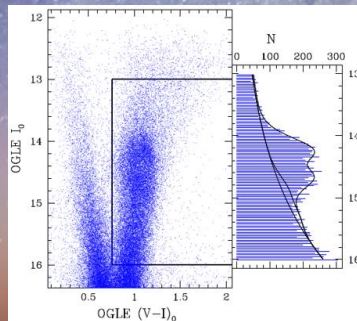


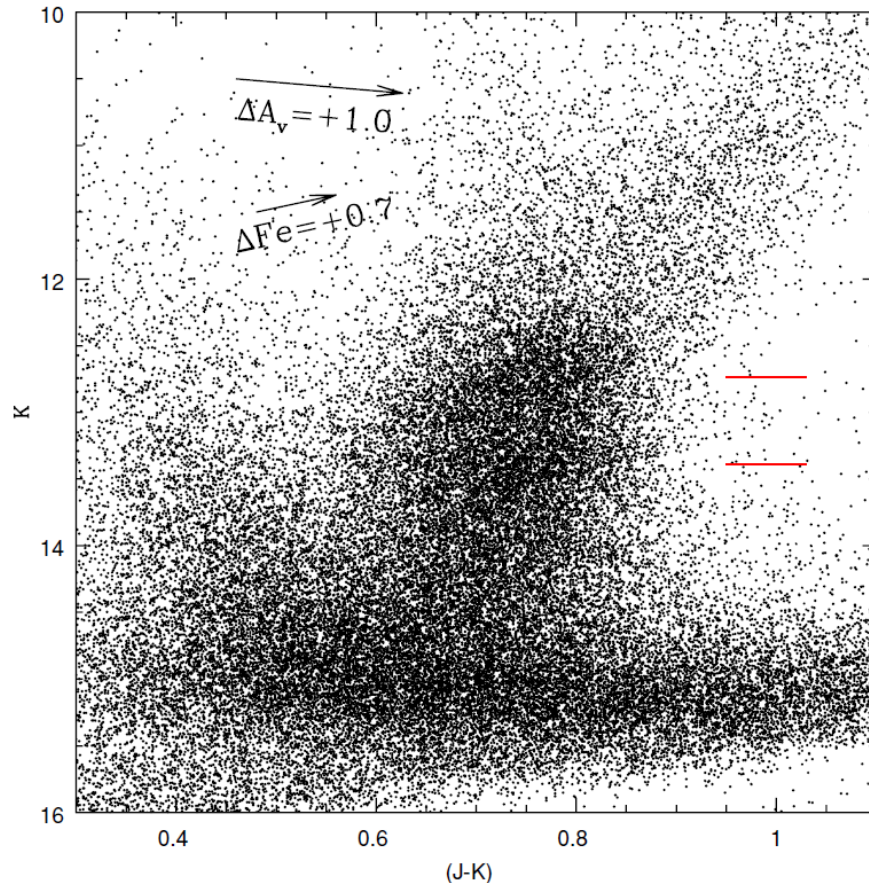
Assembling the Milky Way Bulge from Globular Clusters: Evidence from the Double Red Clump



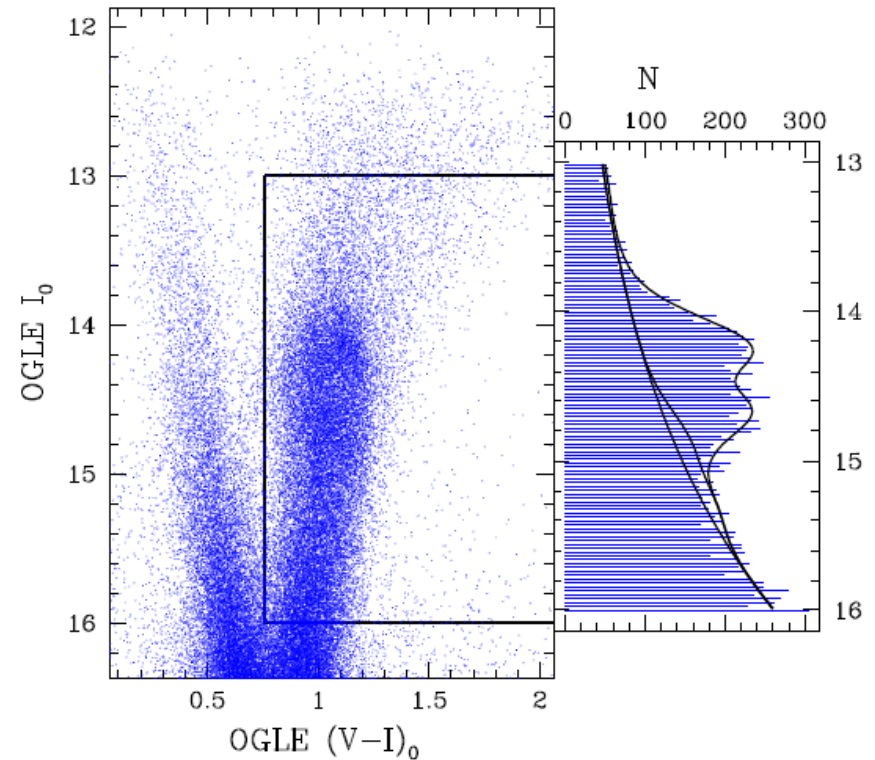
Young-Wook Lee
Yonsei University, Seoul, South Korea

Dongwook Lim, Seungsoo Hong, Chul Chung, Sohee Jang, Jenny Kim

Double Red Clump (RC) in the MW Bulge

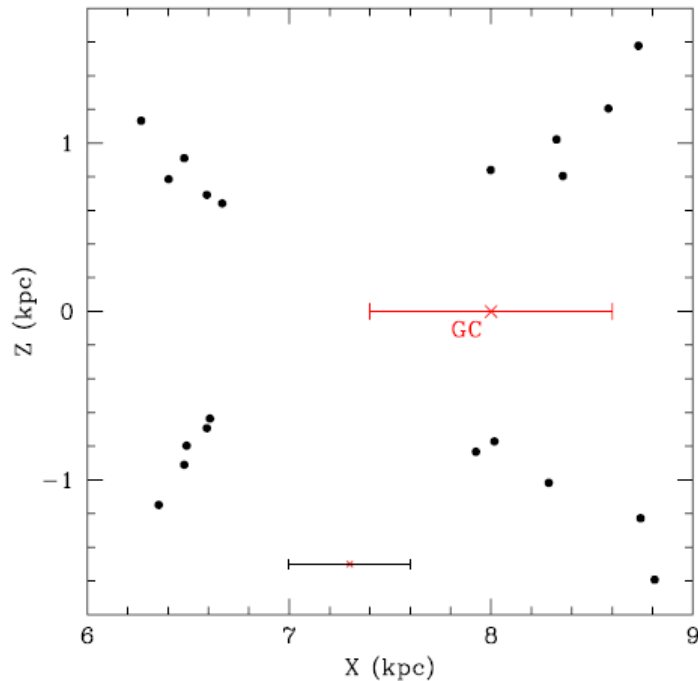


RC stars = metal-rich counterpart
of core-He-burning HB stars



Discovery of Two RCs (l $>$ 5.5 deg):
McWilliam & Zocalli 2010; Nataf et al.
2010 \rightarrow only among metal-rich ($[Fe/H] >$
 -0.5) stars

A Giant X-Shaped Bulge in the Milky Way?



X-Shaped Bulge from bar instability:

bright RC (foreground) + faint RC (background)

McWilliam & Zocalli 10; Nataf+10, 15; Shen, Kormendy+10; Ness, Freeman+12, 13; Li & Shen 12; Wegg & Gerhard 13; Vasquez+13; Rojas-Arriagada+14; Gonzalez+15; Ness & Lang 16... **140+ papers**

→ **Even high latitude field of the bulge has bar (pseudo bulge) characteristic**

But, a drastically different interpretation has been suggested! (Y.-W. Lee+2015)

Discovery of Multiple Populations in Globular Clusters

letters to nature

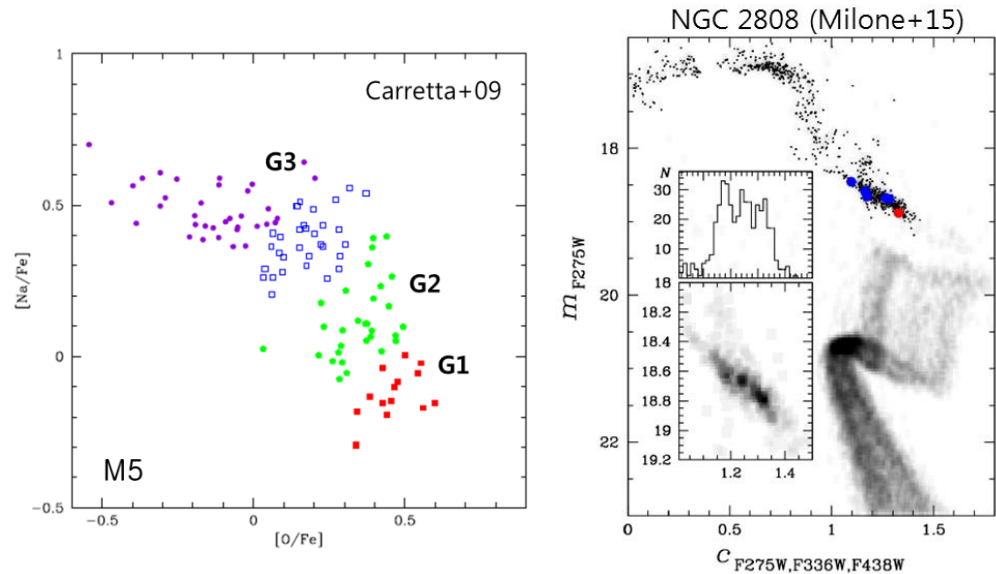
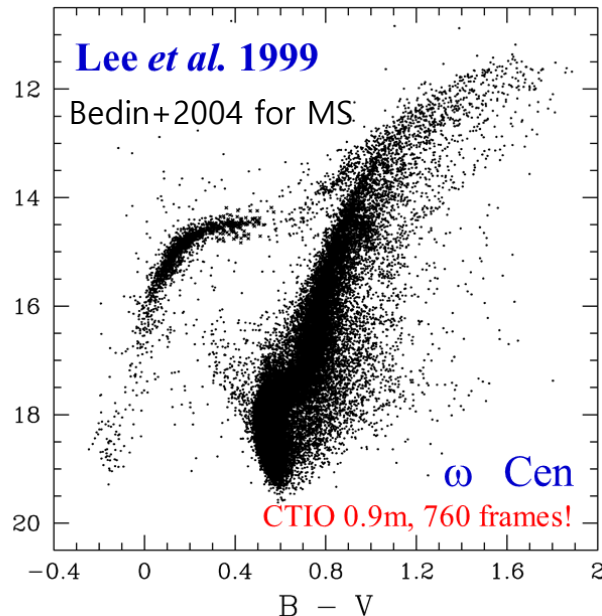
Multiple stellar populations in the globular cluster ω Centauri as tracers of a merger event

Y.-W. Lee*, J.-M. Joo*, Y.-J. Sohn*, S.-C. Rey*, H.-c. Lee* & A. R. Walker†

* Center for Space Astrophysics, Yonsei University, Seoul 120-749, Korea

† National Optical Astronomy Observatories/Cerro Tololo Interamerican Observatory (NOAO/CTIO), Casilla 603, La Serena, Chile

The discovery that the ω Centauri cluster contains several distinct stellar populations is quite surprising. The most massive globular cluster in the Galaxy and ω Centauri is younger than that of ω Centauri more than 10 times. The discovery of multiple populations in ω Centauri is a unique phenomenon observed only in GCs!



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; Yona+14; Piotto+15; Milone+15; Lim+15; Jang+Lee 15; Han+15.. Renzini 2015; Bastian+Lardo 2018...

700+ papers!

G1: Normal He

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

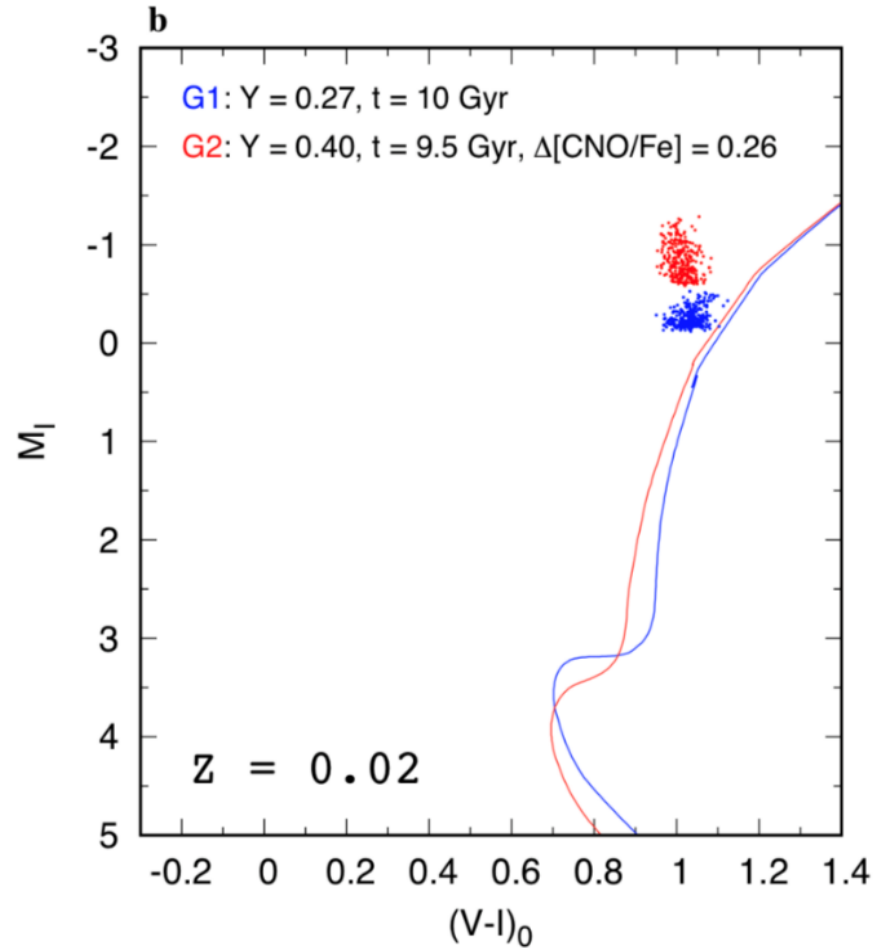
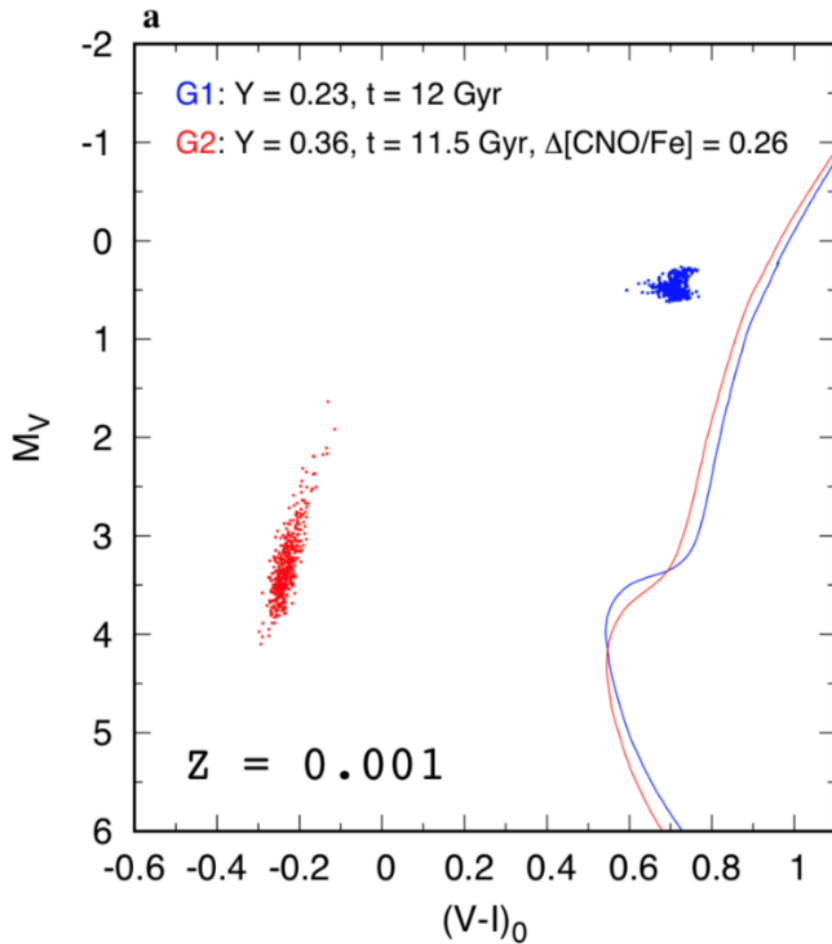
by AGB, WMS, (SNe)

& O, Mg depleted

Unique phenomenon observed only in GCs!

In the metal-rich regime..

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



Synthetic HB models

Y.-W. Lee & S. Jang 2016

(using Yonsei-Yale evolutionary tracks)

$\Delta Y = 0.13$

Explains metallicity dependence of double RC!

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. Ferraro¹, E. Dalessandro¹, A. Mucciarelli¹, G. Beccari², R. M. Rich³, L. Origlia⁴, B. Lanzoni¹, R. T. Rood⁵, E. Valenti^{6,7}, M. Bellazzini⁴, S. M. Ransom⁸ & G. Cocozza⁴

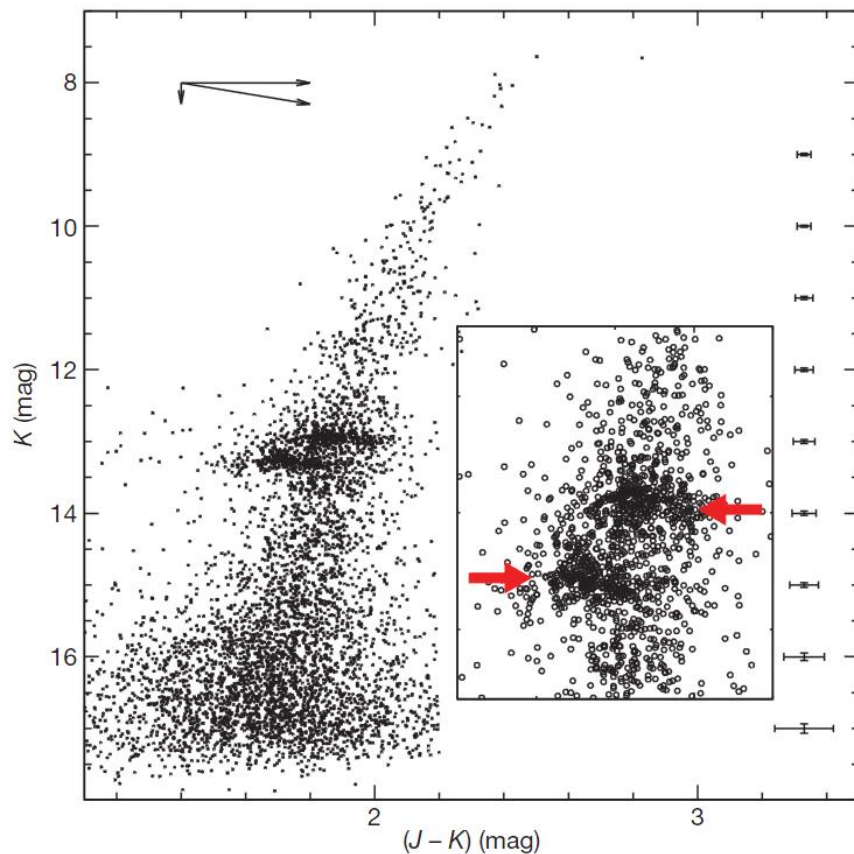
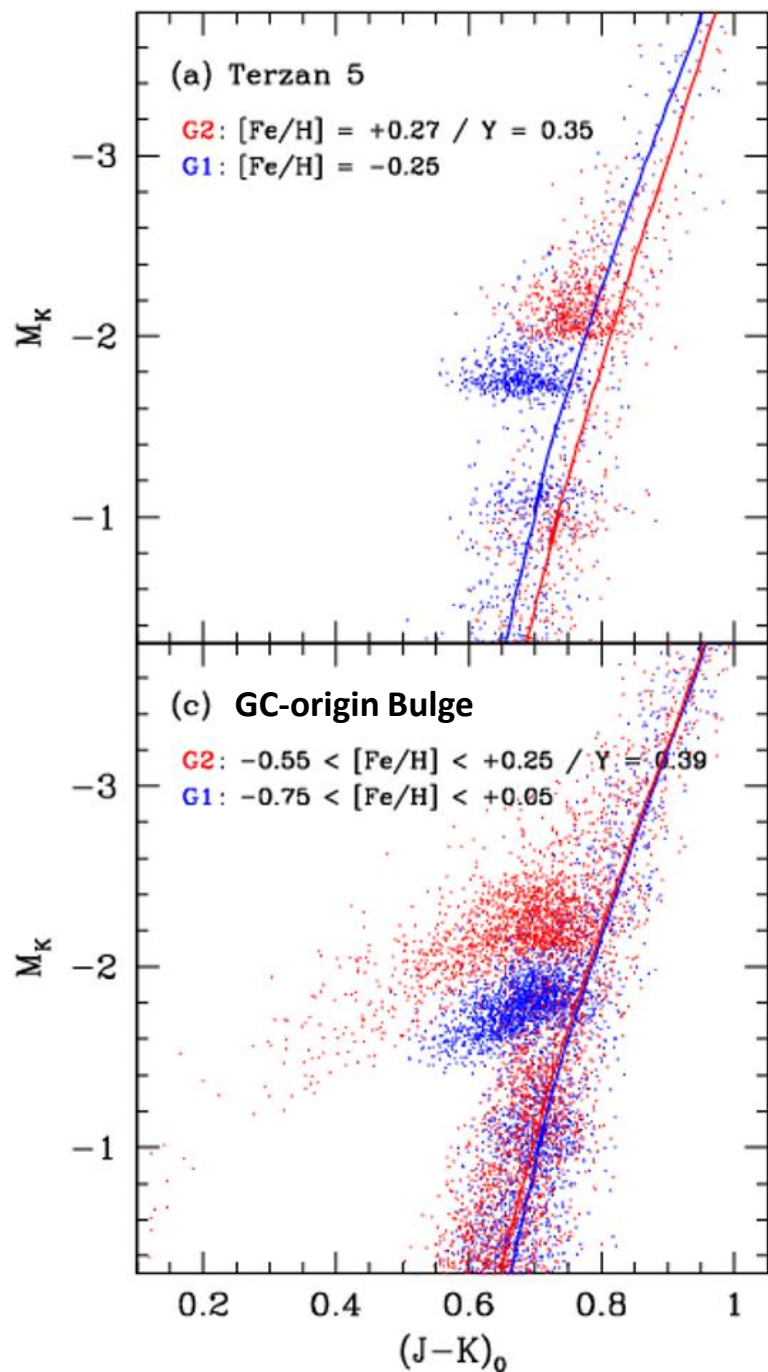


Figure 2 | The two horizontal branch clumps of Terzan 5. Main panel, MAD

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; Joo+2017)

→ Very analogous to the double
RC in bulge!



Multiple Population Models for the Double Red Clump in the Milky Way Bulge

Synthetic HR diagrams using He & N enhanced Yonsei-Yale (Y^2) HB evolutionary tracks & isochrones

G1: normal-He

$$\Delta Y / \Delta Z = 2$$

Y = 0.27 at $[\text{Fe}/\text{H}] = -0.1$

G2: enhanced-He

$$\Delta Y / \Delta Z = 6$$

Y = 0.39 at $[\text{Fe}/\text{H}] = -0.1$

(cf. Renzini 1994; Nataf+2013)

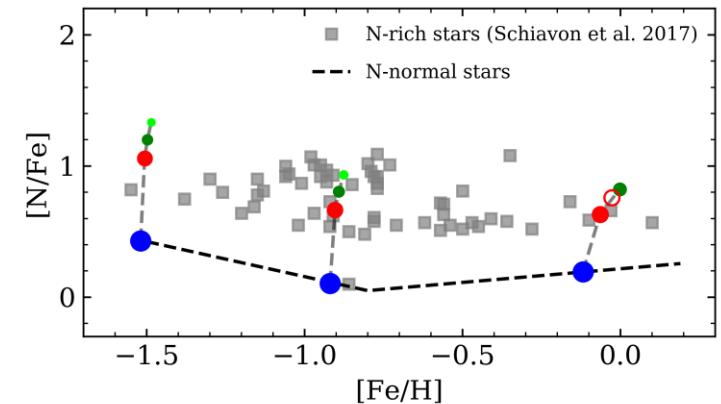
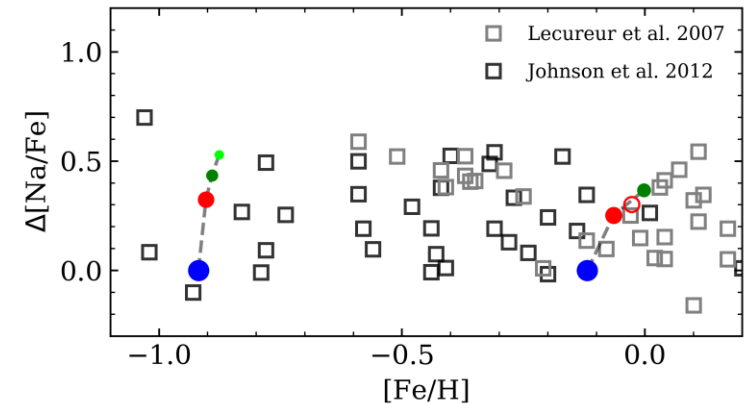
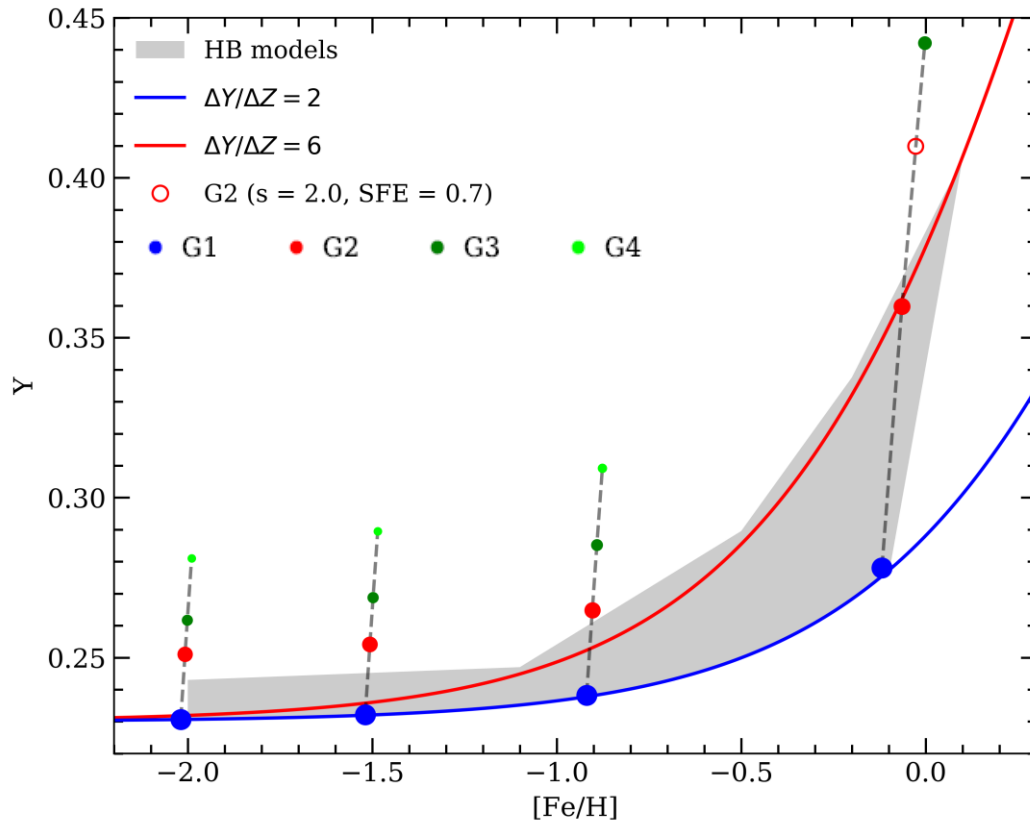
Lee, Joo & Chung 2015

Lee & Jang 2016

Joo, Lee & Chung 2017

(see also Lopez-Corredoira 2016, 2017)

Our chemical evolution models predict a strong metallicity dependence of $\Delta Y(G2-G1)$! (J. Kim & Y.-W. Lee 2018, ApJ)



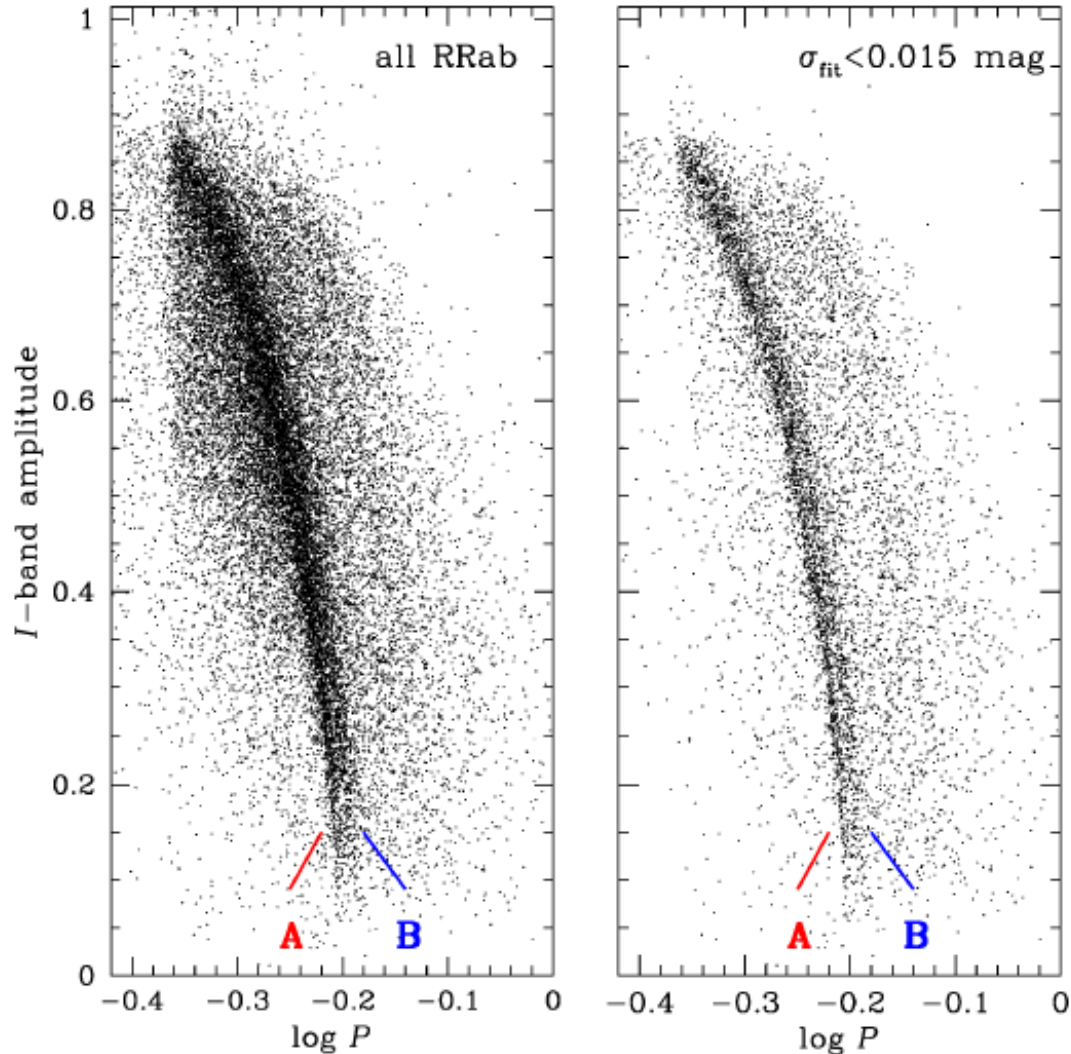
This is mostly due to the winds of metal-rich massive stars (Maeder 92; Meynet 08)

Also consistent with the observed spreads in $[Na/Fe]$ & $[N/Fe]$ in MW bulge

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

Two populations of RR Lyrae variables in the bulge

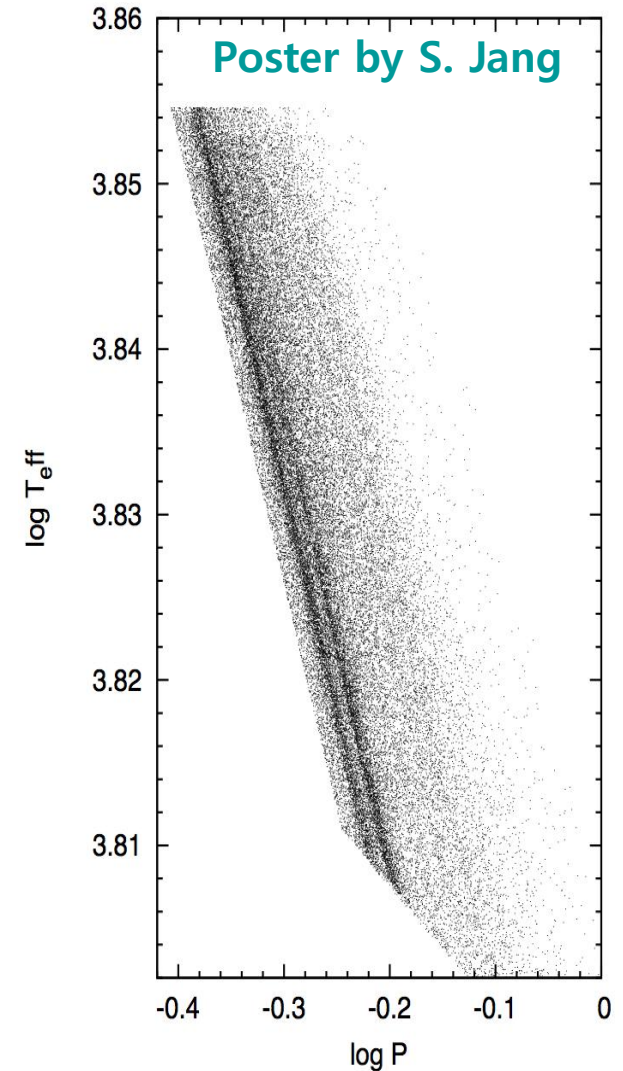
(Pietrukowicz et al. 2015)



$\langle [\text{Fe}/\text{H}] \rangle = -1.1$

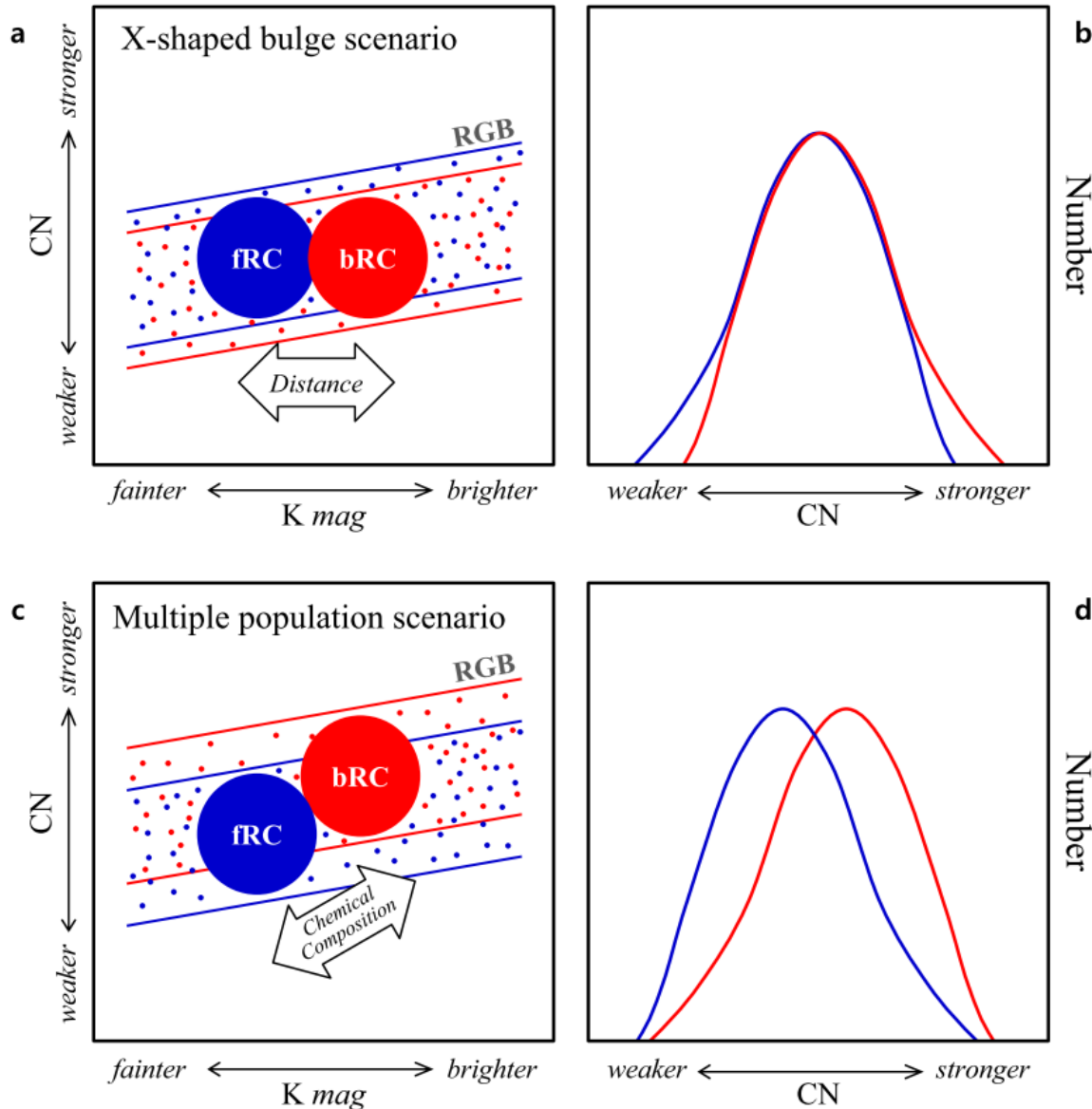
Our model

(Lee & Jang 2016)



$\Delta Y (\text{G2-G1}) = 0.012$

Two scenarios predict different placements of bRC & fRC stars in K magnitude vs. CN index diagram!



**Chemical tagging
with CN-band:**

Most GCs host CN-strong
G2 & CN-normal **G1** stars

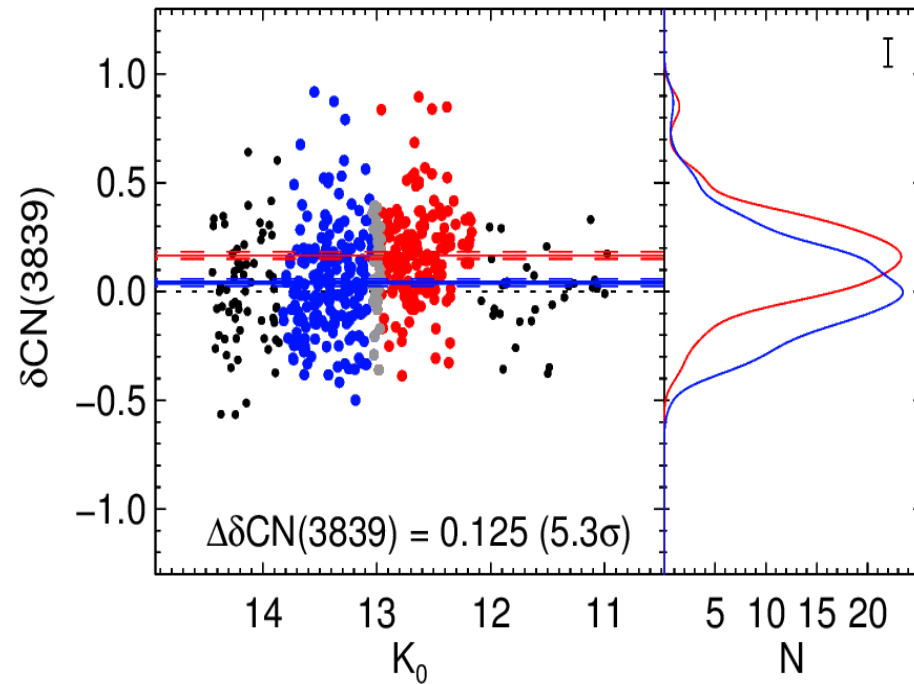
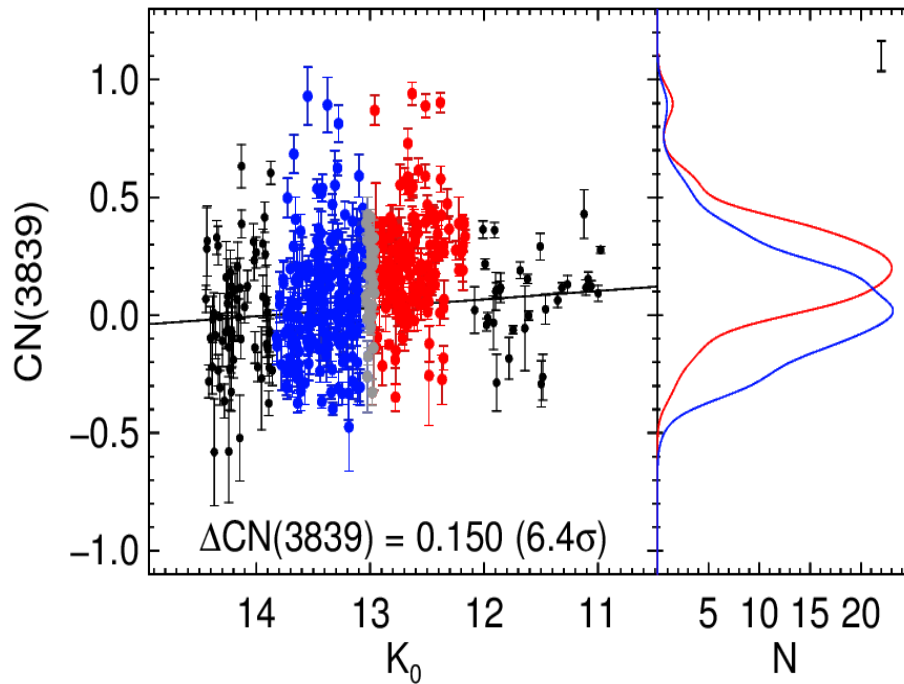
→ **CN traces N**

→ N-rich **G2** stars also
enhanced in He & Na

Unique phenomenon
observed only in GCs!

Talk by Dongwook Lim

Bright RC stars are CN-enhanced!!



$$\Delta\delta\text{CN} = 0.13 \text{ (} 5.3\sigma \text{)}$$

$$\Delta\delta\text{CN}(\text{G2+}, \text{G1}) = 0.43$$

(similar to GCs: Lim+15)

Similar results from CN4142

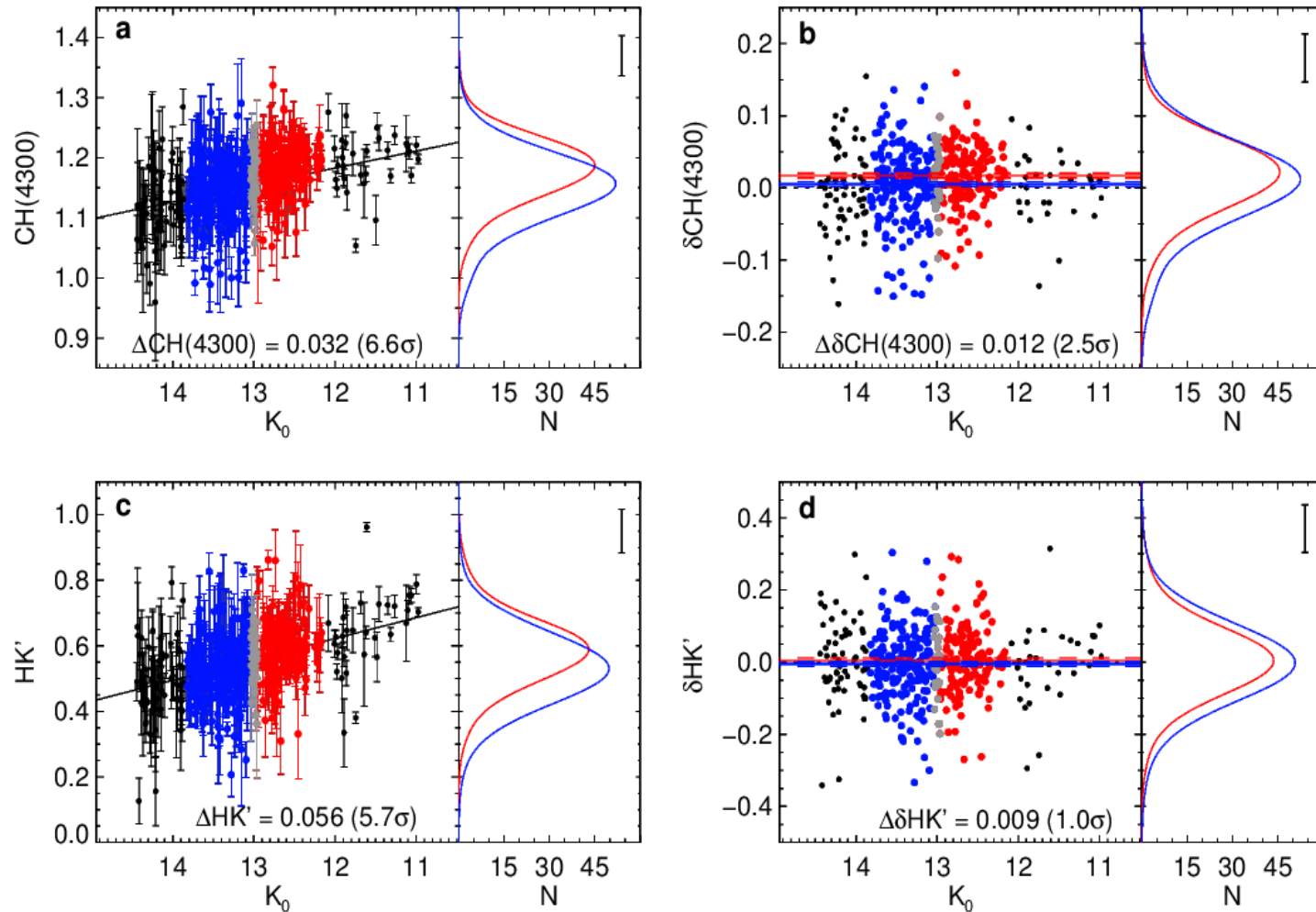
LCO 2.5m spectroscopy

CN, Na, & He enhanced stars are discovered only in GCs! → Well-established chemical tagging (e.g., Martell+2011)

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

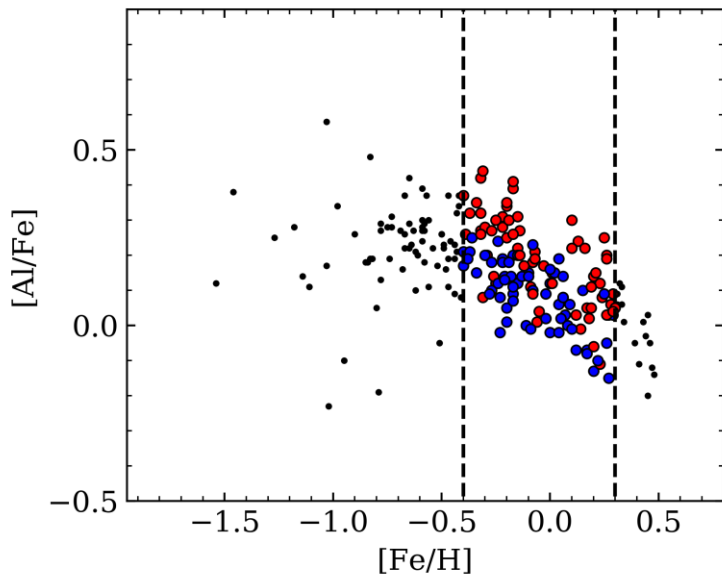
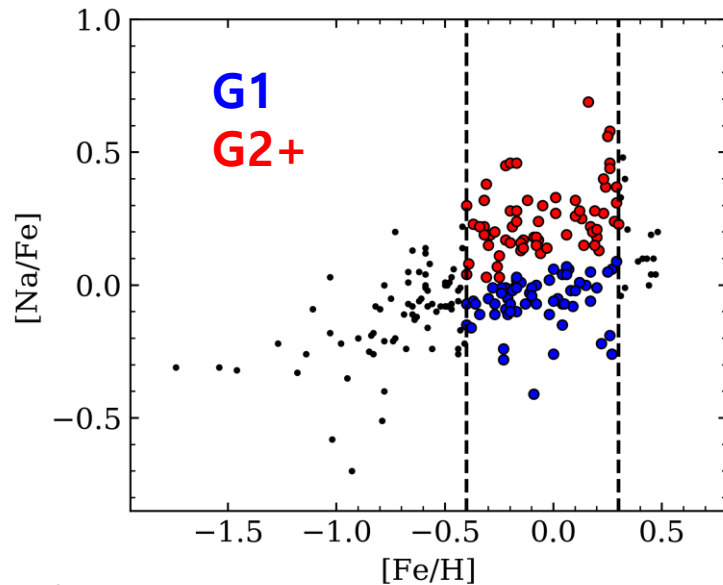
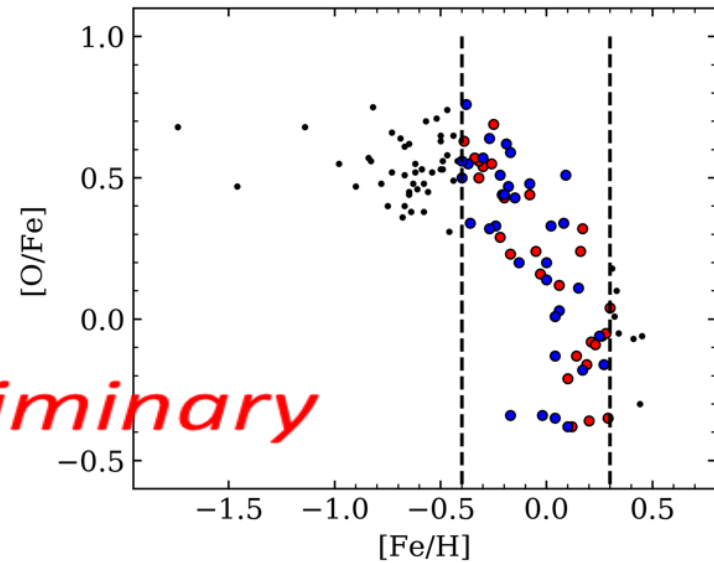
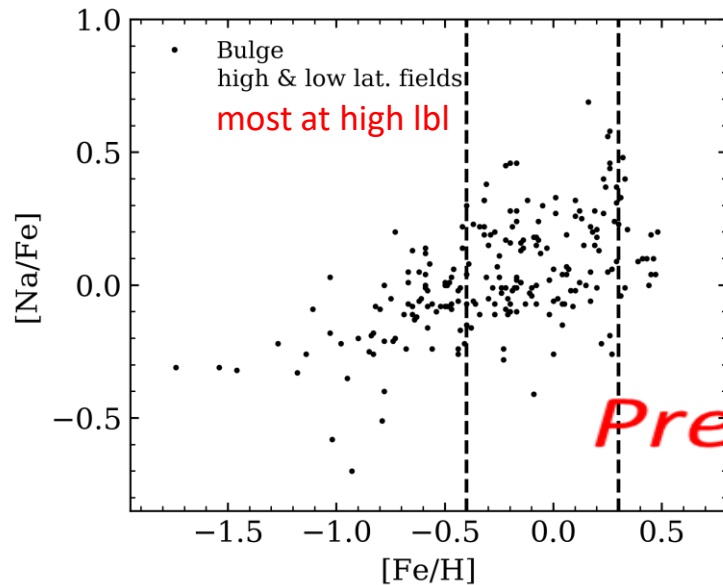
Y.-W. Lee, Hong, Lim+2018 (See Poster by S. Hong)

Unlike CN, the differences in CH and Ca abundances are negligible between the stars in two RC zones → **Consistent with GC-origin!**

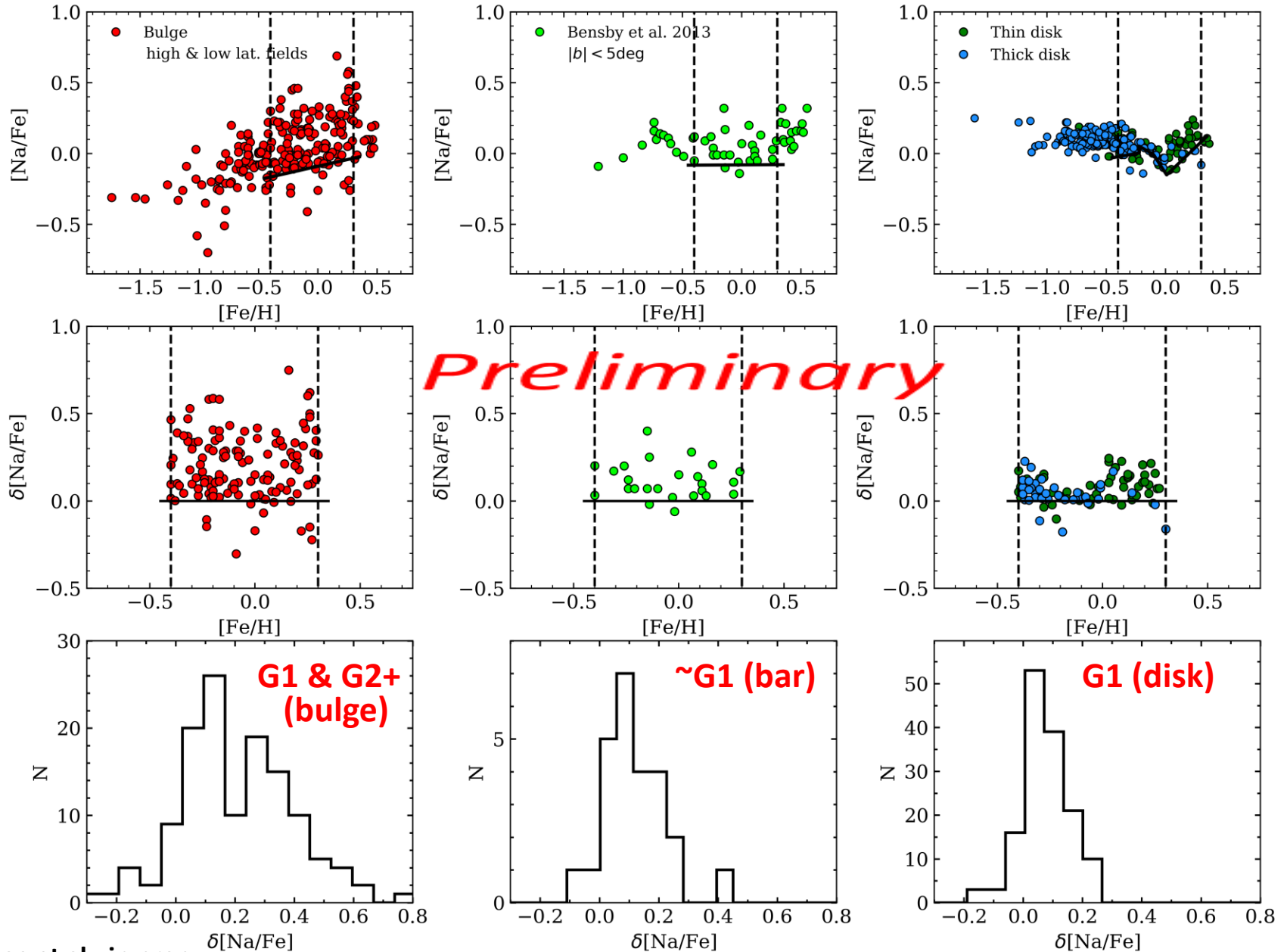


Na bimodality of bulge RGB stars! (data from Johnson+12, 14)

→ Smoking gun evidence for **G1** & **G2+** from GCs!

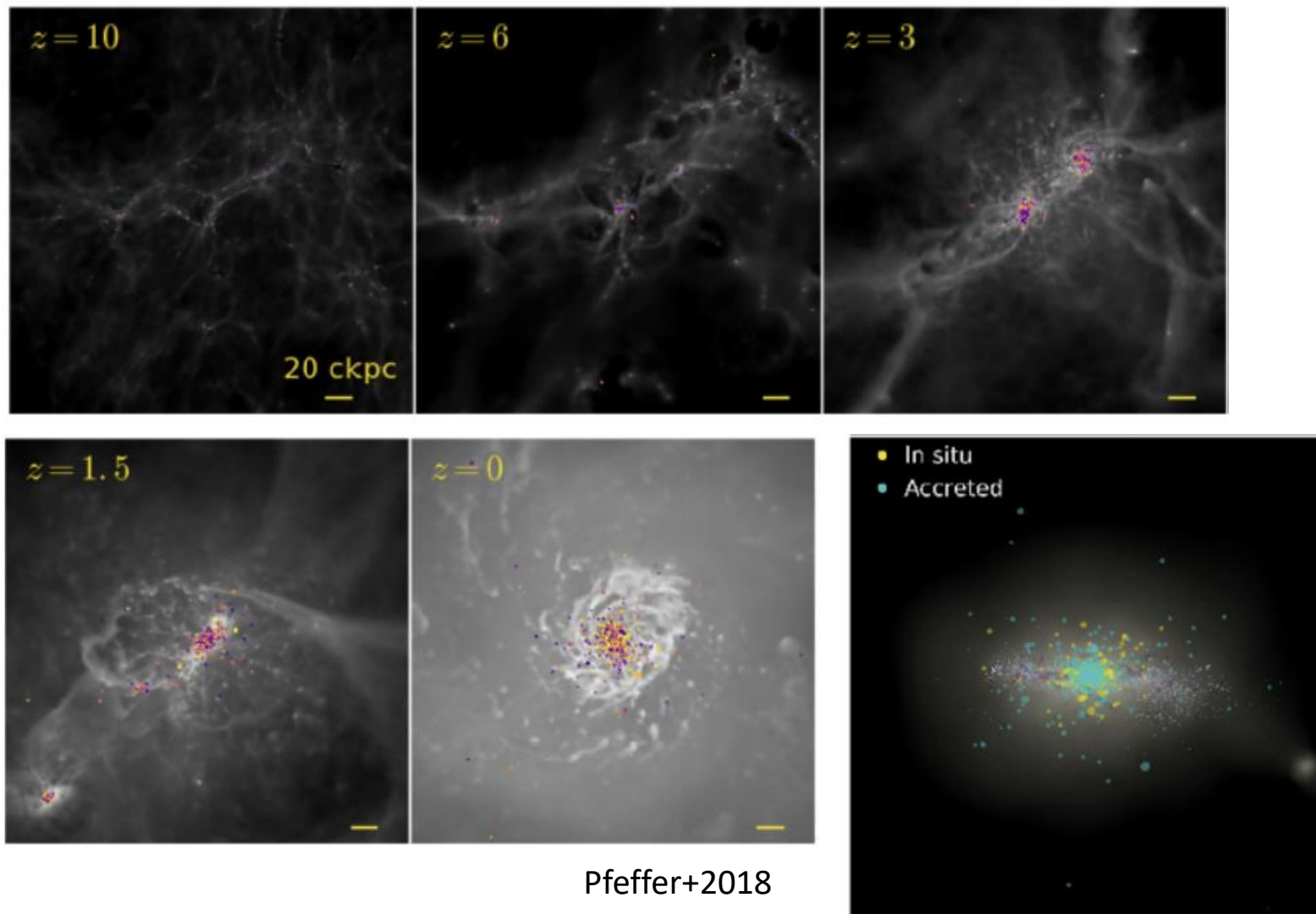


(True) Bulge stars are not from the bar or disk! (data: Johnson+12, 14)



Recent cosmological hydro-N-body simulations predict GC-origin bulge with rotation

(e.g. Kruijssen 2015; Pfeffer+2017; Renaud+2017; Kravtsov & Gnedin 2005)



Proto-GCs could form in a clump in “clump-origin bulge”

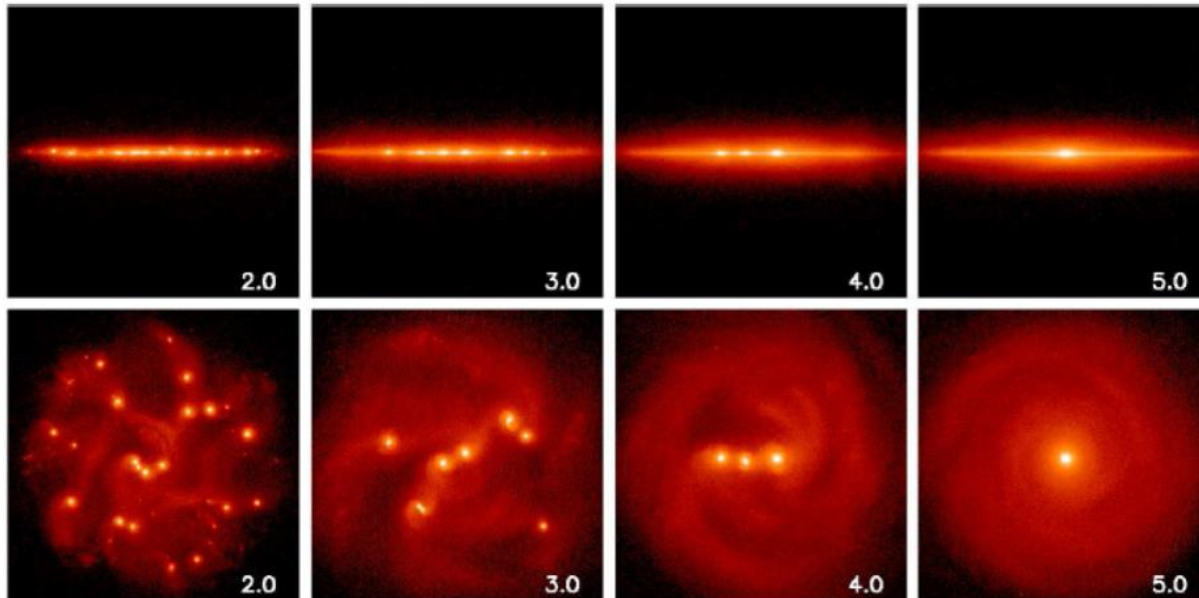
“Clump-origin bulge” (Noguchi+1999; Elmegreen+2008; Inoue+Saitoh 2012)

→ reproduces observed rotation & boxy bulge

“Clumps” with $\sim 10^7 - 10^8 M_\odot$ are observed at high- z

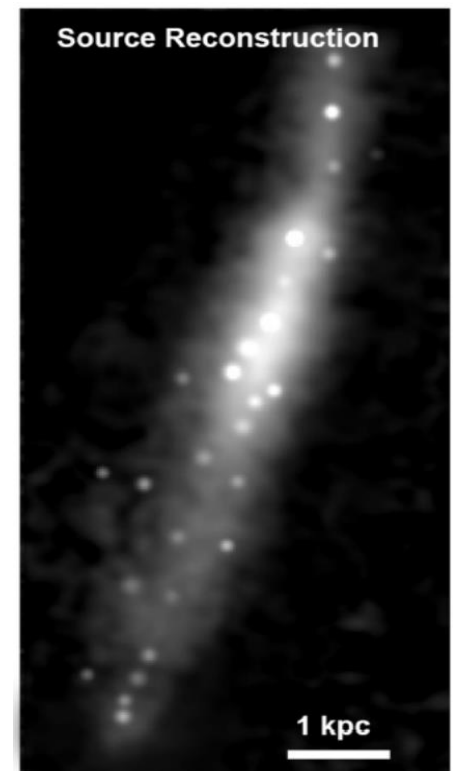
(Vanzella+2017; Johnson+2017; Dessauges-Zavadsky+2017; Cava+2018)

“Clump” = cluster of many GCs (Shapiro+2010; Bekki 2017; Elmegreen 2018)



Inoue+Saitoh 2012

Johnson+
2017

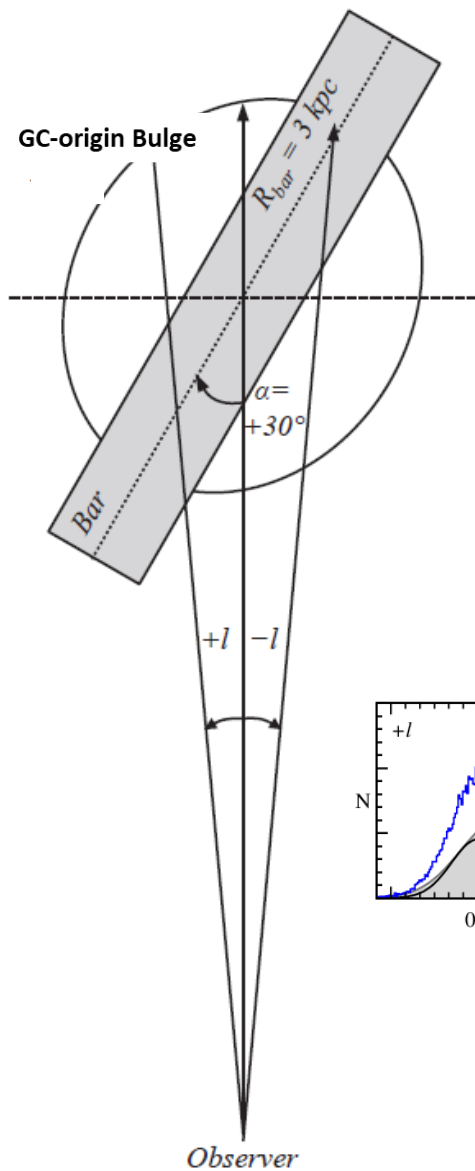


Summary & Implications

1. Most stars in the *true* MW bulge (best found at $|b| > 6$ deg) were provided by disrupted globular clusters!!
2. Current view on the 3D structure of the MW bulge (e.g., Wegg & Gerhard 2013) should be re-examined, as it is based on previous interpretation of double RC!
3. Early-type galaxies would be similarly prevailed by G2 & G1 originated in proto-globular clusters! (Chung, Yoon, Lee 2011, 2017; Talks by Chung & Schiavon)
→ Massive ETGs & their GCs are also CN & Na enhanced!! (e.g., Worthey 1998)
4. Gaia distances & spectroscopy can provide further test!

See also **AAS Nova**, 27 July 2018

“Red Clump Stars and the History of the Galactic Bulge”



Composite Bulge:

Bar embedded in "GC-origin Bulge"

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

$$\text{Double RC} = f(b, l)$$

Latitude dependence

$$\rightarrow \text{Bar/Bulge} = f(b)$$

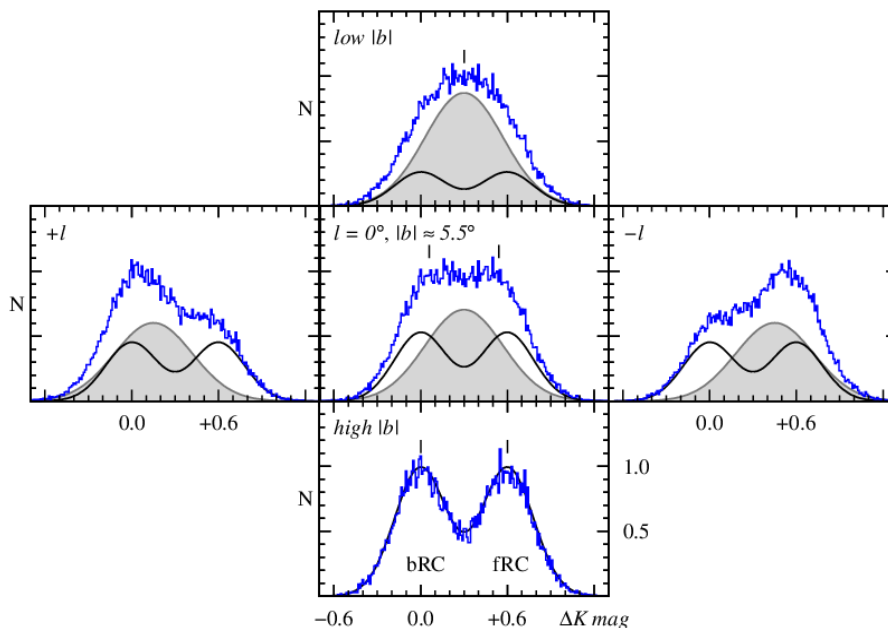
Longitude dependence

\rightarrow Tilted Bar embedded in Bulge

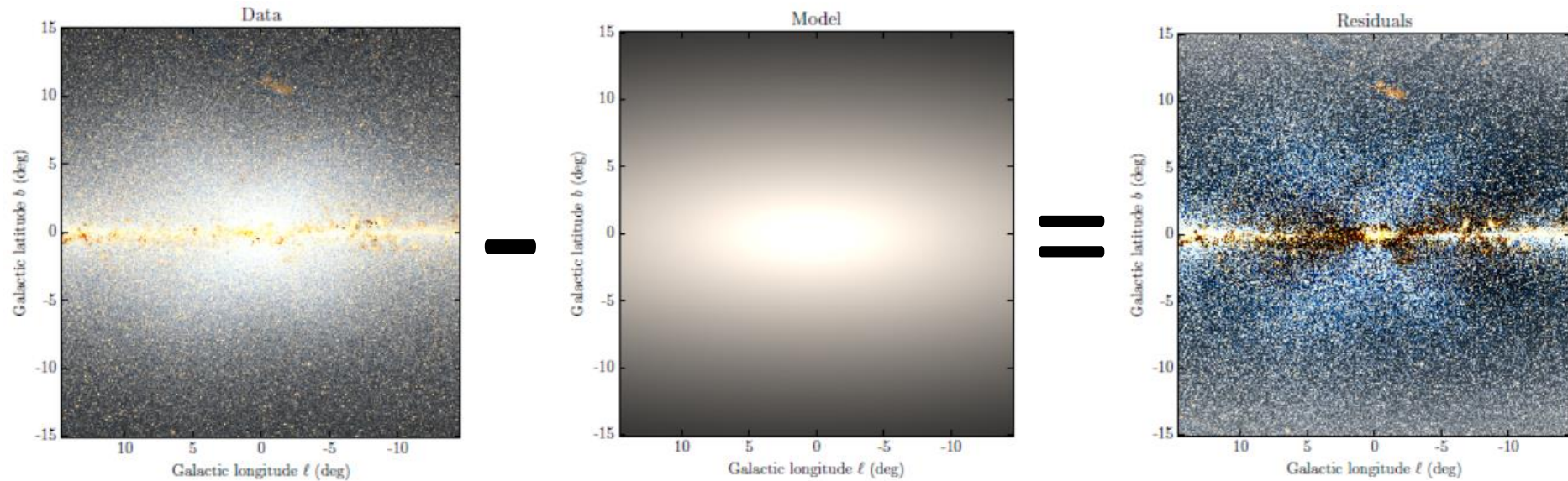
Bar: monomodal in gray

Bulge: bimodal

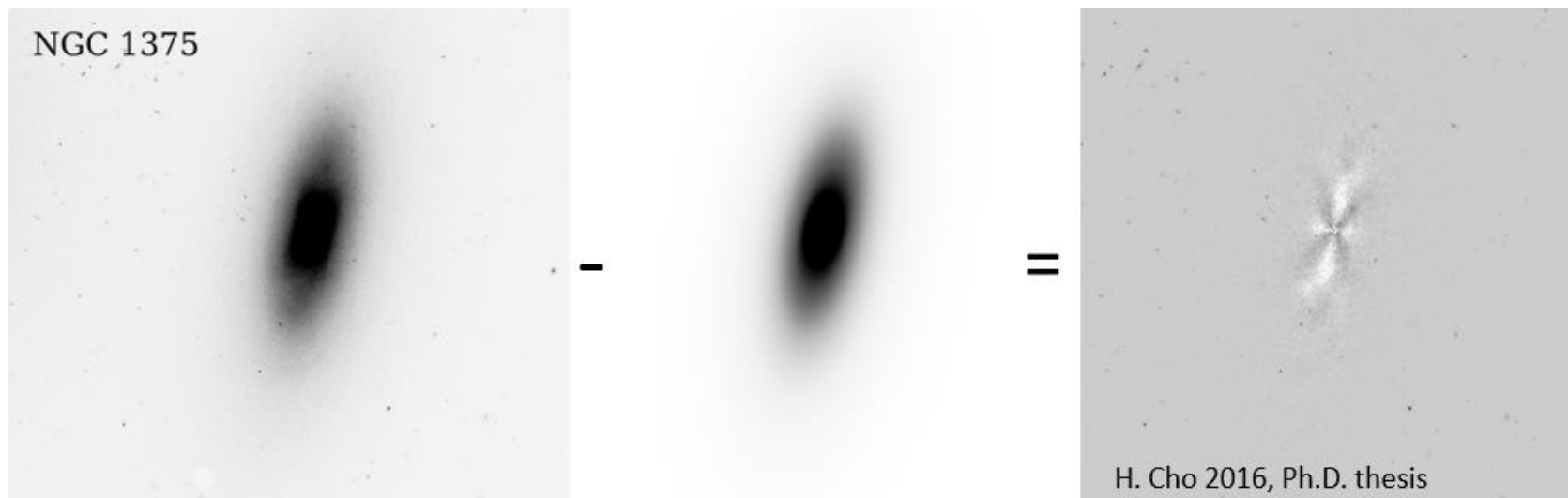
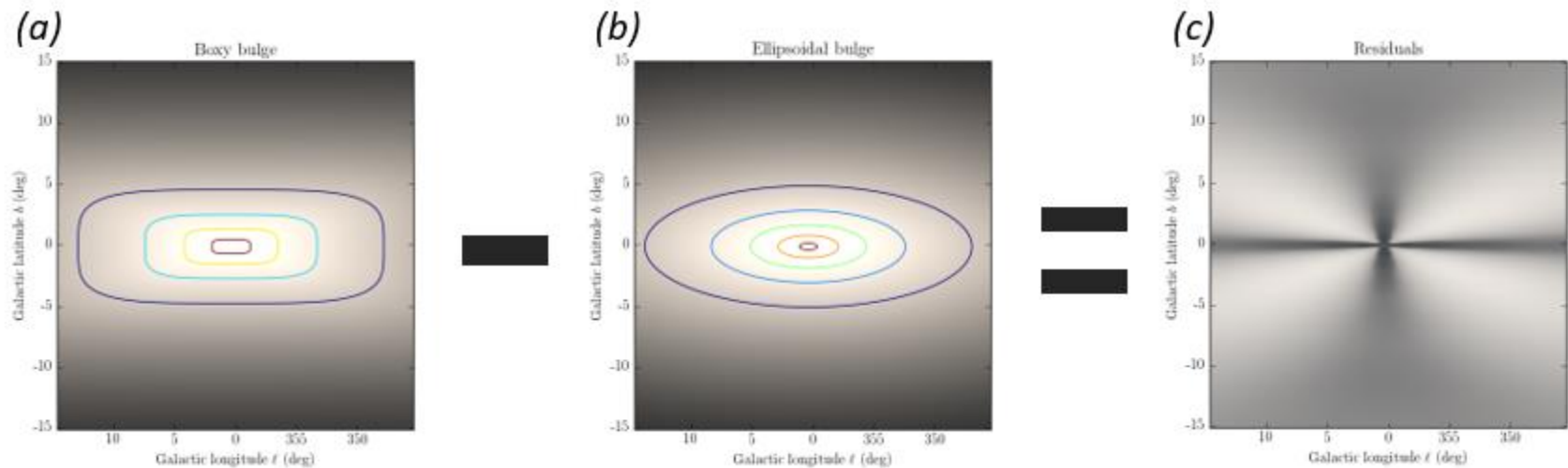
Bar + GC-origin-Bulge: blue



Ness & Lang 2016: X from WISE residual map?

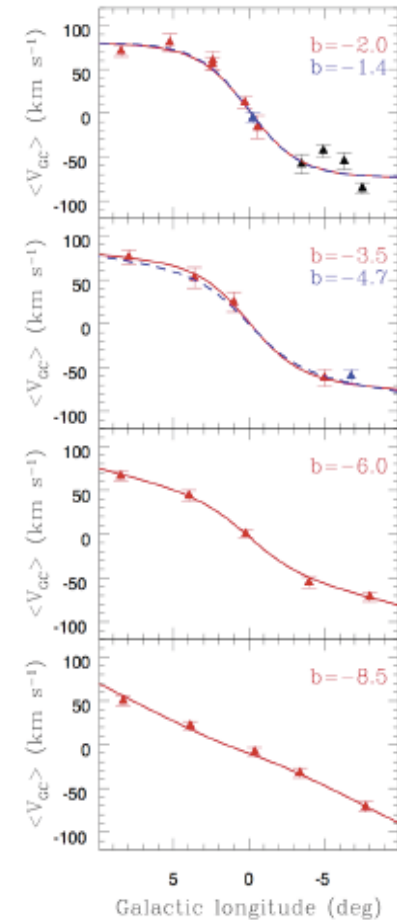
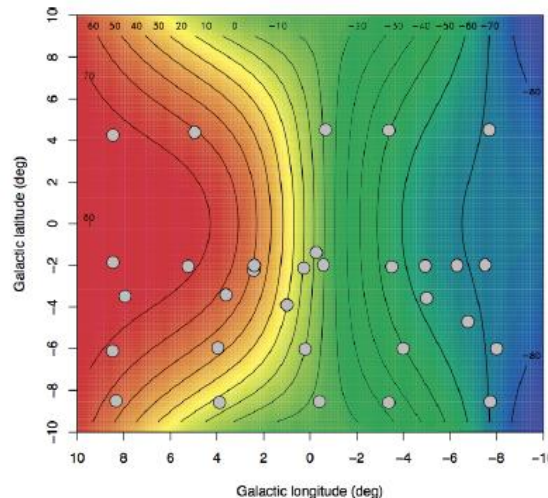
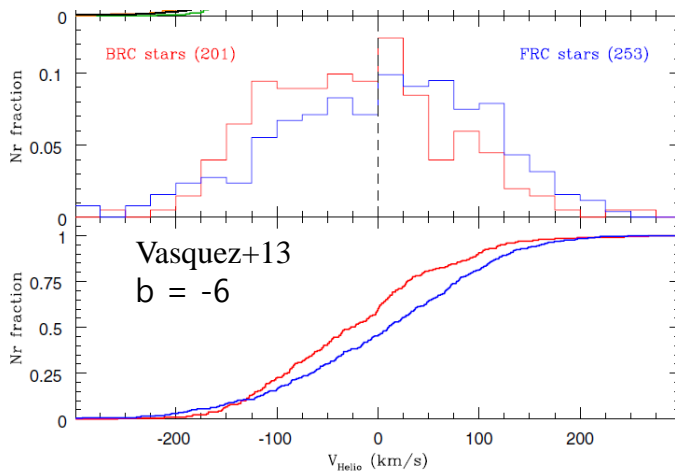


When an ellipsoid is subtracted from a boxy structure,
an artificial X-shaped structure always remains (Han & Lee 2018)



Observed kinematics are consistent with composite bulge (*Bar* + *GC-origin bulge*)!

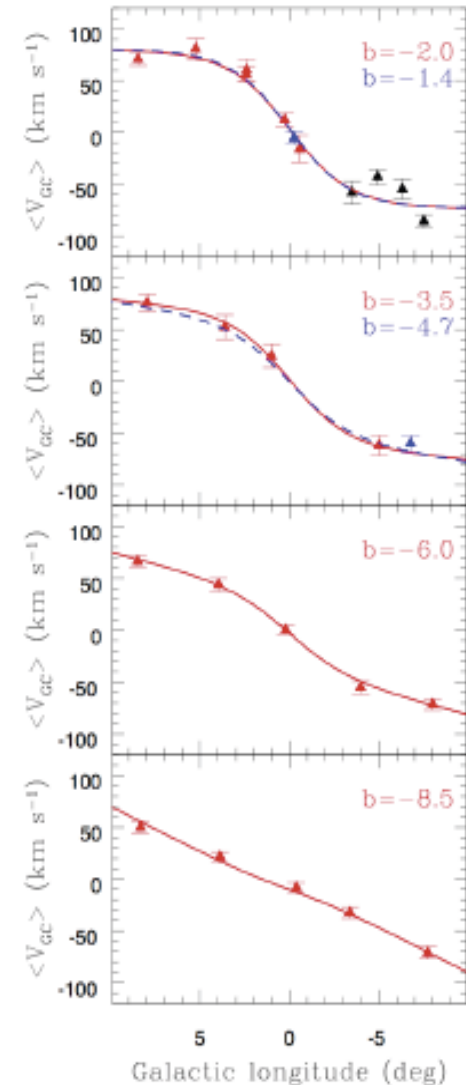
- **Cylindrical rotation at $l| < 6$** (Ness+13; Zoccali+14): *low lat. is dominated by bar*
- **Some ΔV_r (bRC – fRC) at $b = -6$** (Vasquez+13): *Bar + Bulge at low $l|$, & bar is in streaming motion*
- **No ΔV_r (bRC – fRC) at $b = -8, -10$** (De Propris+11; Uttenthaler+12; Rojas-Arriagada+14): *Consistent with our GC-origin bulge dominated scenario at high $l|$*



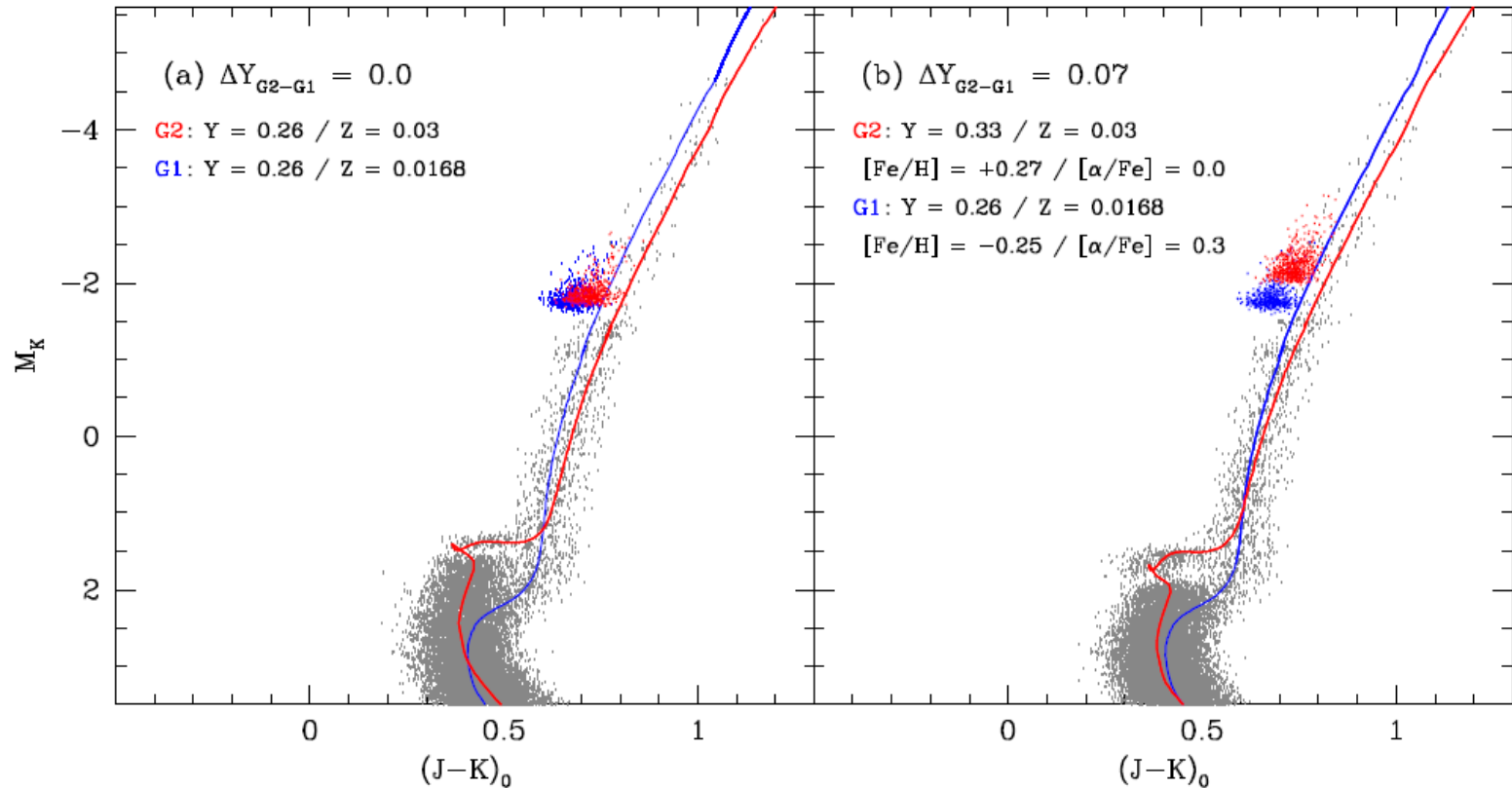
Observed kinematics at l $>$ 6 are consistent with GC-origin bulge!

- **Rotation at l $>$ 6** (Zoccali+2014, 15..)

- (1) Empirically, metal-rich GCs show significant rotation (~ 168 km/s; Zinn 1985, Y.-W. Lee+2007).
- (2) Theoretically, “clump-origin bulge” (Noguchi+1999; Elmergreen+ 2008; Inoue+Saitoh 2012) naturally shows significant rotation.
- (3) Recent cosmological hydro-N-body simulations predict GC-origin bulge with rotation (e.g. Kruijssen 2015; Pfeffer+2017; Renaud+2017).
- (4) “Classical bulge” even could absorb some angular momentum from the bar (K. Saha+2012, 15).

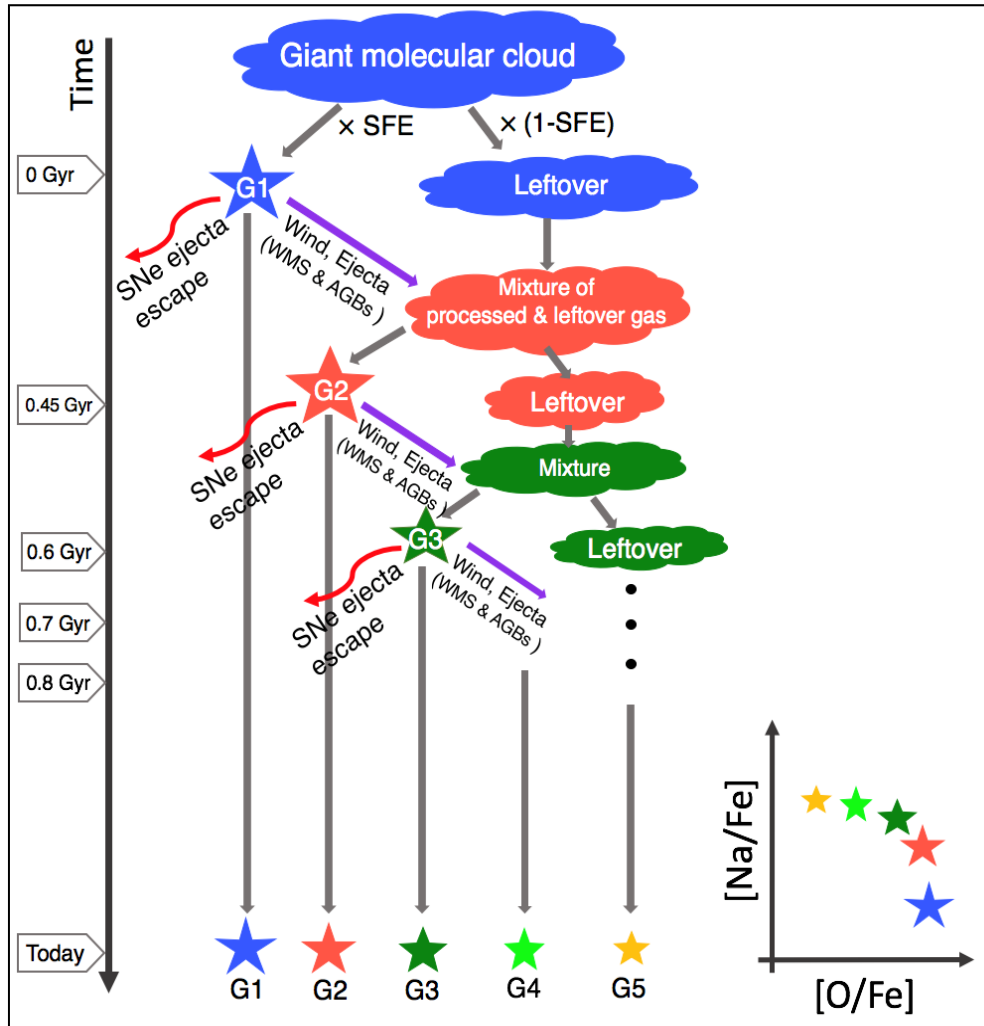


Terzan 5



When the observed Δt , $\Delta[Fe/H]$ & $\Delta[\alpha/Fe]$ (Ferraro+2016; Origlia+2011) are taken into account, **we still need a large $\Delta Y \sim 0.07$** (Joo, Lee, & Chung 2017)

Chemical Evolution Models (J. Kim & Y.-W. Lee 2018)



Major assumptions/ingredients:

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

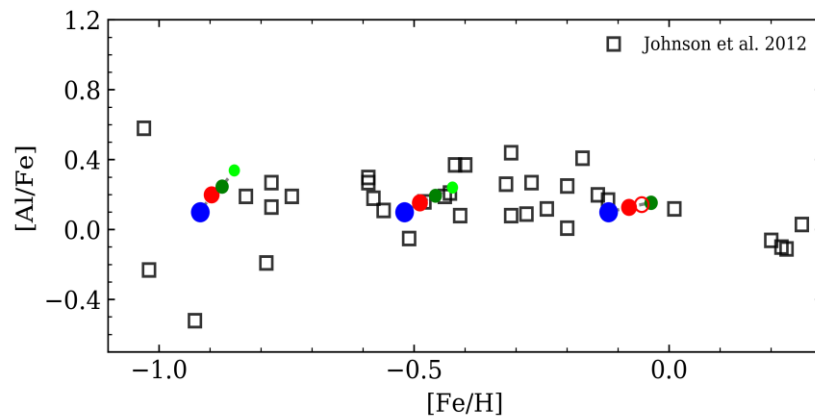
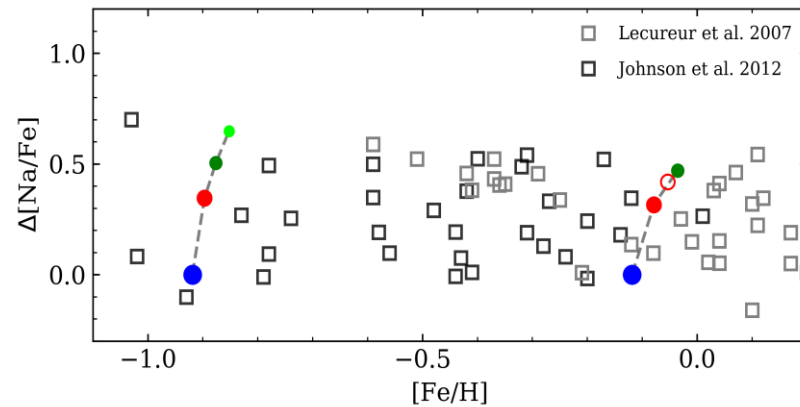
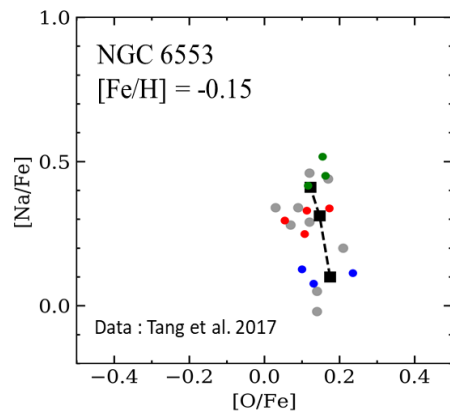
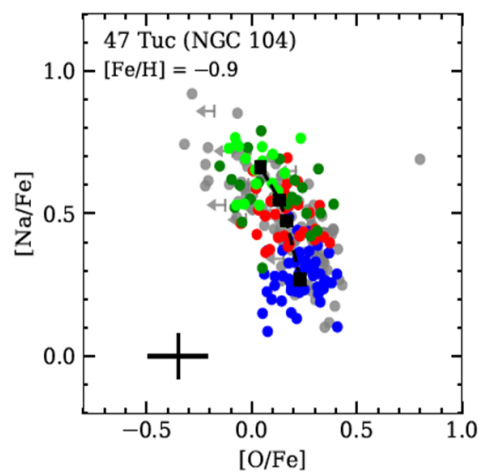
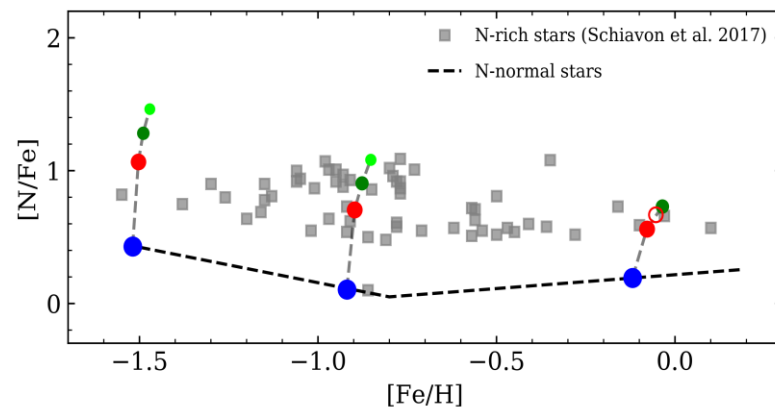
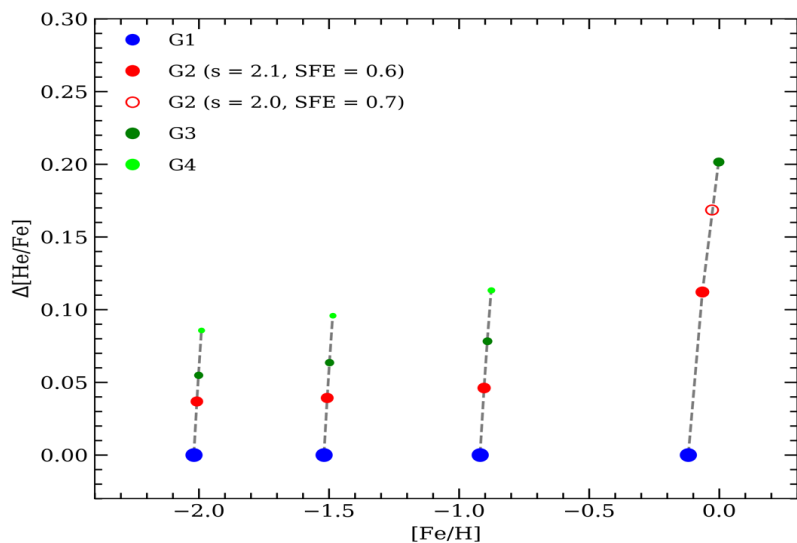
→ Chemical evolution is dictated by AGB & WMS (winds of massive stars)

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

3. IMF slope $s \sim 2$, SFE $\sim 60\%$

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

5. No "mass budget problem"



J. Kim & Y.-W. Lee 2018

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 2018).
4. The **bright RC stars are enhanced in CN**, which traces N, Na, & He! The $\Delta \text{CN}(\text{bRC-fRC})$ is consistent with $\Delta \text{CN}(\text{G2-G1})$ observed in GCs! (Lee, Hong, & Lim 2018)
5. The **Na bimodality** among bulge RGB stars! Na-rich stars are also Al-rich, which is exactly the behavior we would expect from stars originated in GCs. The Na spread in the true bulge is 2-3 times larger than that of the disk (bar) population. **Population ratio $\text{G2/G1} = \sim \text{bRC/fRC}$!**
6. Our models can reproduce key observations: **$\text{double RC} = f([\text{Fe}/\text{H}], b, l)$** (Lee+2015; Joo+2017)
7. Our (composite bulge) model is **consistent 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 2018).
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, & RR Lyraes** (Lopez-Corredoira 2016, 2017; Pietrukowicz+2015).