are extended to all metallicity regimes…

The Oosterhoff dichotomy reproduced!



Outer Halo (R > 8kpc):

Δt (G1-G2) = 1.4 Gyr

Inner Halo (R < 8kpc):

Δt (G1-G2) = 0.5 Gyr

Δt (Inner-Outer) = 1.2 Gyr

ΔY (G2-G1) = 0.01

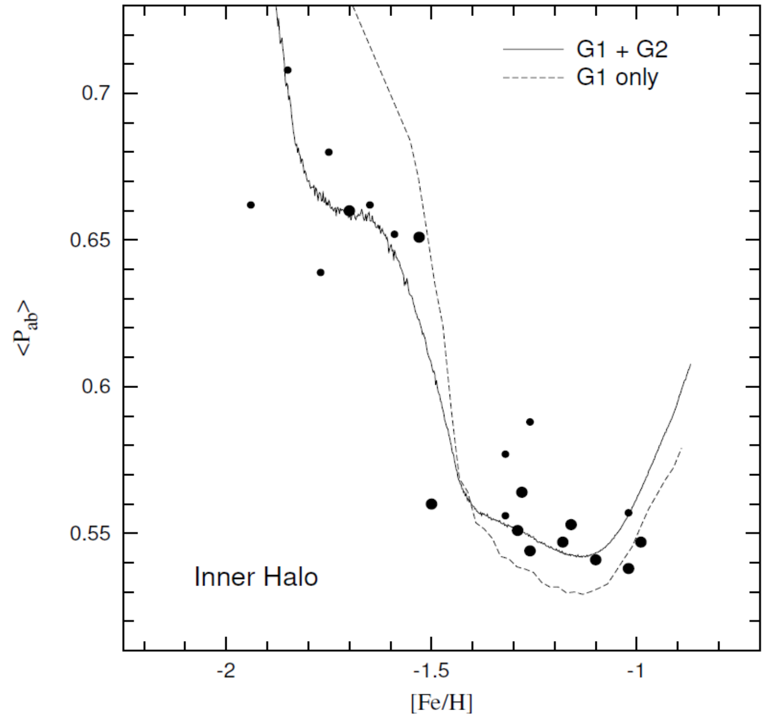
ΔZ_{CNO} (G2-G1) = 0.00035

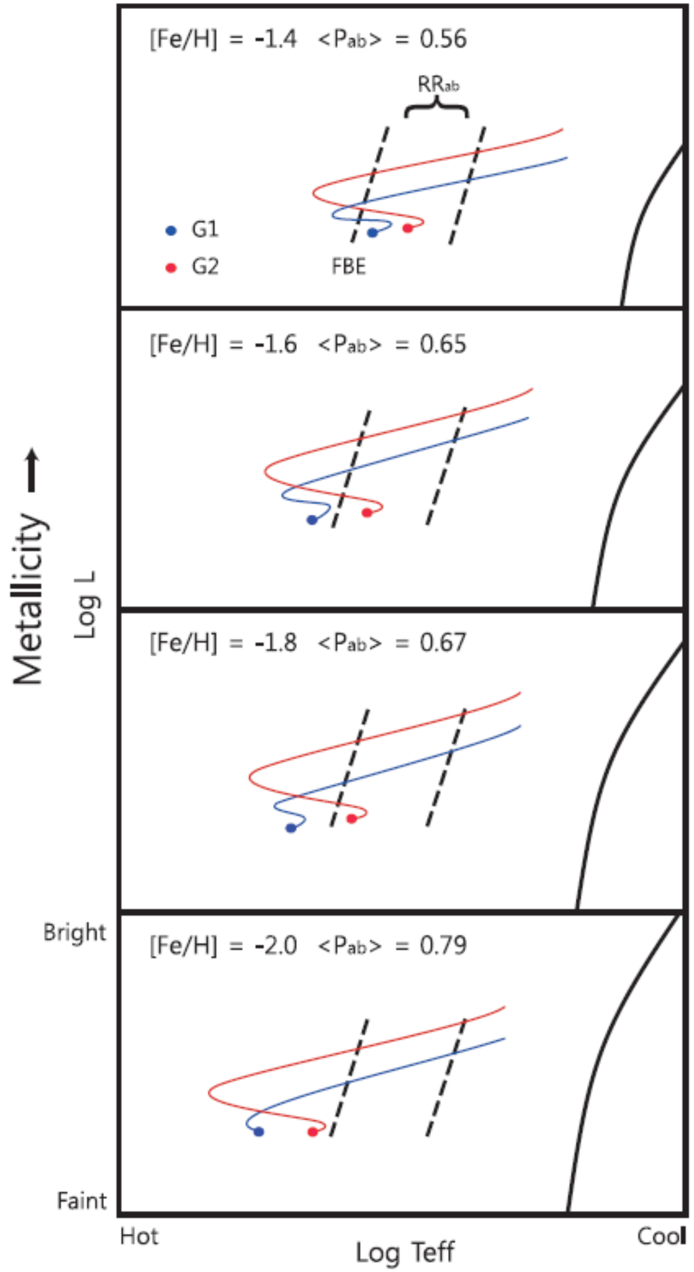
Post-ZAHB evolution effect (Lee+ 90) is still important in the Inner H alo

Jang & Lee 2015

"Two-stage Jump"

in <P_{ab}> for the Inner Halo GCs





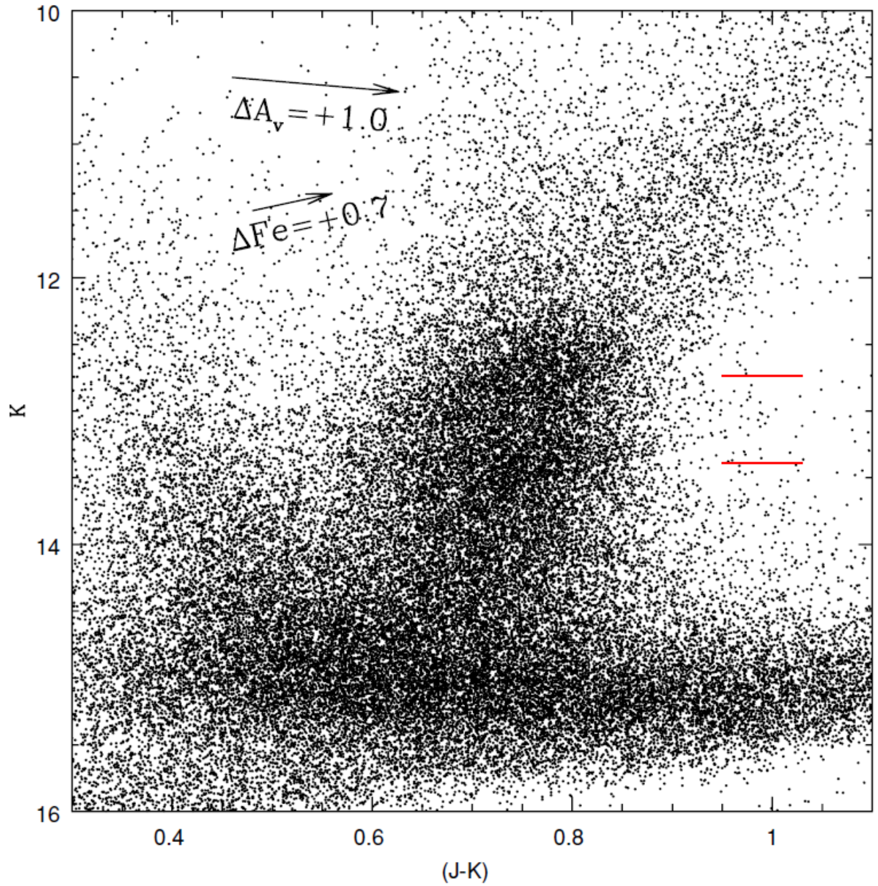
With decreasing metallicity, contribution from G1 & G2 ZA HBs decrease sequentially

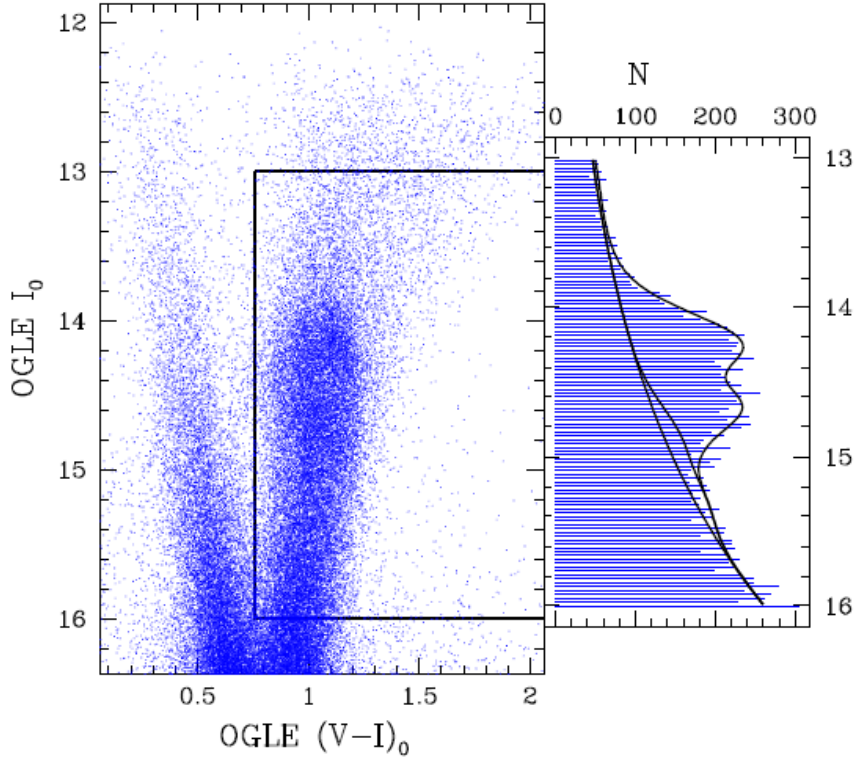
→ Two-stage jump in <Pab> (cf. Lee & Zinn 90)

"Population-shift" effect when Δt (G1-G2) is small

Jang & Lee 2015

Double Red Clump (RC) in the MW Bulge





Discovery of Two RCs (|b| > 5.5):
McWilliam & Zocalli 2010; Nataf et al. 20
10; Saito et al. 2011

Double RC in MW Bulge: Key Observations

(1) ΔK = ΔI = ~0.5 mag

(2) Two RCs have ~identical mean colors

(3) Double RC = *f([Fe/H])*

Only evident among metal-rich stars, while metal-poor popula tions show only faint RC

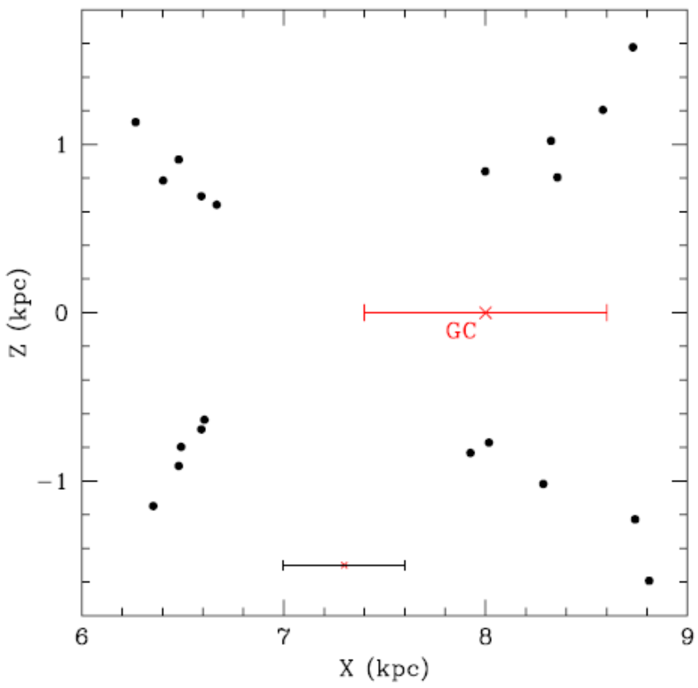
(4) Double RC = *f(b, l)*

Separation vanishes at low latitude,

relative strength of two RCs changes with longitude

McWilliam & Zoccali 2010; Nataf et al. 2010, 2015; Saito et al. 2012; Ness et al. 2012, 2013; Uttenthaler et al. 2012; Rojas-Arriagada et al. 2014

The X-Shaped Bulge in the Milky Way



X-Shaped Bulge from bar instability:

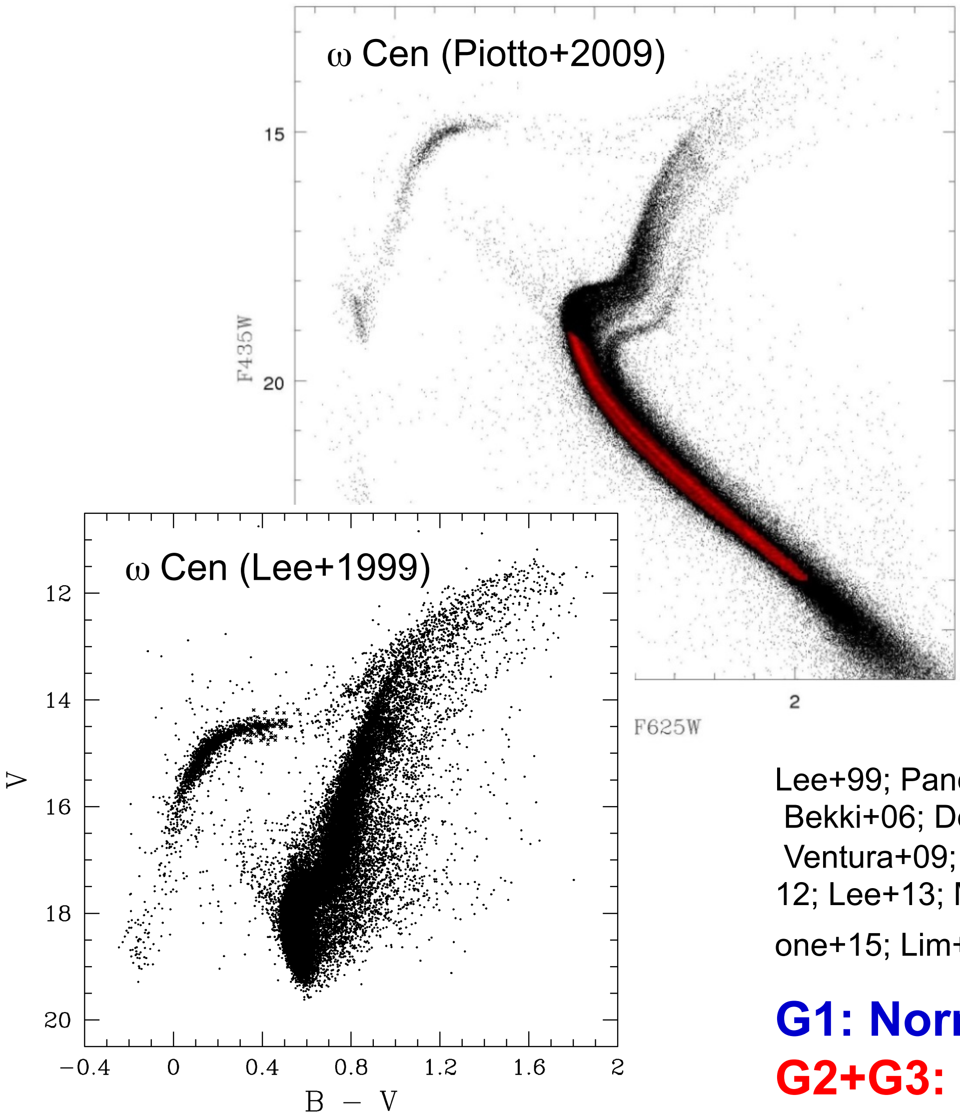
bright RC (foreground) + faint RC (background)

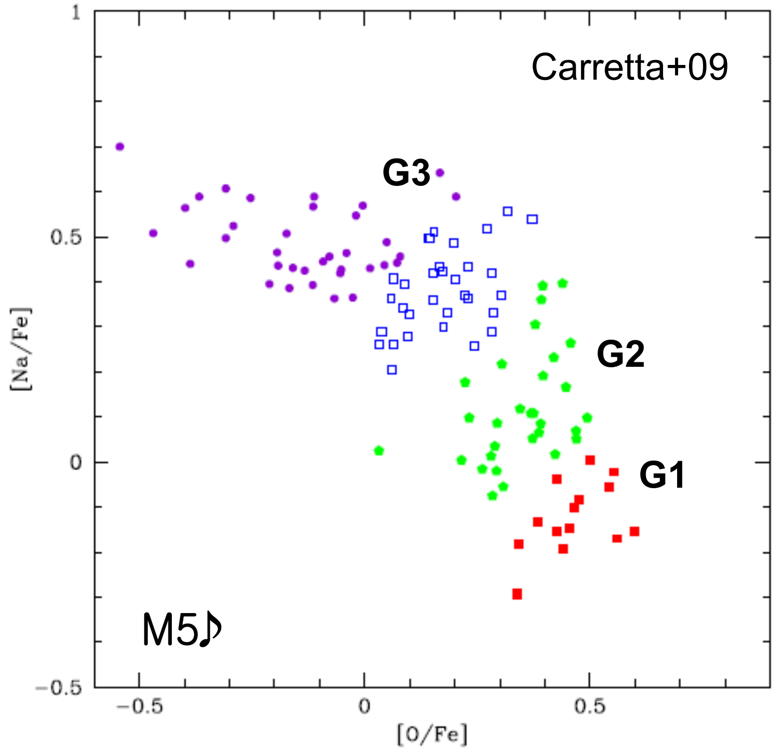
McWilliam & Zocalli 2010; Nataf+2010, 2015; Saito+2012; Ness, Freeman+2012, 2013; Li & Shen 2012; Uttenthaler+2012; Wegg & Gerhard 2013; Vasquez+2013; Rojas-Arriagada+2014; Gonzalez+2015… **100+ papers**

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

But this is most likely an artifact!

Discovery of Multiple Stellar Populations in GCs





Lee+99; Pancino+00; Bedin+04; Norris 04; D'Antona+04; Lee+05; Piotto+05; Bekki+06; Decressin+08; D'Ercole+08; Renzini 08; Carretta+09; Ferraro+09; Ventura+09; Han+09; JWLee+09; Dalessandro+11; Gratton+12; Mucciarelli+12; Lee+13; Marino+14; Da Costa+14; Yong+14; Piotto+15; Nardiello+15; Milone+15; Lim+15; Han+15… **300+ papers!**

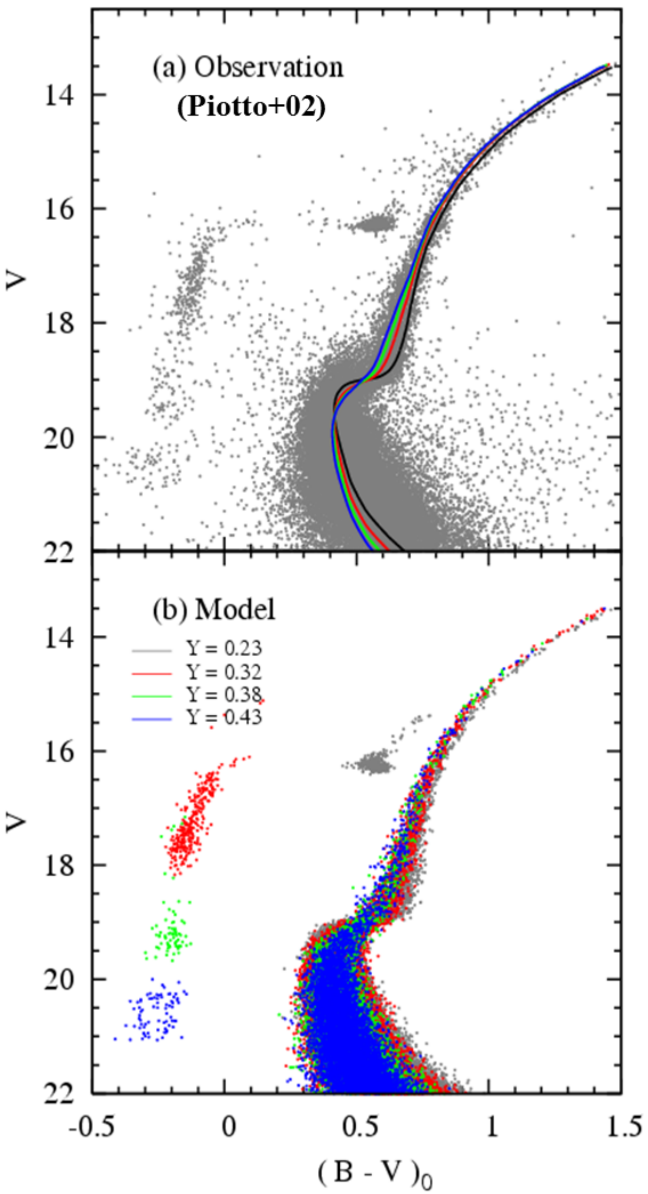
G1: Normal He

G2+G3: He, Na, N.. (Fe, Ca..) enriched

by IMAGB, FRMS, (SNe)

For metal-poor GCs,

Super-He-rich subpopulations are on the bluer HB



NGC 2808

Lee et al. 2005

Models & Spectroscopy:

Lee+94; D'Antona & Caloi 04, 08; Lee+05; Cassisi+09; Gratton+11, 12, 13; Chung+11; Dalessandro+11; Joo & Lee 13; Kunder+13; Jang+14; Marino+14; Jang & Lee 15

But in metal-rich system, they are at brighter RC!

Hint from Terzan 5: A metal-rich bulge GC

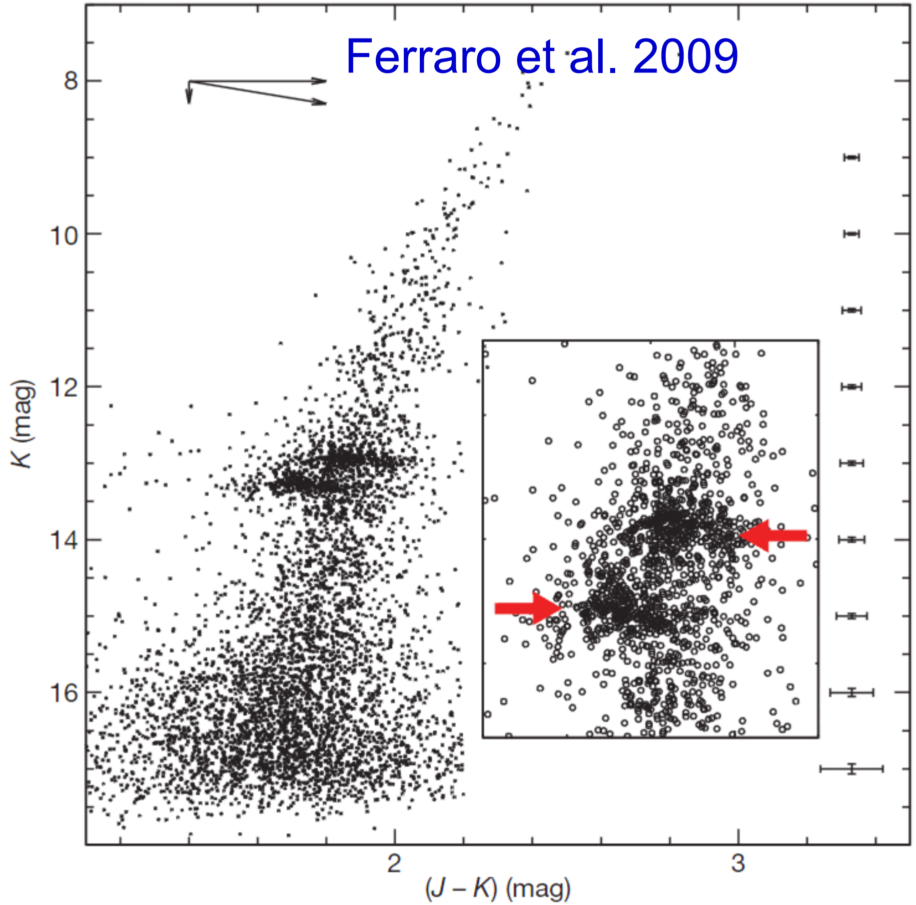
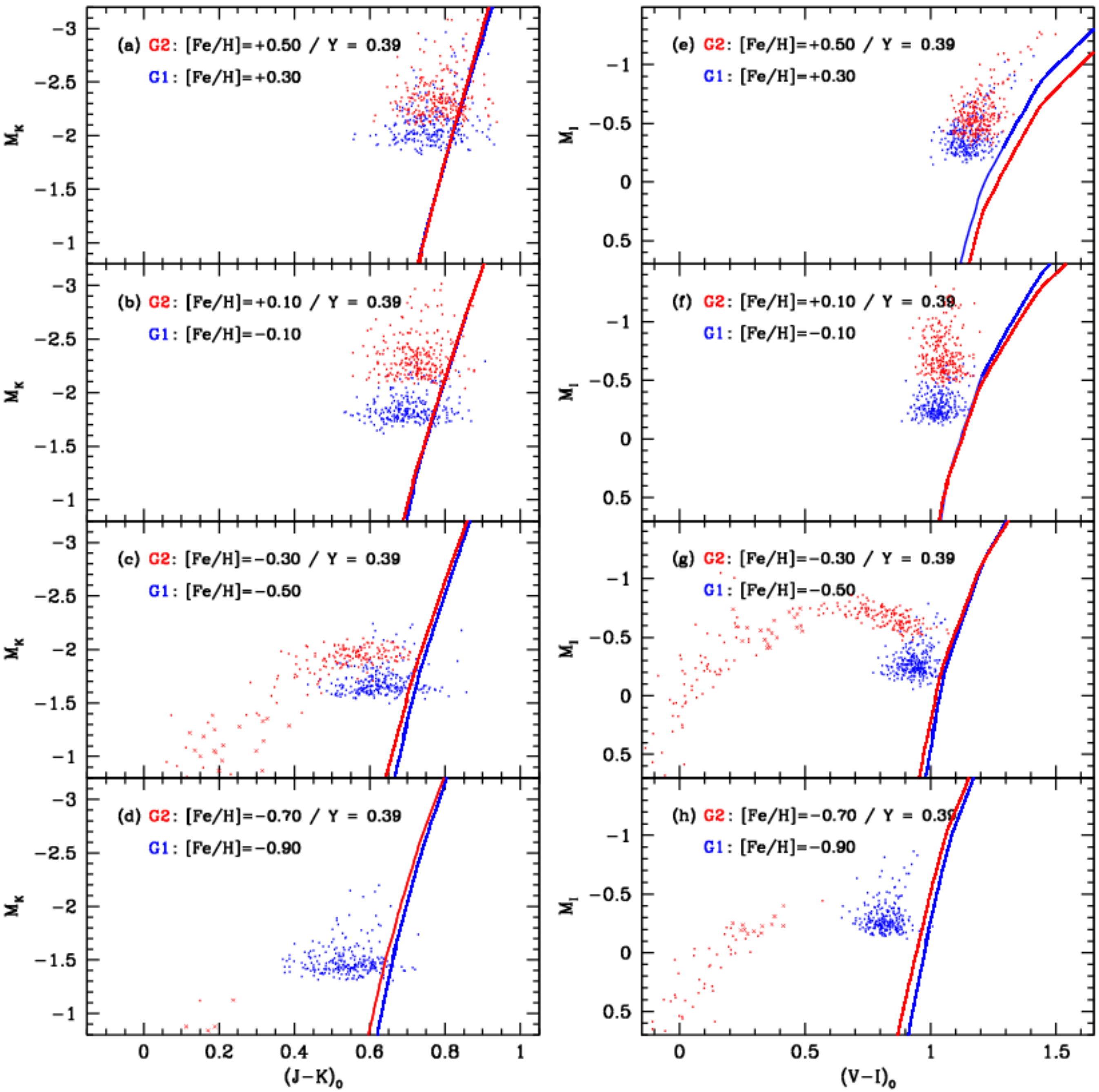


Figure 2 | The two horizontal branch clumps of Terzan 5. Main panel, MAD

Metal-rich counterpart of ω Cen

→ Brighter RC is either 6 Gyr younger (Ferraro+2009) or super-He-rich (D'Antona+2010; Lee+2015)

→ Very analogous to the double RC in bulge!
But dismissed because of the color difference… (McWilliam & Zocalli 2010; Nataf et al. 2010)



Multiple Population Models for the Double RC in Bulge

Synthetic HB models using Y^2 evolutionary tracks

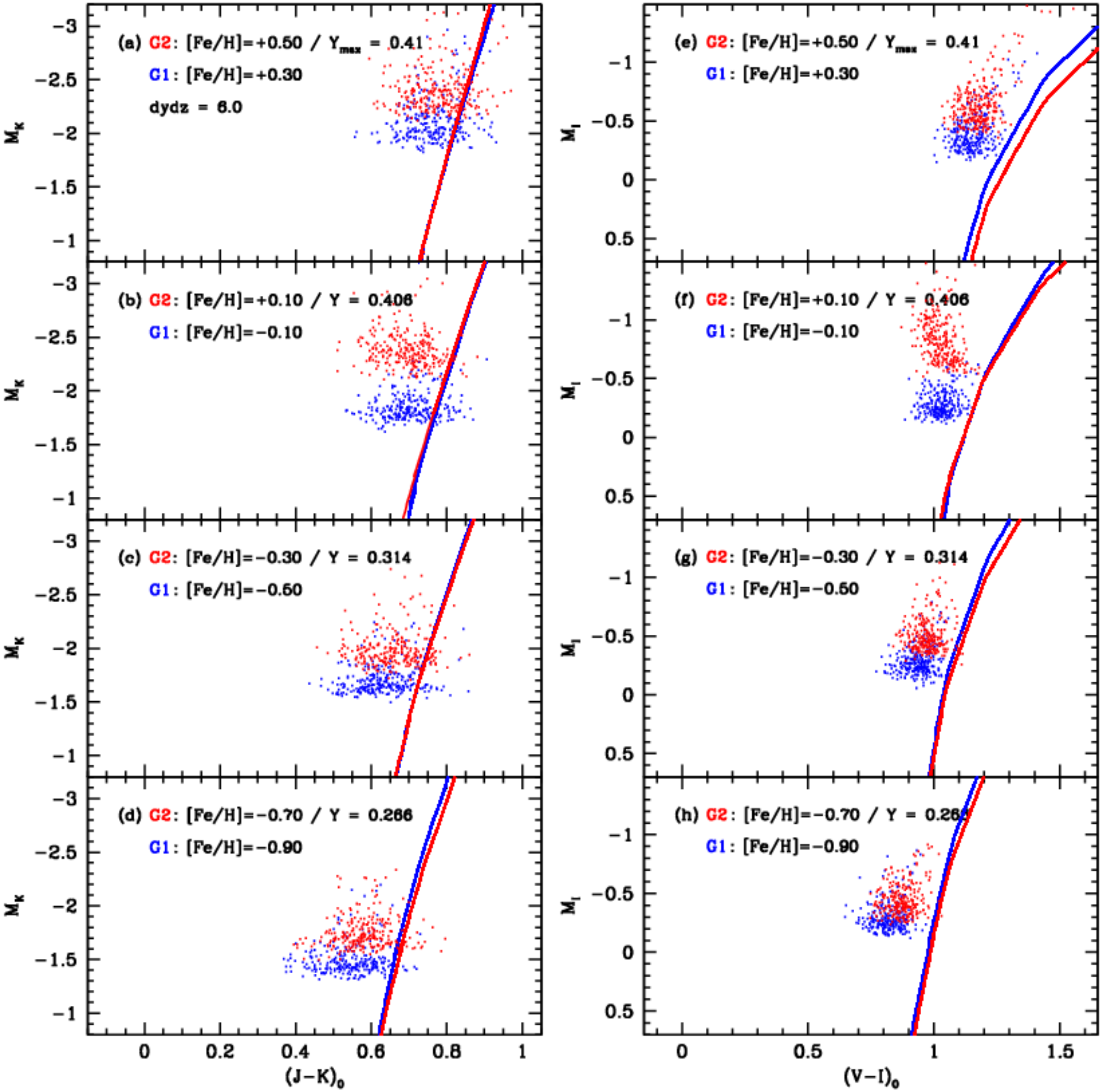
G1: normal-He
$\Delta Y/\Delta Z = 2$, 12 Gyr

G2: super-He-rich
Y = 0.39, 10 Gyr

Δ[Fe/H] = 0.2 dex

Explains metallicity dependence!

Lee, Joo & Chung 2015



Multiple Population Models for the Double RC in Bulge

G1: normal-He
$\Delta Y/\Delta Z$ = 2, 12 Gyr

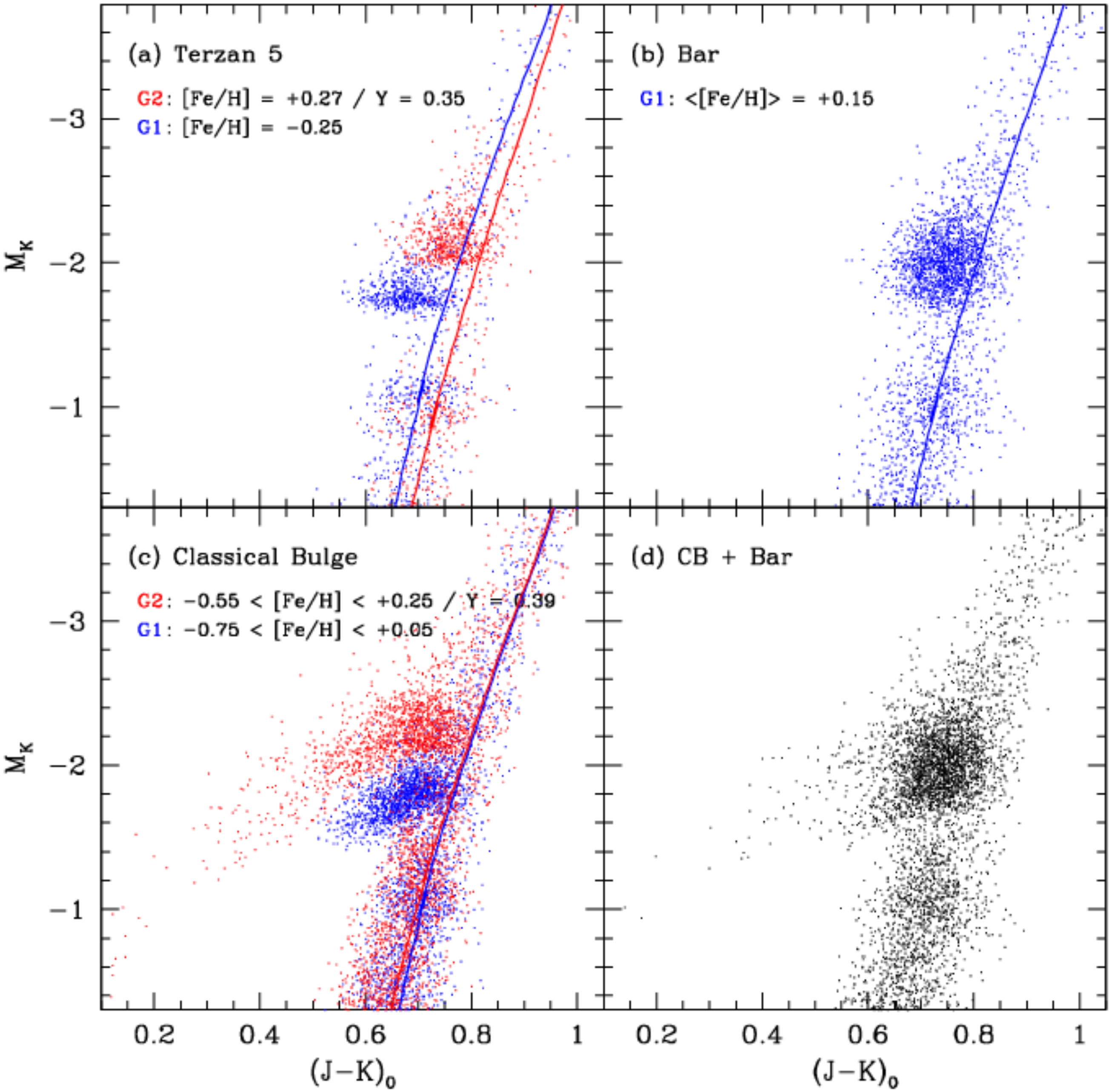
G2: super-He-rich
$\Delta Y/\Delta Z$ = 6, 10 Gyr
(Y_{Max} = 0.41)

Δ[Fe/H] = 0.2 dex

Explains metallicity dependence!

Joo, Lee+, in prep.

Multiple Population Models for the Doub le RC in Bulge



G1: normal-He
$\Delta Y/\Delta Z = 2$

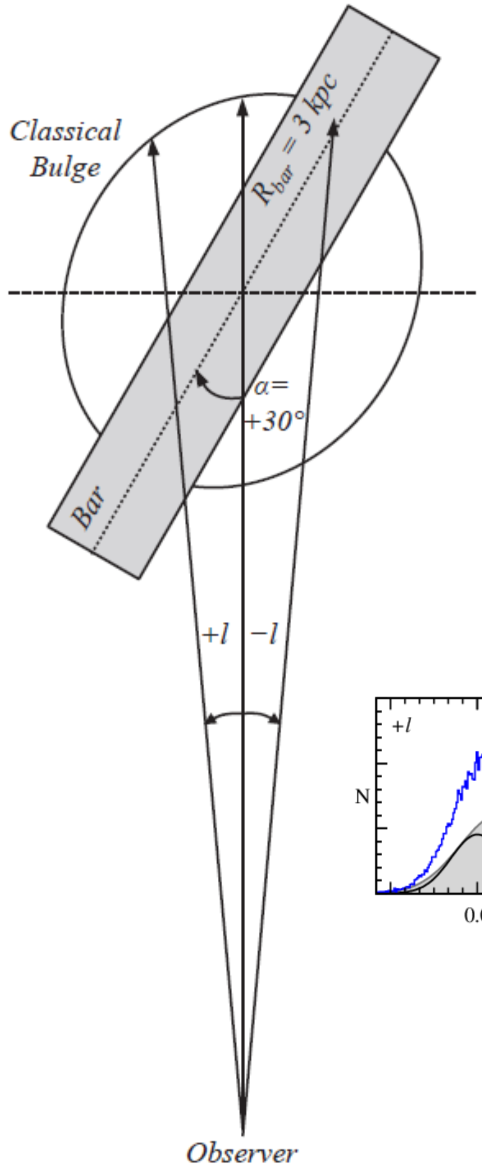
G2: super-He-rich
Y = 0.39

→ At solar [Fe/H], $\Delta Y/\Delta Z$ = 6
(by AGB+FRMS+SNe)

→ *Could form ubiquitous ly in metal-rich syste m!*

→ *Chemical evolution m odel required*

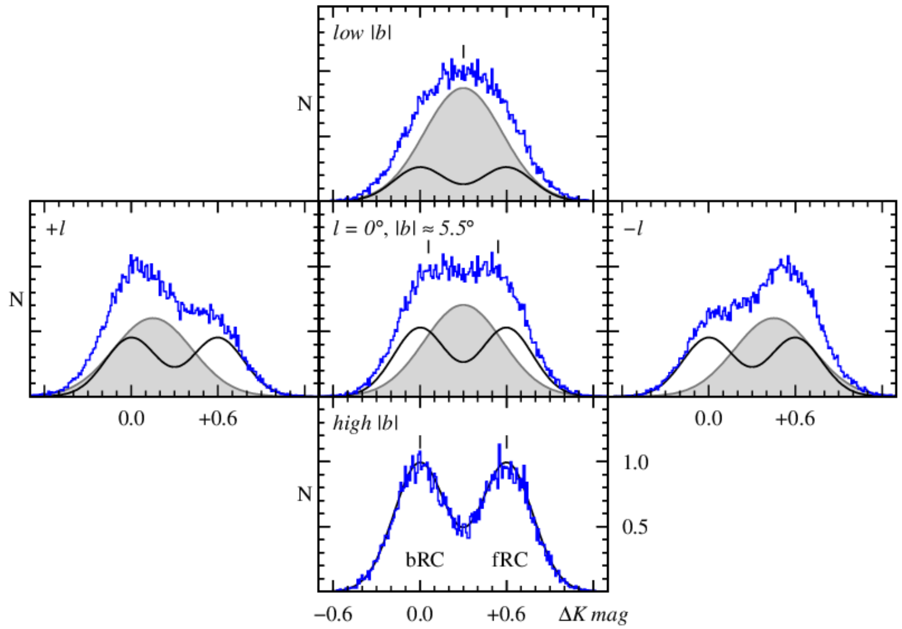
Lee, Joo & Chung 2015



Composite Bulge:

Tilted Bar embedded in a Classical Bulge (CB)

(Babusiaux et al. 2010; Hill et al. 2011; Erwin et al. 2014; Rojas-Arriagada et al. 2014, Zoccali et al. 2014; Saha 2015)



Double RC = *f (b, l)*

Latitude dependence
→ Bar/CB = *f(b)*

Longitude dependence
→ Tilted Bar embedded i n CB

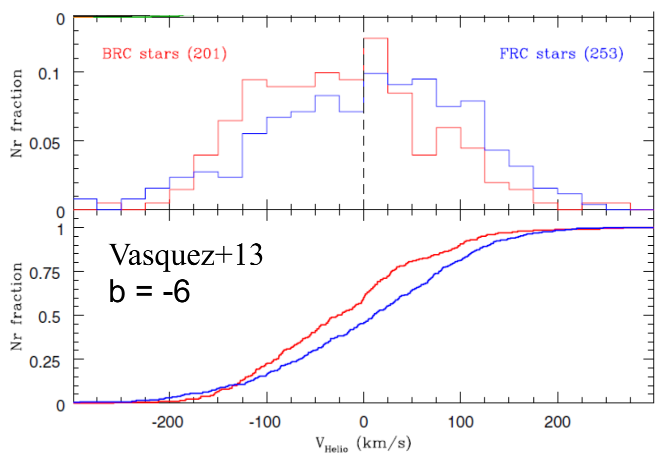
Bar: monomodal in gray
CB: bimodal
Bar+CB: blue

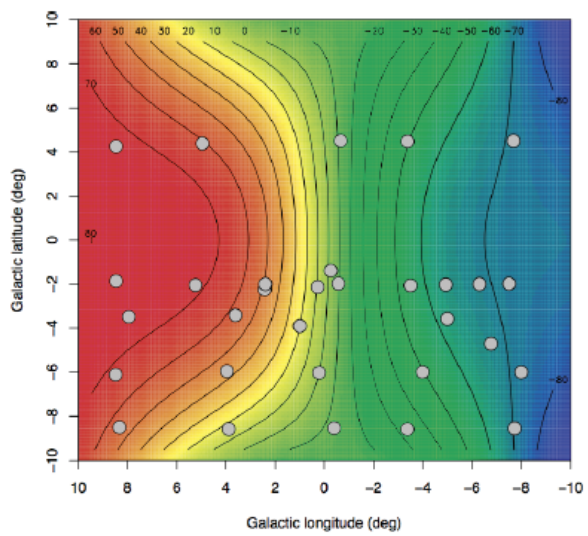
Observed kinematics are not inconsistent with our scenario!

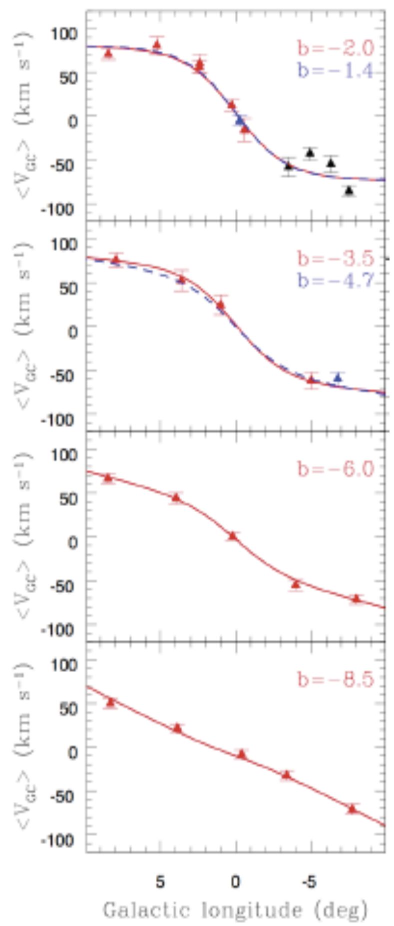
- **Cylindrical rotation at |b| < 6** (Ness+13; Zoccali+14): *low |b| is dominated by bar, CB could have absorbed angular mom entum from bar* (Saha+15; Zoccali+14)

- **Some ΔVr (bRC – fRC) at b = -6** (Vasquez+13): *Bar + CB at low |b|, & bar is in streaming motion*

- **No ΔVr (bRC – fRC) at b = -8, -10** (De Propris+11; Uttenth aler+12; Rojas-Arriagada+14): *Consistent with our CB dominated scenario at high |b|*



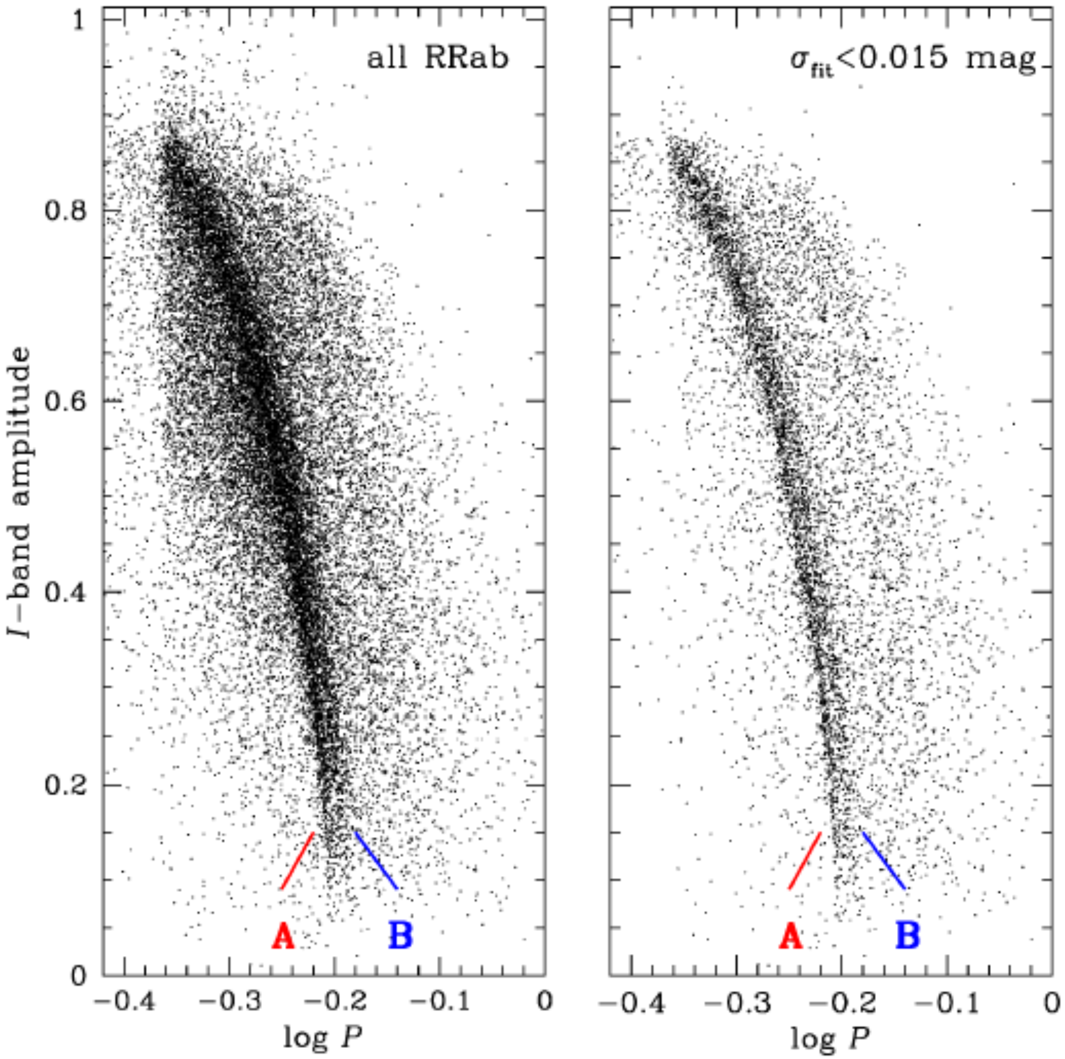




At metal-poor regime, our models can also reproduce…

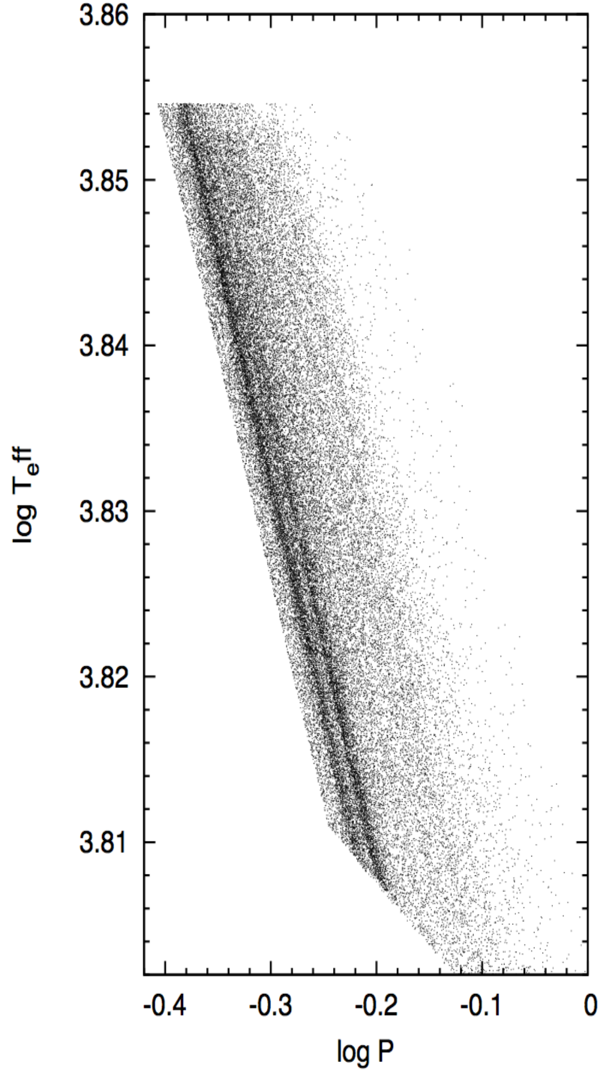
Two populations of RR Lyrae variables in the bulge

(Pietrukowicz et al. 2014)



Our model

(Lee & Jang, in prep.)

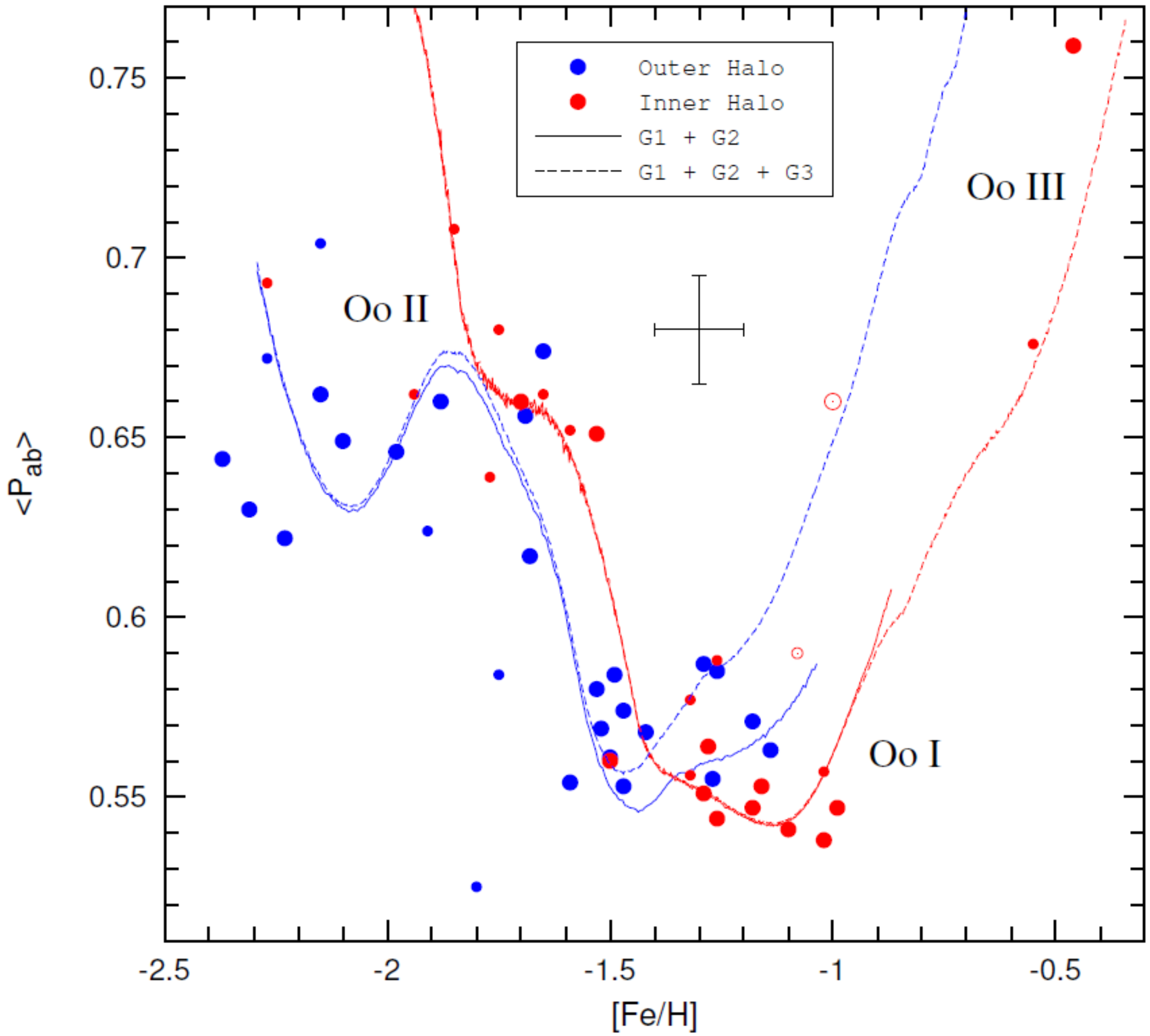


<[Fe/H]> ~ -1.0

ΔY (G2-G1) ~ 0.015

Multiple population models can also reproduce…

The Oosterhoff dichotomy: 76 year old problem



Oosterhoff Dichotomy:

"Population-Shift" within the instability strip

RR Lyraes from

G1 for Oo I,

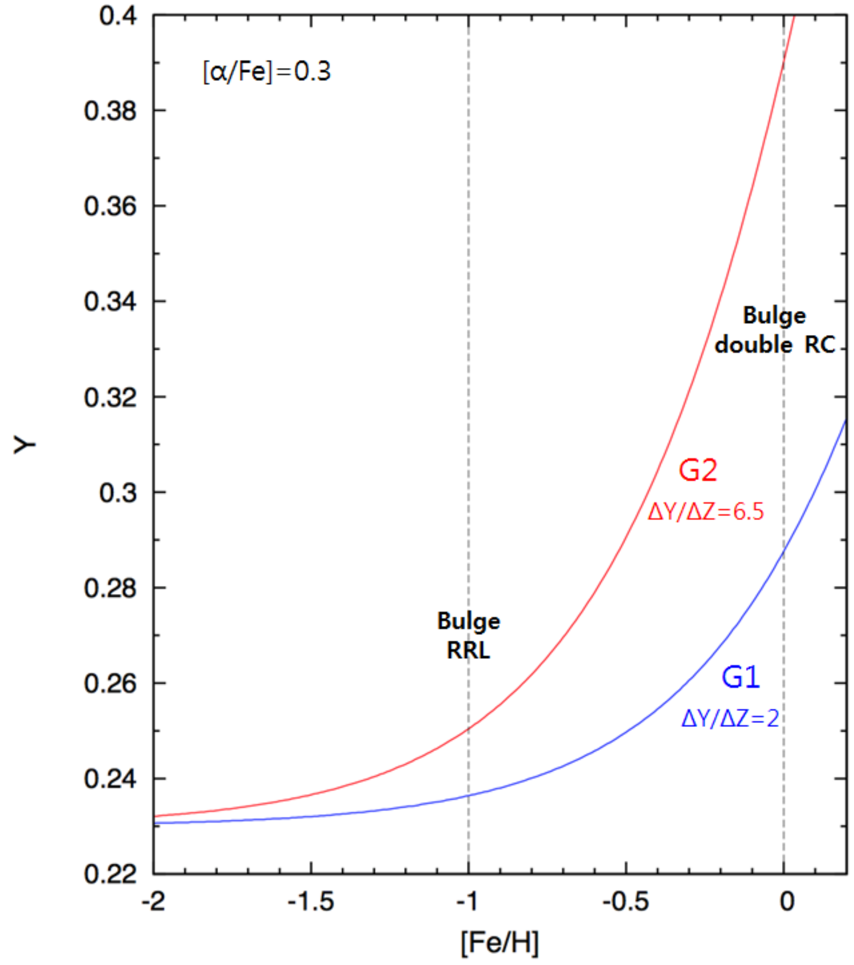
G2 for Oo II,

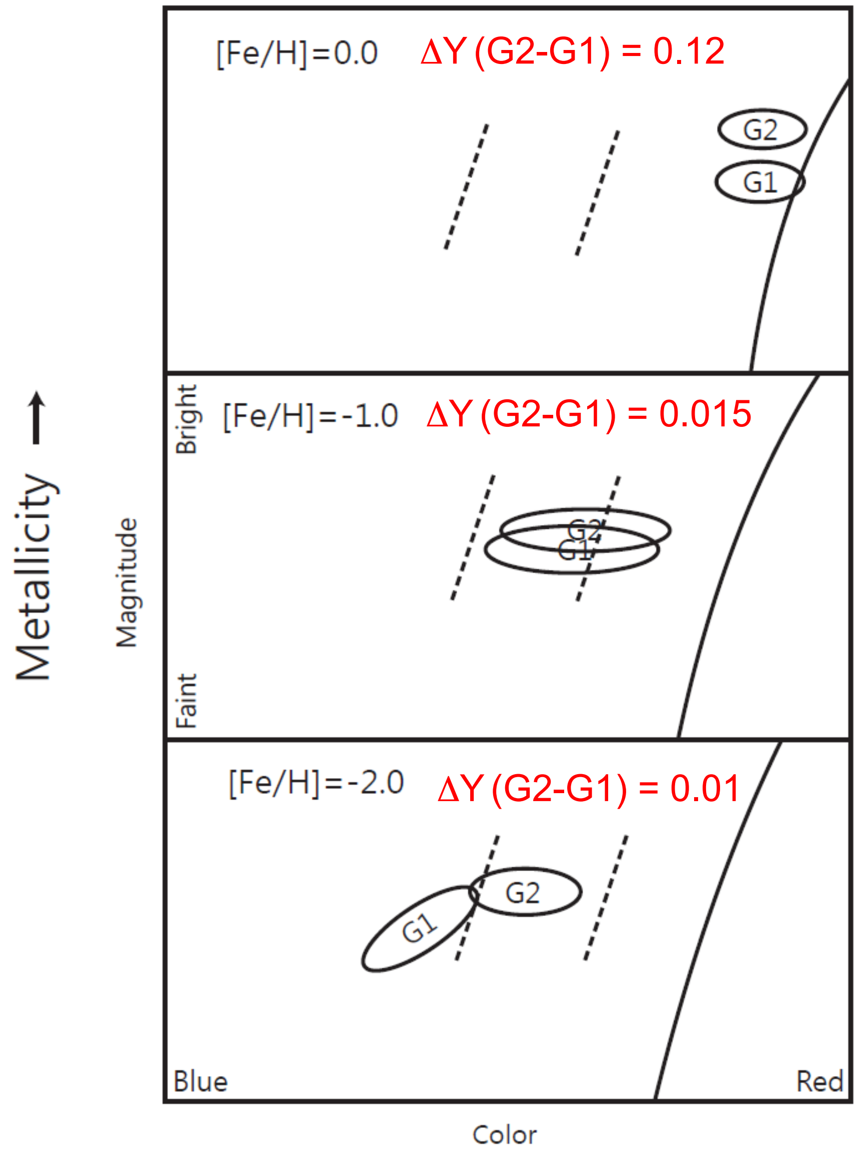
(G3 for Oo III)

ΔY (G2-G1) = 0.01

Jang & Lee 2015

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





Summary & Implications

(1) Double RC in MW bulge is another manifestation of multiple populations in me tal-rich regime, rather than the distance effect (Lee et al. 2015)

→ *Gaia can confirm this!*

(2) MW bar is not sufficiently buckled to form X-shaped structure

→ *previous studies on the structure of the bulge (based on RC) should be re-examined*

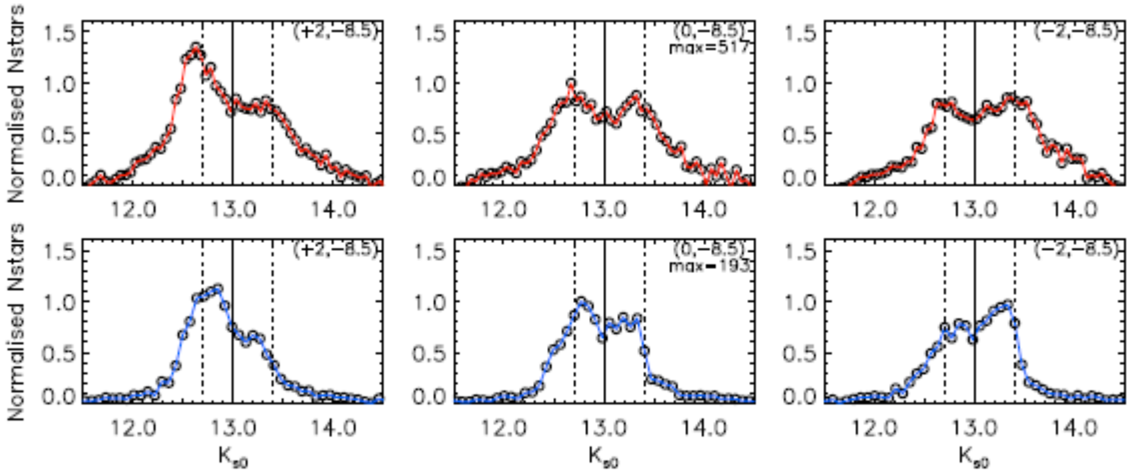
(3) Stars in CB component were provided by disrupted "building blocks" such as T erzan 5 (massive GCs)! NB. γ-ray emission from MW center best explained by MSPs pro vided by disrupted GCs (Brandt+Kocsis 2015)

(4) Early-type galaxies would be similarly prevailed by super-helium-rich populatio n!! → *Impacts on population synthesis, such as Na enhanced gE (van Dokkum & Conroy 20 10) & UV upturn (Chung, Yoon, & Lee 2011)*

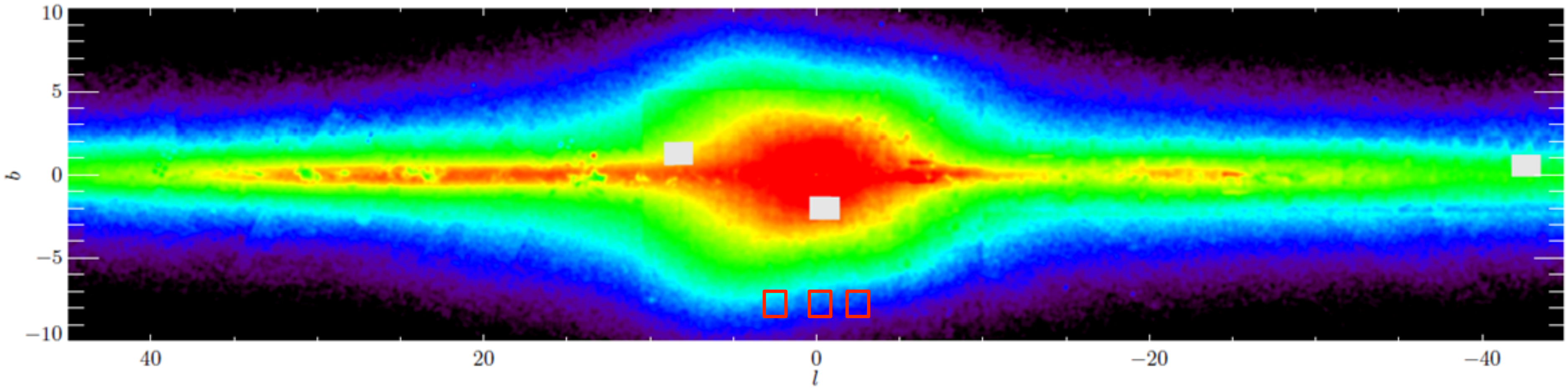
(5) The same multiple population models can explain two populations of RR Lyrae variables in the bulge, and the Oosterhoff dichotomy in the halo (Jang & Lee 2015)

(6) Astronomers repeat the same mistakes: intrinsically brighter (fainter) population is often misinterpreted as a distance effect

Gonzalez et al. 2015

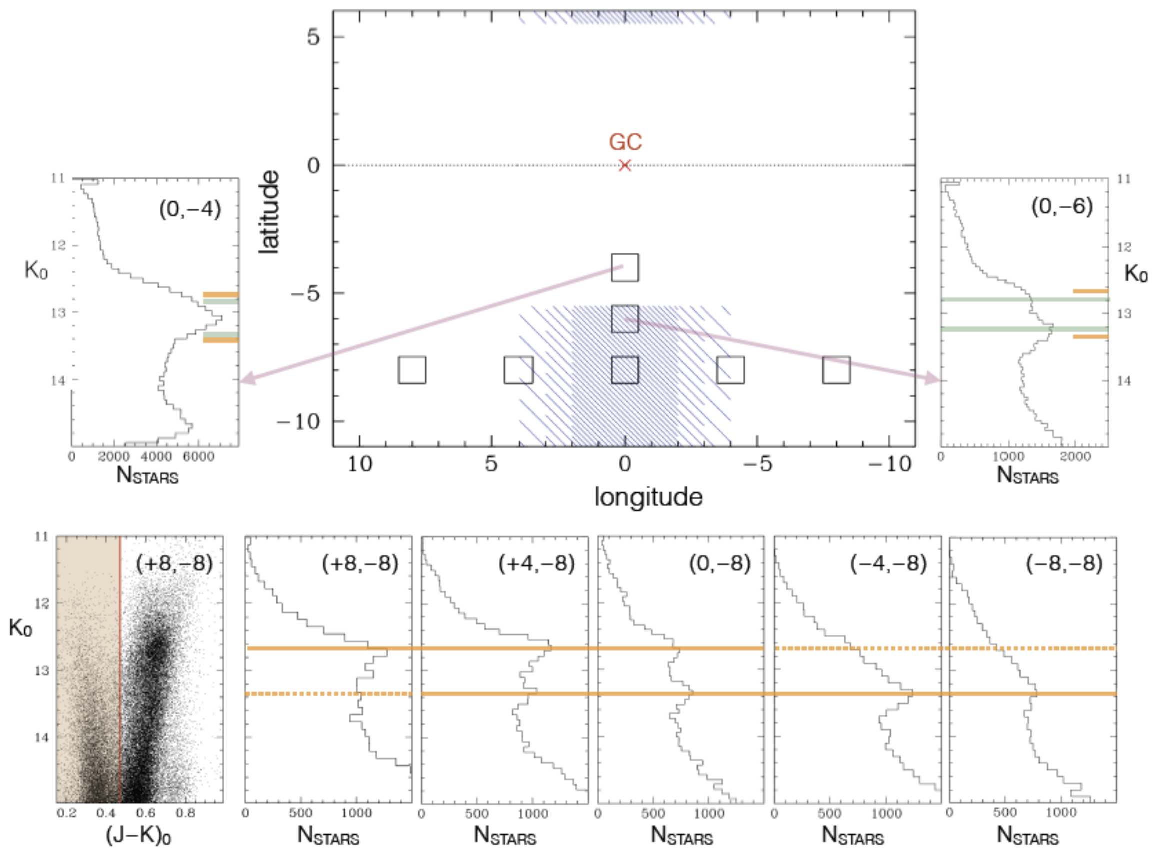


This longitude dependence at b = -8.5 is understood by
(1) tilted bar+CB & effect of p erspective
(2) metallicity effect

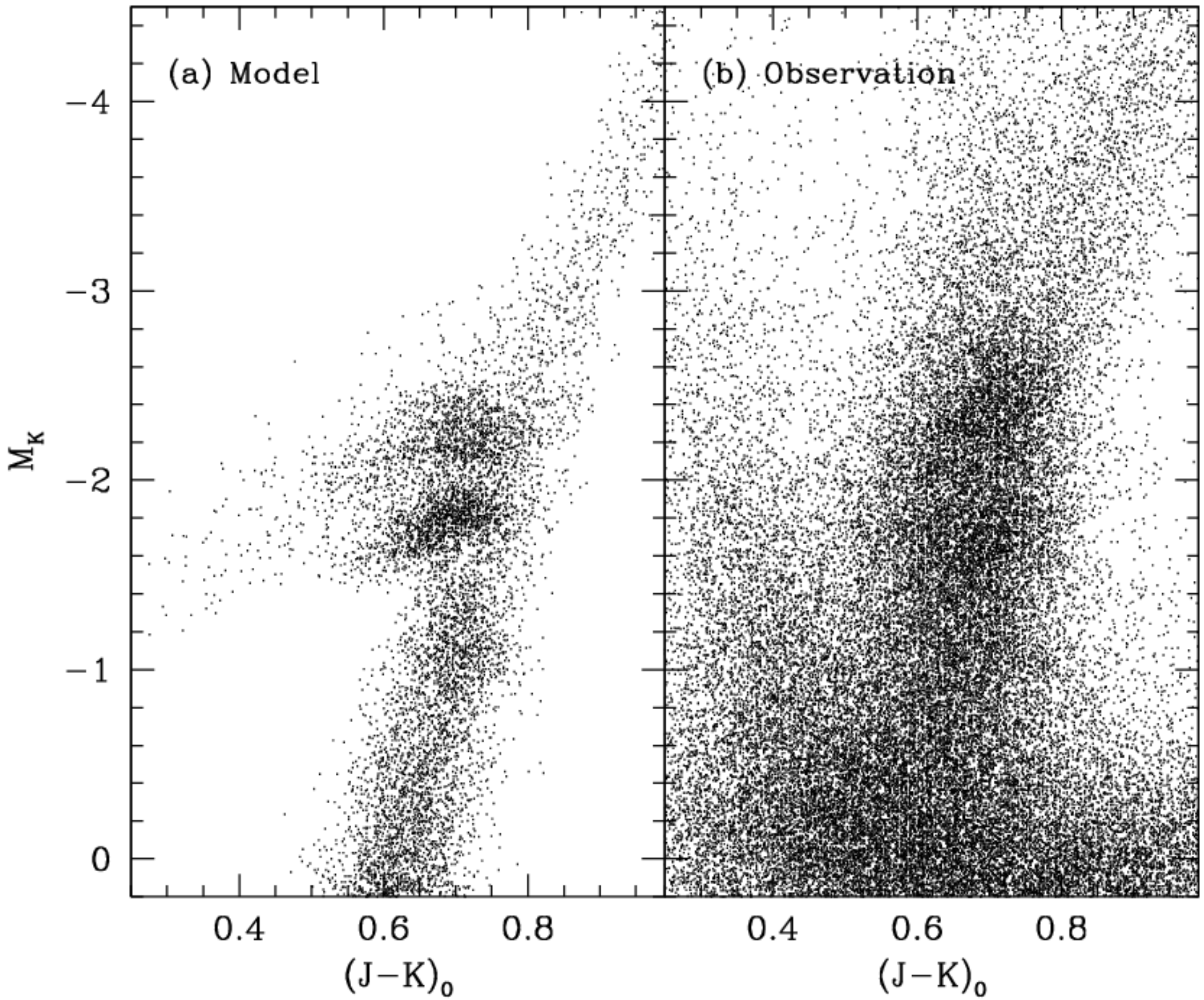


Wegg+15

Gonzalez et al. 2015



Comparison of our model with observation



2MASS data for b = -8 deg:

bulge+ foreground disk contamination

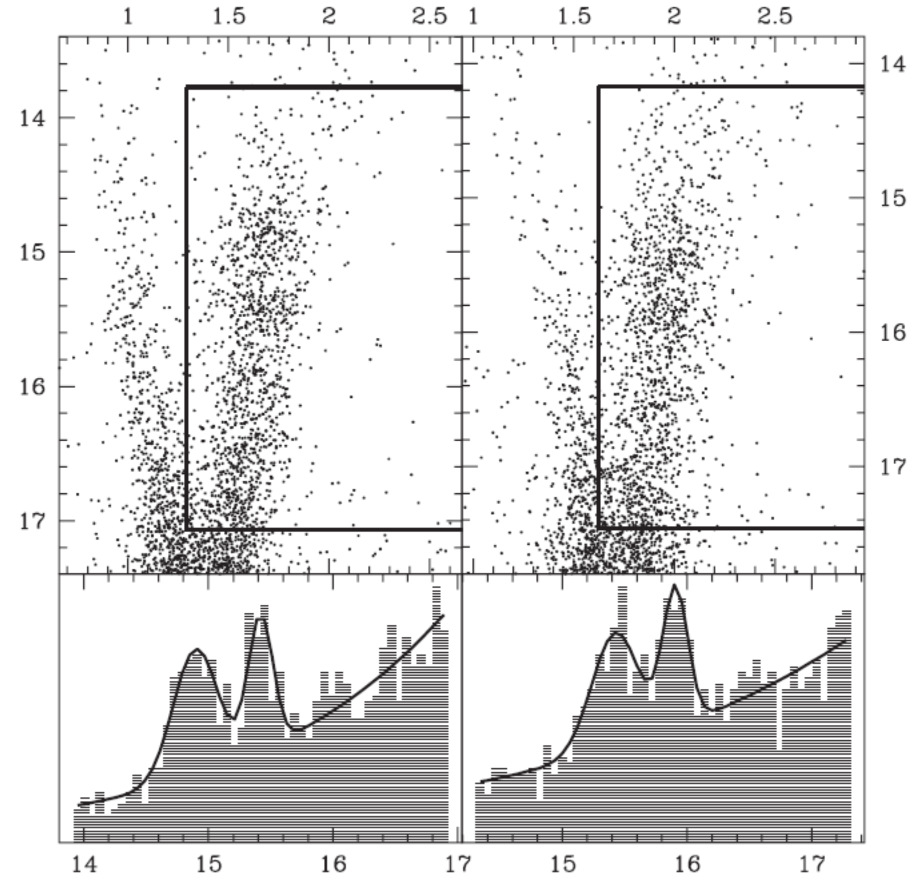
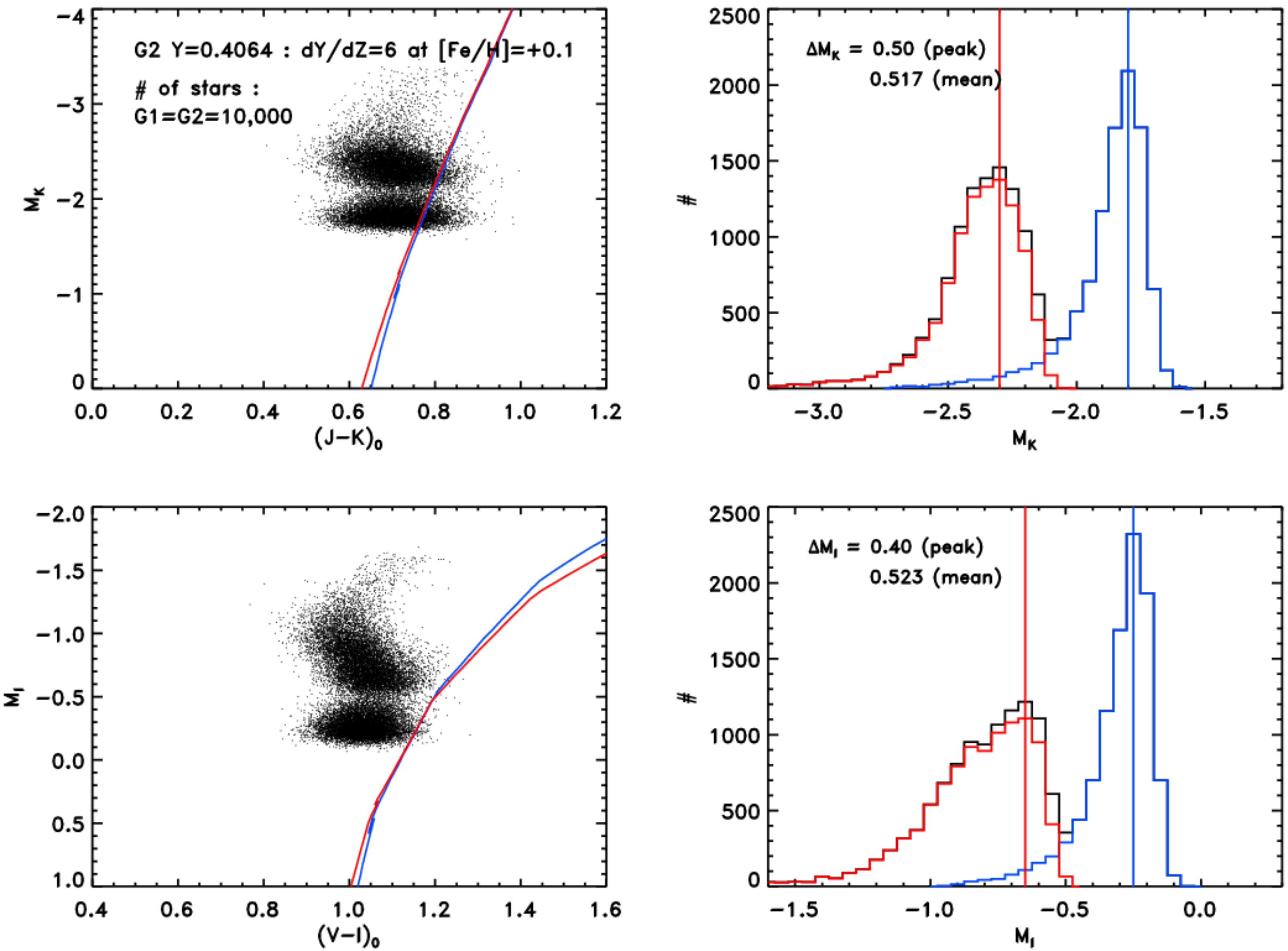


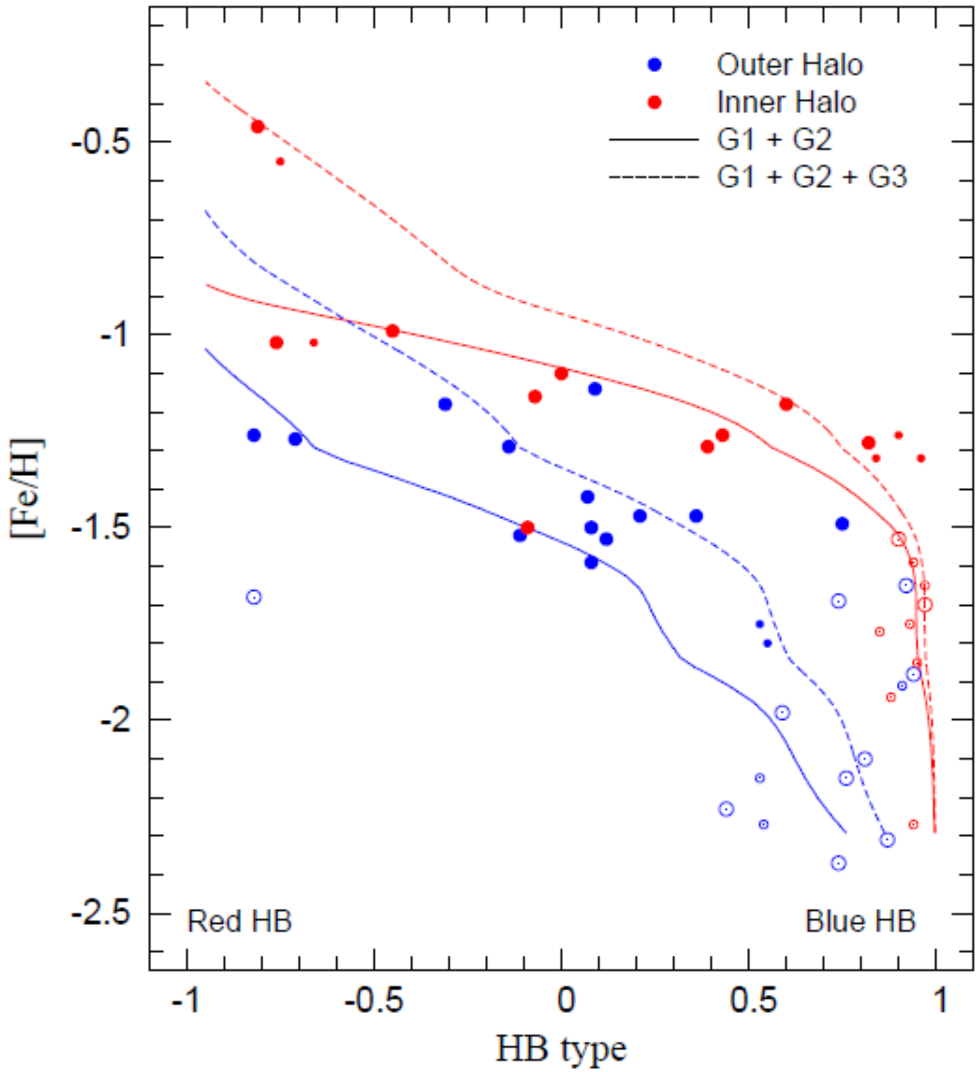
Figure 3. CMDs and brightness distribution with best-fit double clump model for two locations. Left: $(l, b) = (0.27, -5.77)$, the $\Delta\chi^2 = 26.7$ when a second Gaussian is fit, the parameters are $(m_{\mathrm{RC},1}, \sigma_{\mathrm{RC},1}, N_{\mathrm{RC},1}, m_{\mathrm{RC},2}, \sigma_{\mathrm{RC},2}, N_{\mathrm{RC},2}) = (14.90, 0.18, 166.42, 15.42, 0.10, 98.51)$. Right: $(l, b) = (-0.28, 5.76)$, the $\Delta\chi^2 = 14.4$. The parameters are: $(m_{\mathrm{RC},1}, \sigma_{\mathrm{RC},1},$

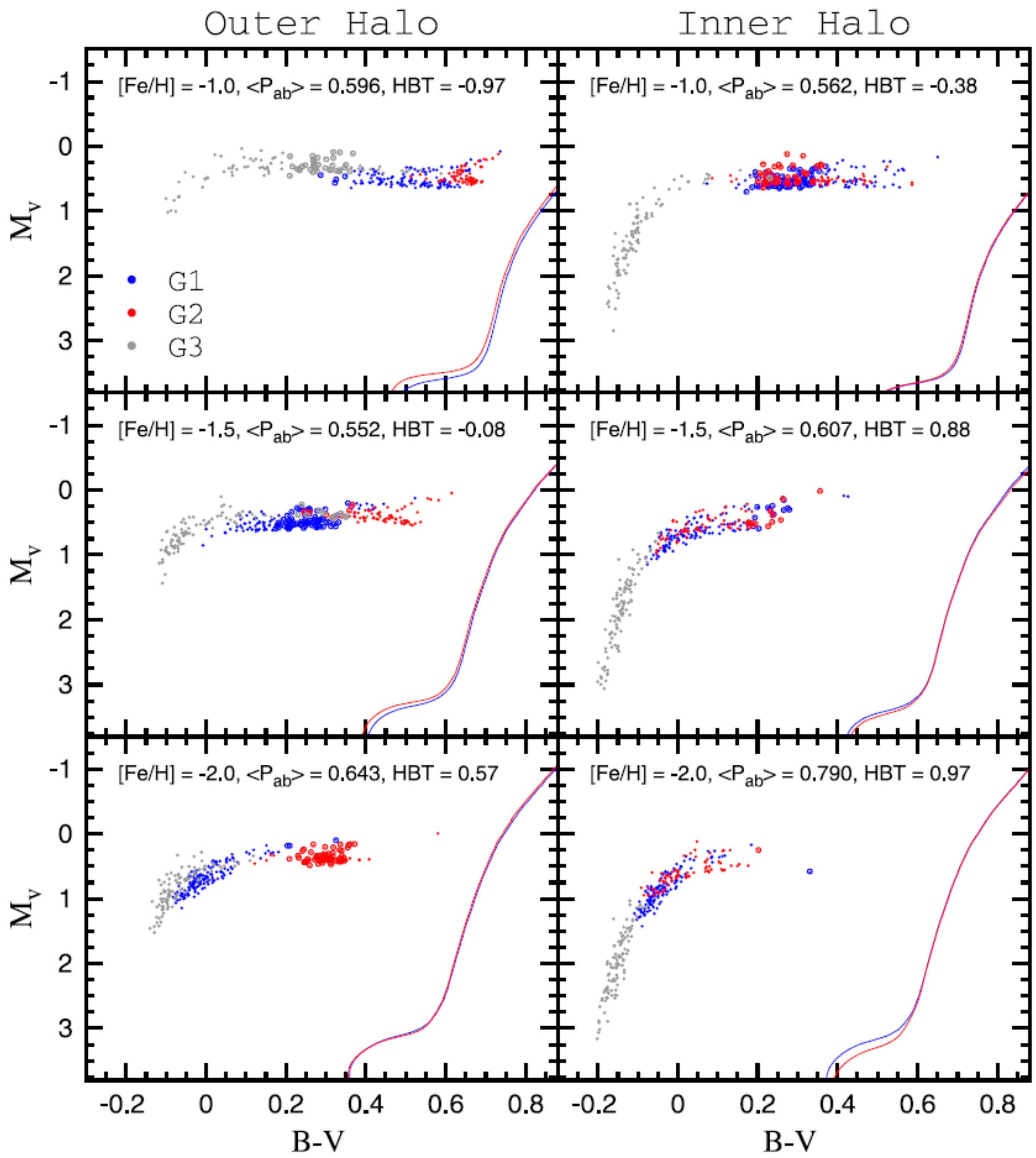
Nataf+2010



G2 Y=0.4064 : dY/dZ=6 at [Fe/H]=+0.1
# of stars :
G1=G2=10,000
M_K
$(J-K)_0$
ΔM_K = 0.50 (peak)
0.517 (mean)
#
M_K
M_I
$(V-I)_0$
ΔM_I = 0.40 (peak)
0.523 (mean)
#
M_I

The HB morphology versus metallicity diagram





Outer Halo
Inner Halo
[Fe/H] = -1.0, <P$_{ab}$> = 0.596, HBT = -0.97
[Fe/H] = -1.0, <P$_{ab}$> = 0.562, HBT = -0.38
[Fe/H] = -1.5, <P$_{ab}$> = 0.552, HBT = -0.08
[Fe/H] = -1.5, <P$_{ab}$> = 0.607, HBT = 0.88
[Fe/H] = -2.0, <P$_{ab}$> = 0.643, HBT = 0.57
[Fe/H] = -2.0, <P$_{ab}$> = 0.790, HBT = 0.97
G1
G2
G3
M_V
B-V

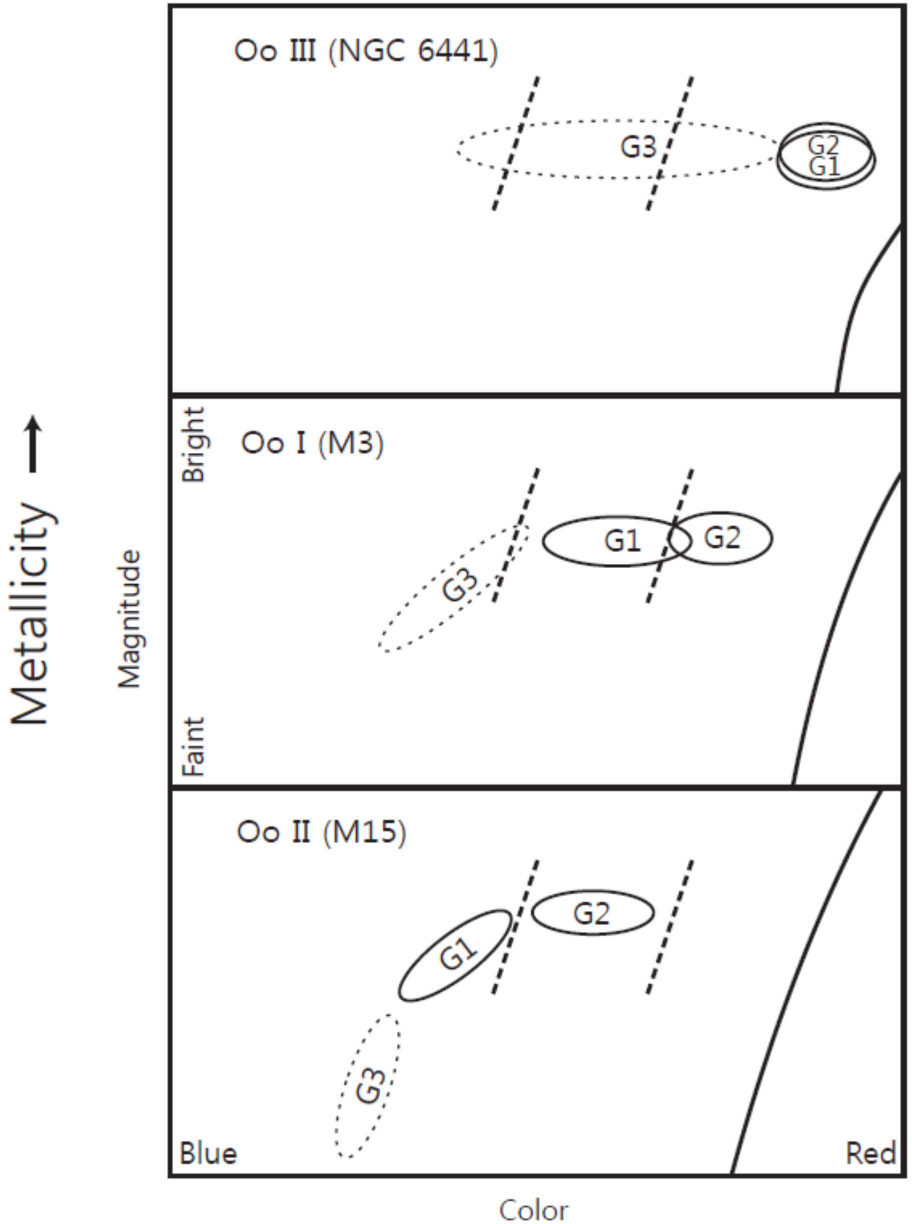
“Population shift”

within the instability strip

→ **P-shift**

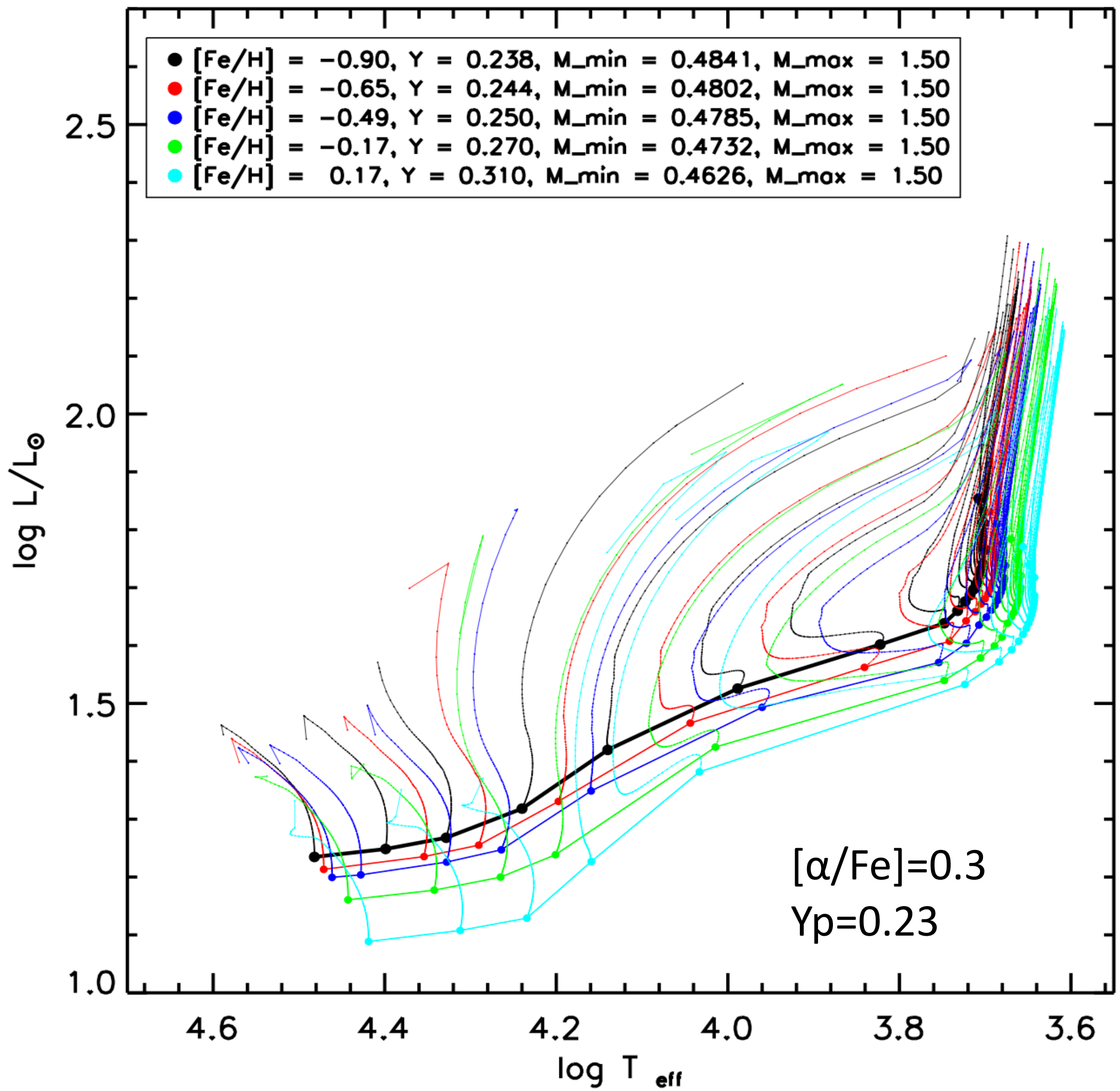
RR Lyraes are produced mostl
y by G1 for M3 (Oo I), by G2
for M15 (Oo II), &
by G3 for NGC 6441 (Oo III),
respectively.

NB. Evolution effect is still importa
nt for the Oo II GCs in the inner hal
o (Jang & Lee 2015)



The Y^2 Evolutionary Tracks for HB & RC

(RC = metal-rich counterpart of HB)



Z=0.004
0.007
0.01
0.02
0.04

Credit: Chongsam Na