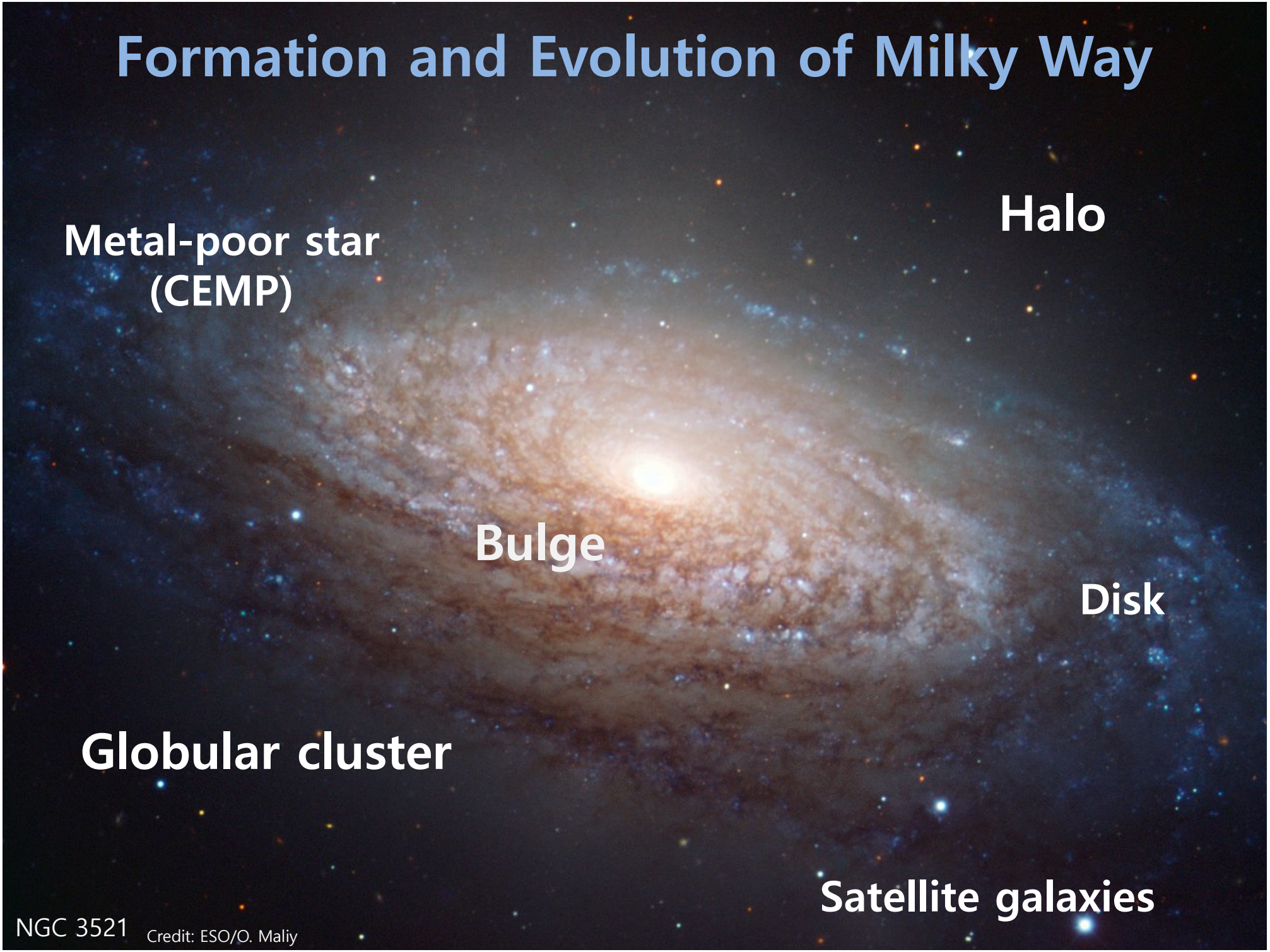
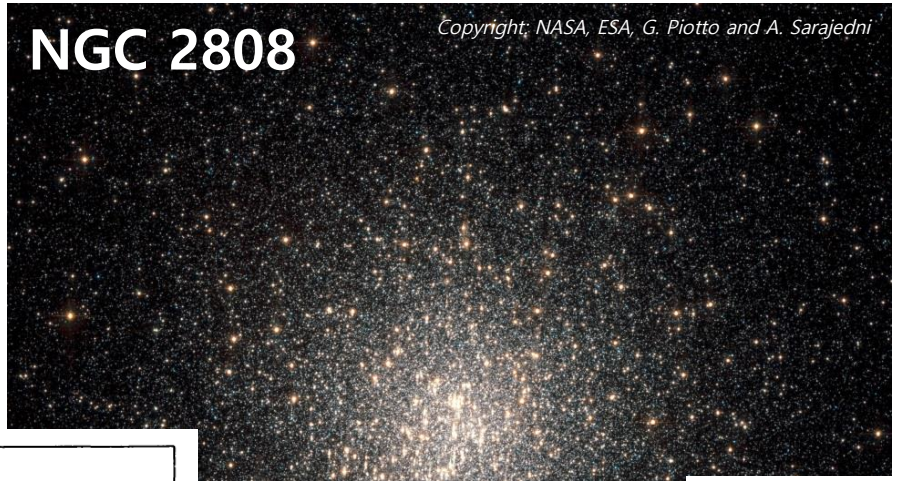
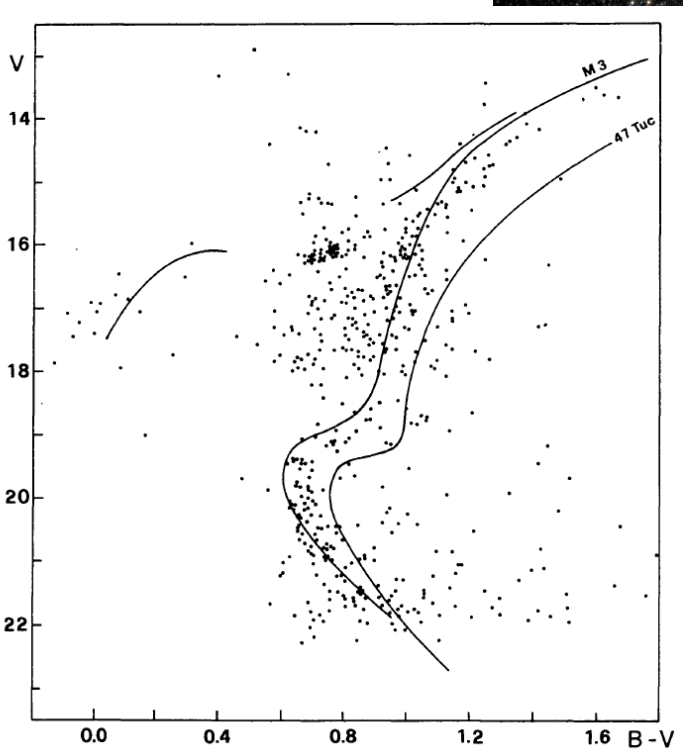
Multiple Stellar Populations in the Globular Clusters and Milky Way Bulge


Formation and Evolution of Milky Way
Halo
Metal-poor star
(CEMP)
Bulge
Disk
Globular cluster
Satellite galaxies
NGC 3521
Credit: ESO/O. Maliy

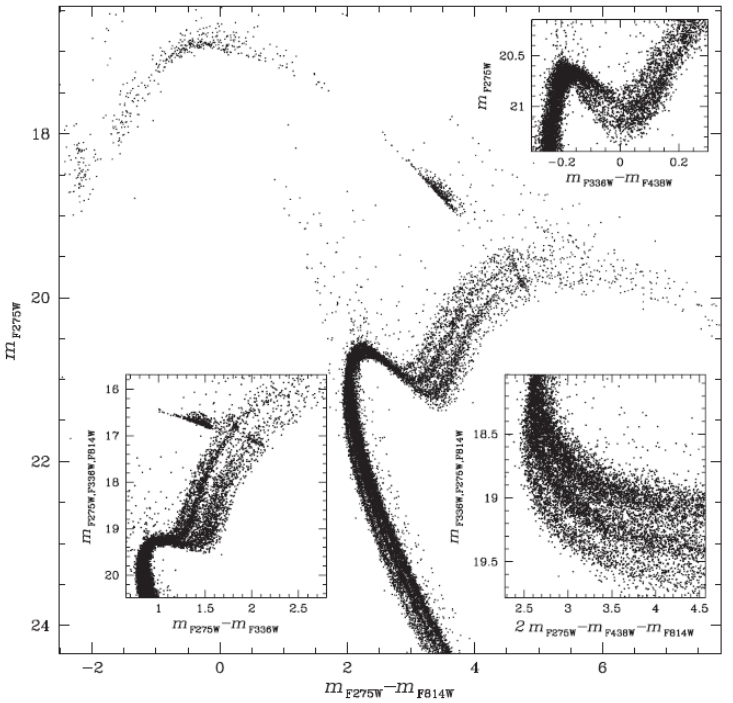
Globular Clusters with Multiple Populations





Gratton & Ortolani 1986

Danish 1.5m telescope

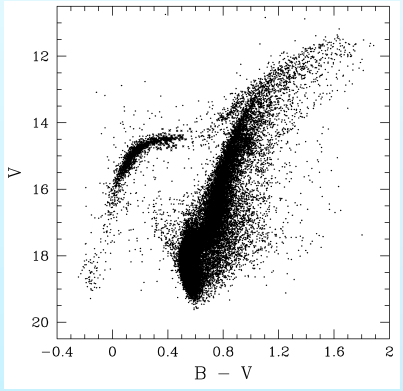


Milone et al. 2015

Hubble Space Telescope

To reach this stage

Photometry



Multiple population in ω-Cen
Lee et al. 1999

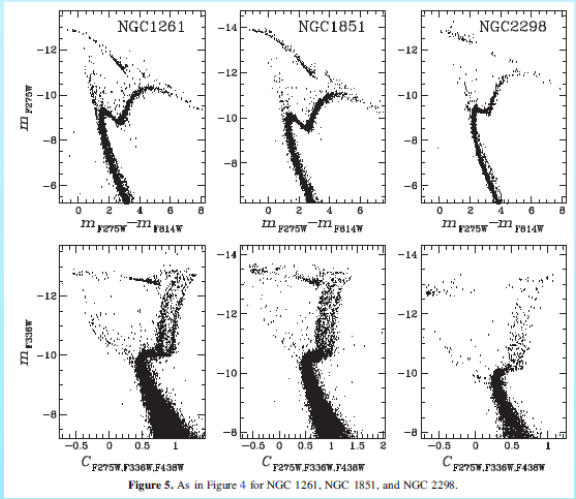
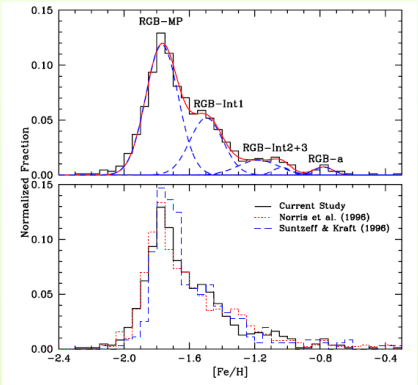


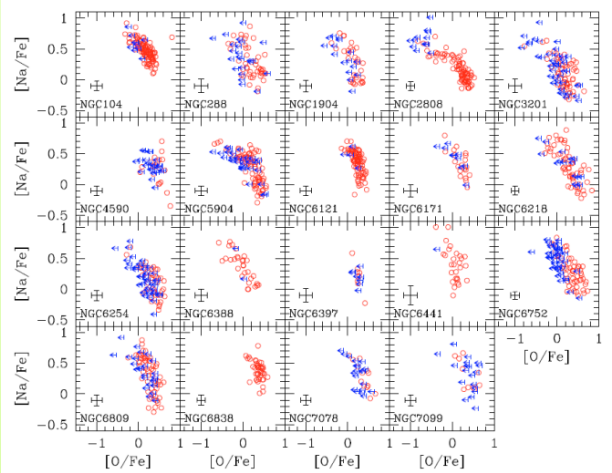
Figure 5. As in Figure 4 for NGC 1261, NGC 1851, and NGC 2298.

HST UV Legacy Survey *Piotto et al. 2015*

Spectroscopy

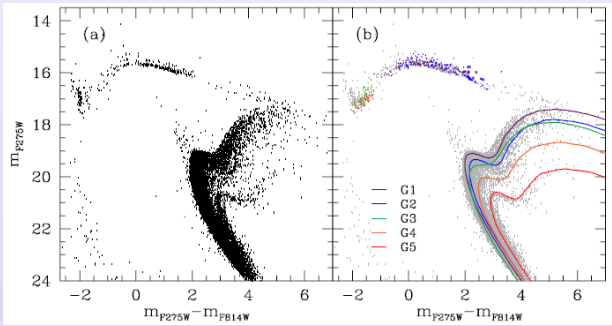
[Fe/H] variation in ω-Cen
Johnson & Pilachowski 2010





Na-O anticorrelation *Carretta et al. 2009*

Theory/Model



Stellar population model for ω-Cen
Joo & Lee 2013

Time (Myr)	0–3	5–40 → 8	40–60 8–6.5	60–90 6.5–5	90–100 ~5	100–120–? 5–4	>200 <3
$M/M_{\odot}$							
Population	FG	No SF	Extreme	Intermediate	late–interm., CNO, s and Fe enriched		
Events	FG	SN II	SAGB	Massive AGB s-process ↑	CNO ↑ s-process ↑ ↑ →	CNO ↑ ↑ → Yes/No	C-star type ejecta
				← ← ← ← ← ← ← ← SN II → → → → → → → → → delayed		→ → SN Ia → →	
				..... Episodes of re-accretion.....			
				Classic clusters			
NGC 2808	FG	No SF	Pure ejecta SF	Diluted gas SF	Strong diluted SF	First SN Ia SF, SN Ia epoch	
NGC 2419	FG	No SF	Pure ejecta SF	← ← ← ← Delayed SN II epoch → → → →		SN Ia epoch	
M4	FG	No SF	← ← Diluted gas SF → →		Stop (SN Ia?)		
				Double SGB clusters			
M22, NGC 1851, NGC 6656, NGC 5286	FG	No SF	First dilution SF Fe initial	Delayed SN II epoch no SF	Fast recollapse, burst SF, Fe ↑	SN Ia epoch	
				Triple SGB clusters			
M2	FG	No SF	First dilution SF Fe initial	Delayed SN II epoch no SF	Fast recollapse, burst SF, Fe ↑	First SN Ia SF, SN Ia epoch SF Fe ↑↑	

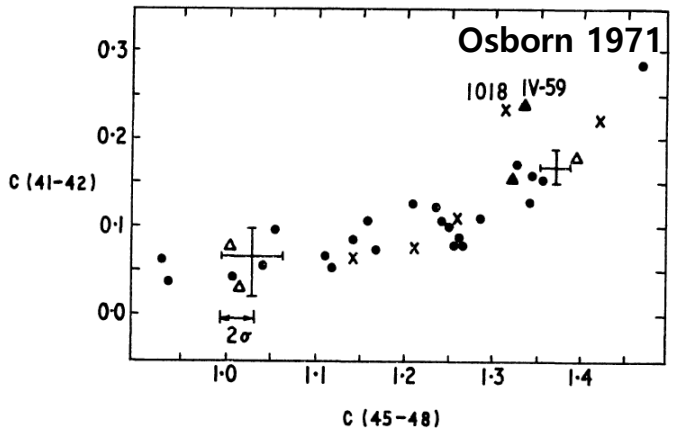
Single model for multiple population
D'Antona et al. 2016

Globular Cluster
with
Multiple Stellar Populations

Low Resolution Spectroscopy

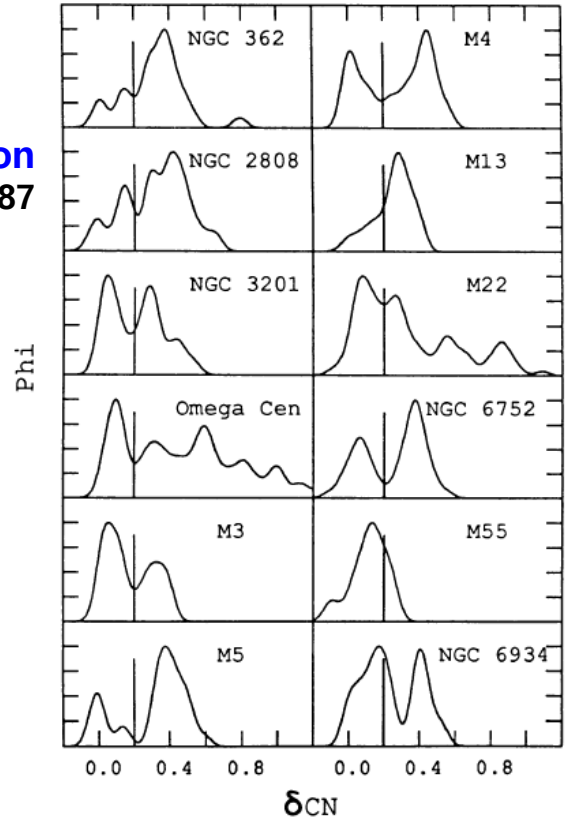
40 years ago!

CN-strong stars in M5 and M10

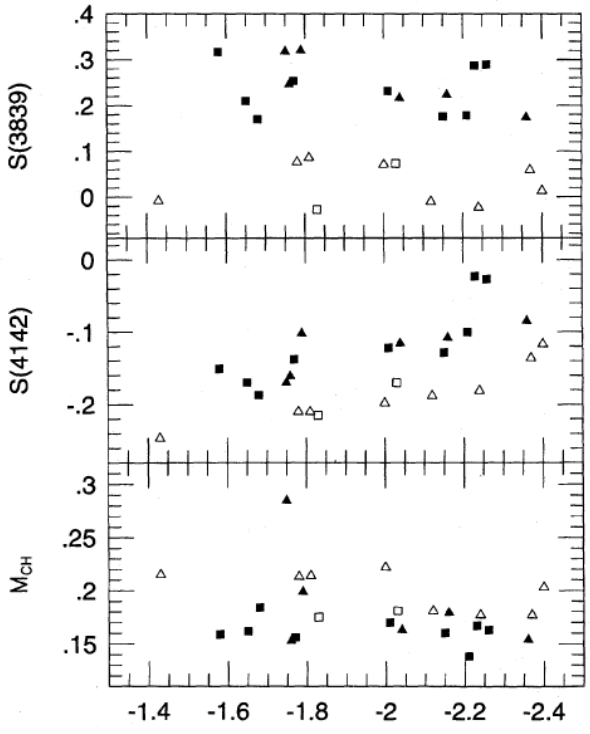


CN distribution

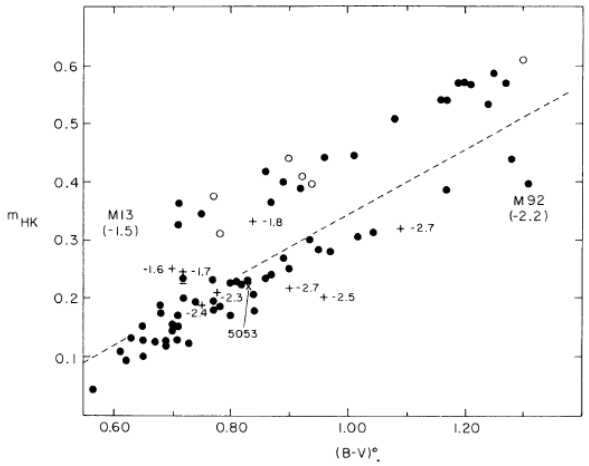
Norris 1987



CN-CH anticorrelation



Smith et al. 1996



Calcium line strength

Suntzeff 1980

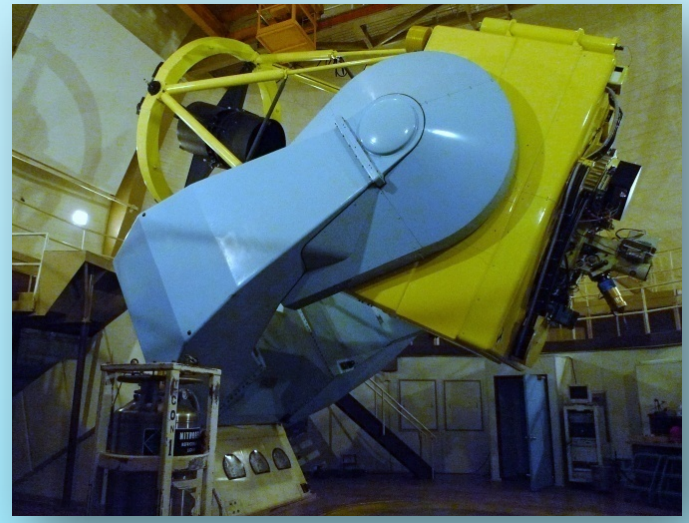
Low resolution spectroscopy was a useful probe to study globular clusters.

Low resolution spectroscopy in multiple population phenomenon

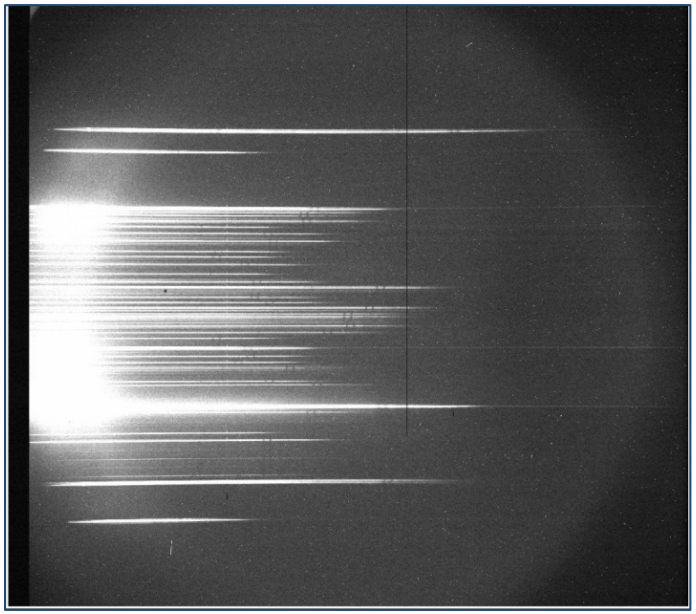
Low-Resolution Spectroscopy

The 2.5m Irénée du Pont Telescope at LCO, Chile

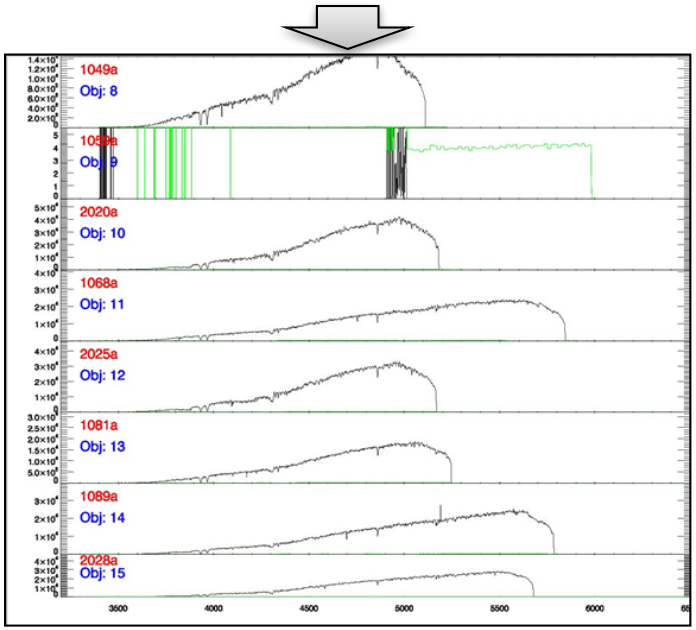
- **Observations: June 2011 ~ June 2017**
- **Multi-object spectroscopy**
- **WFCCD** (Wide Field Reimaging CCD camera)
- FOV ~ 25′ x 25′
- HK grism
- Pixel scale ~ 0.484 ″/pix
- Dispersion ~ 0.8 Å/pix
- Central wavelength ~ 3700Å
- **RGB stars in 14 Milky Way GCs**



du Pont 2.5m telescope



Raw data



SEDs

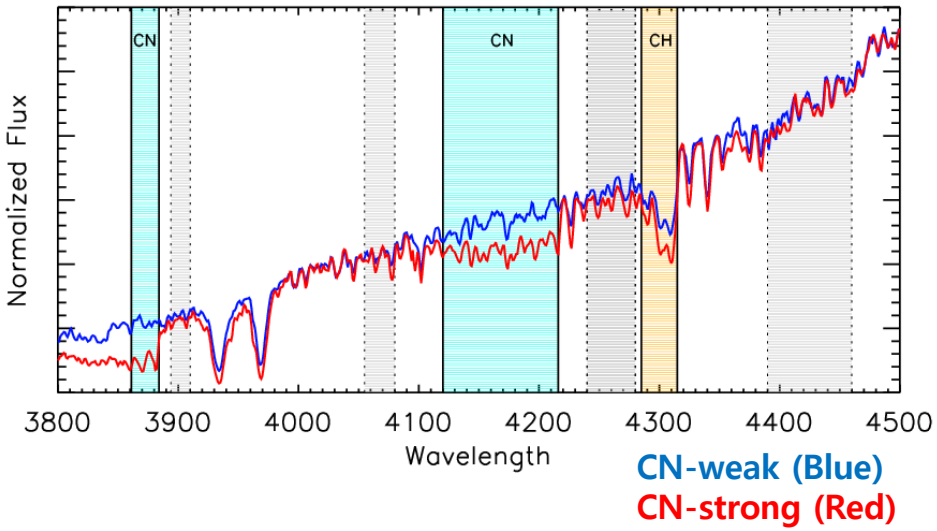
Spectral Indices (CN, CH & HK')

Light element (CN & CH)

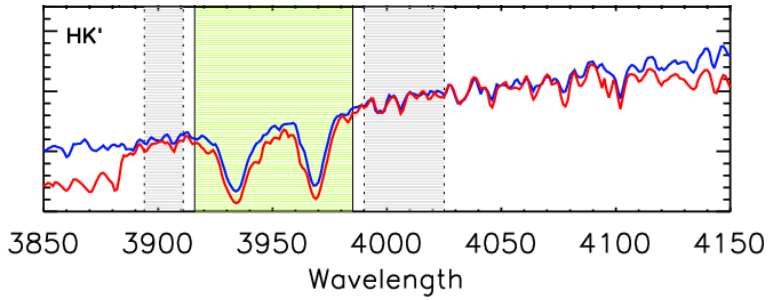
$$S(3839) = -2.5\ \log \frac{\int_{3861}^{3884} F_\lambda}{\int_{3894}^{3910} F_\lambda}$$

$$CH4300 = -2.5\ \log \frac{\int_{4285}^{4315} F_\lambda}{0.5 \int_{4240}^{4280} F_\lambda + 0.5 \int_{4390}^{4460} F_\lambda}$$

(Norris & Freeman 1979)



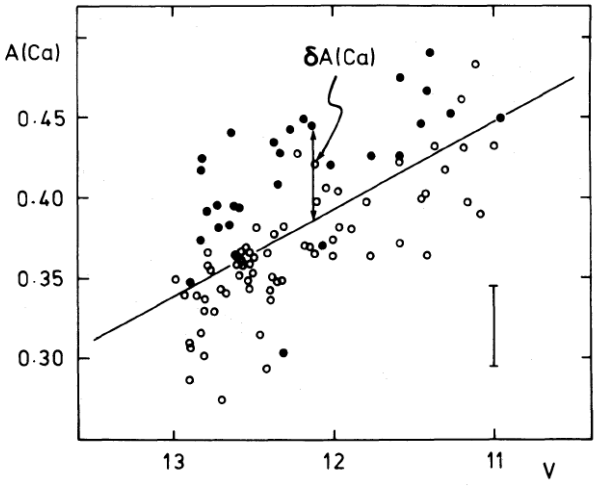
CN-weak (Blue)
CN-strong (Red)



Heavy element (Calcium)

$$HK' = -2.5\ \log \frac{\int_{3916}^{3985} F_\lambda}{2 \int_{3894}^{3911} F_\lambda + \int_{3990}^{4025} F_\lambda}$$

(Lim et al. 2015)



Delta (δ) Index

Absorption line = **Abundance** + T_{eff} + Surface Gravity

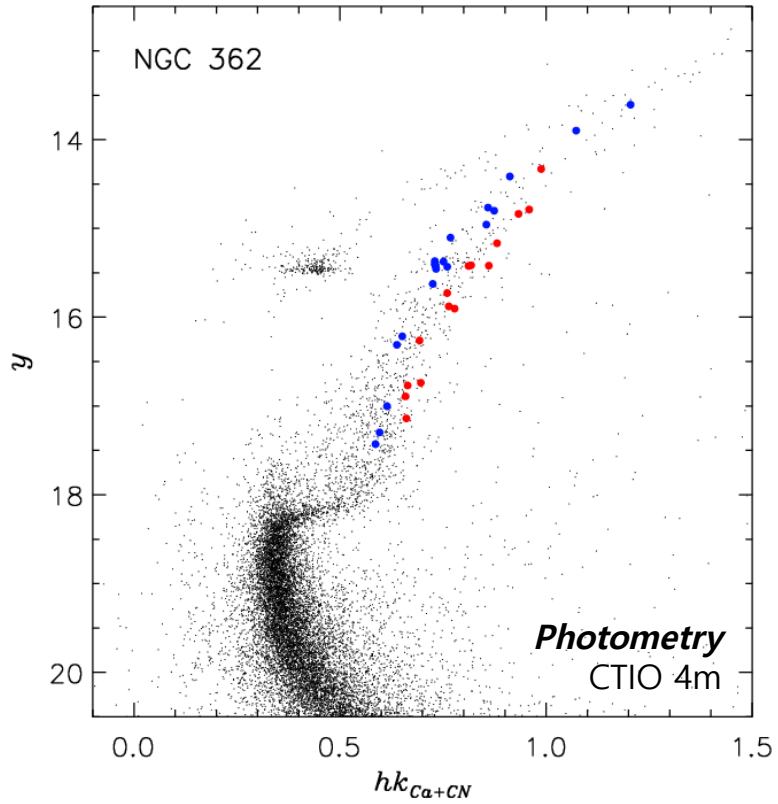
- We calculated delta indices (**δCN**, **δHK'**, and **δCH**) as the difference between original values and least square fitting lines to minimize the effect of effective temperature and surface gravity.

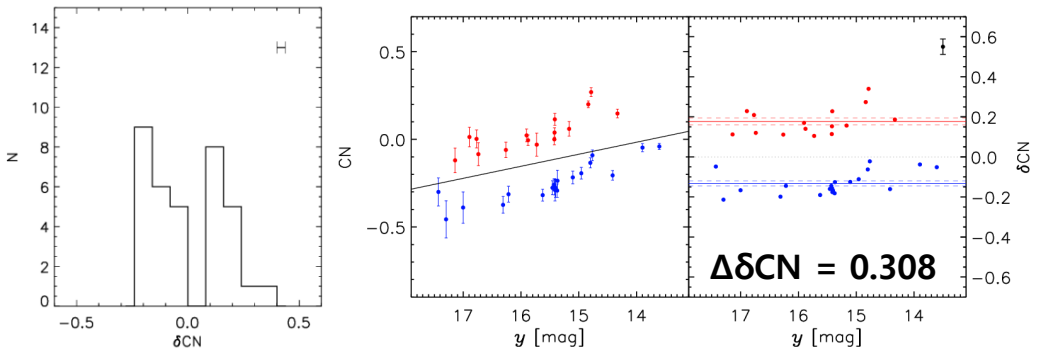
Norris & Freeman 1983

δA(Ca) index

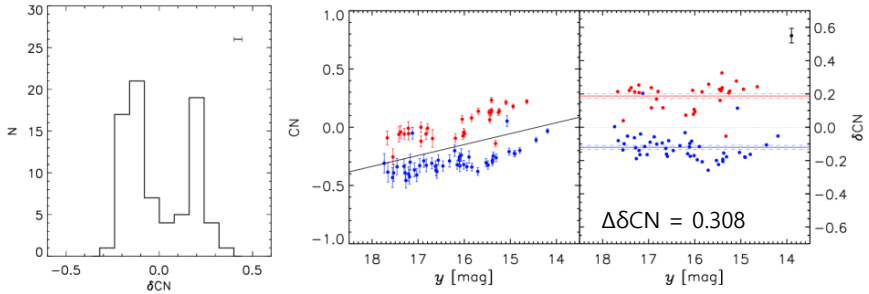
1. Multiple populations with different CN index

NGC 362

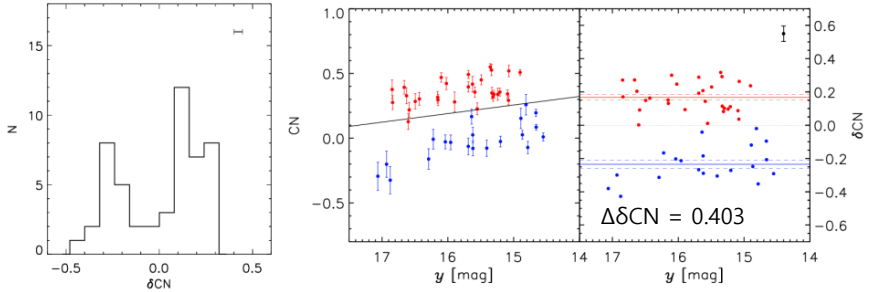




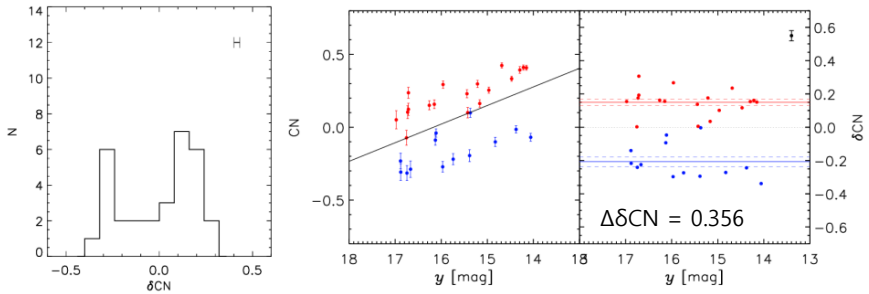
NGC 288



NGC 6266



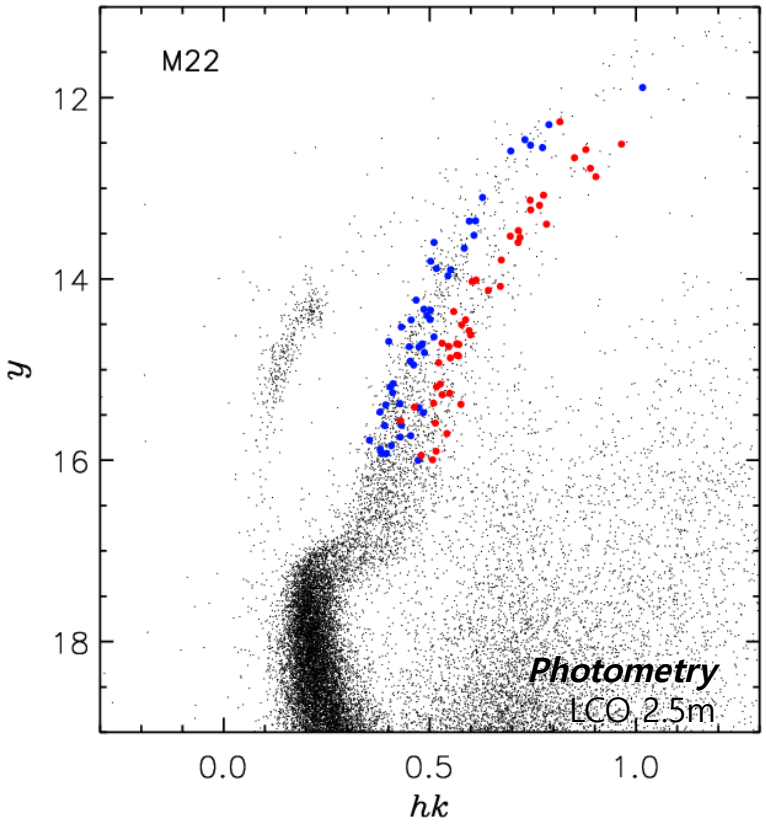
NGC 6723

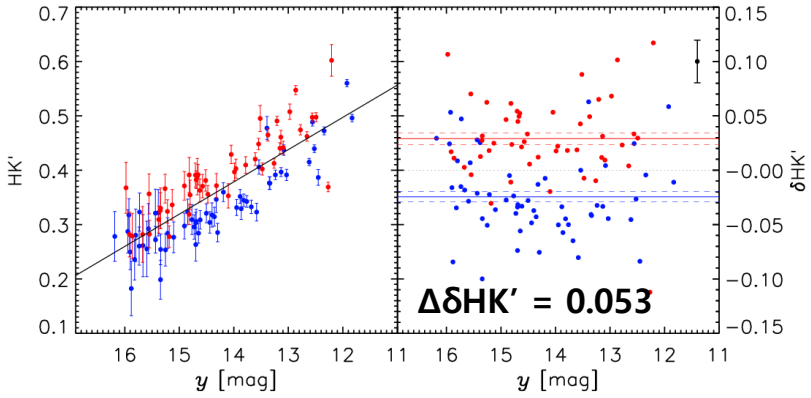


✓ We find multiple stellar population with different CN index in every target GCs, except NGC 6397.

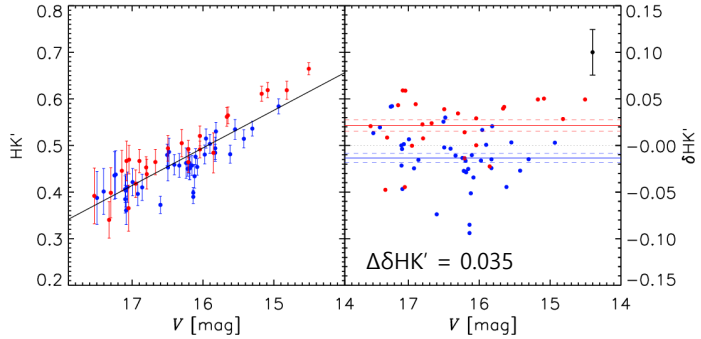
2. Multiple population with different HK' index (Ca)

M22

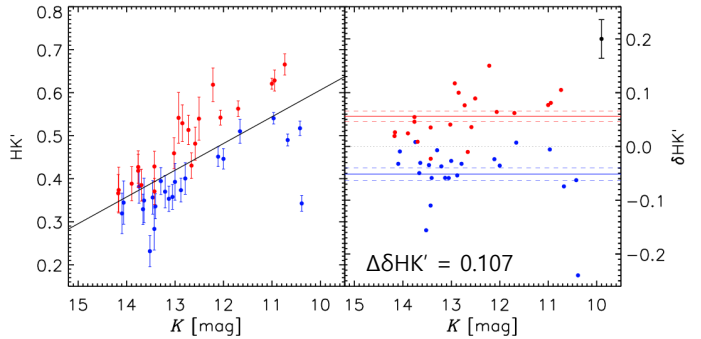




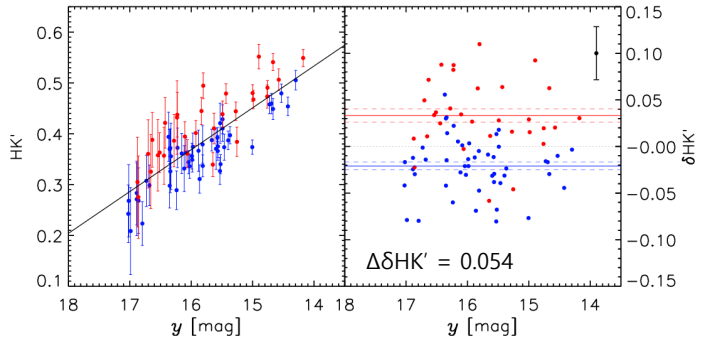
NGC 1851



NGC 5286

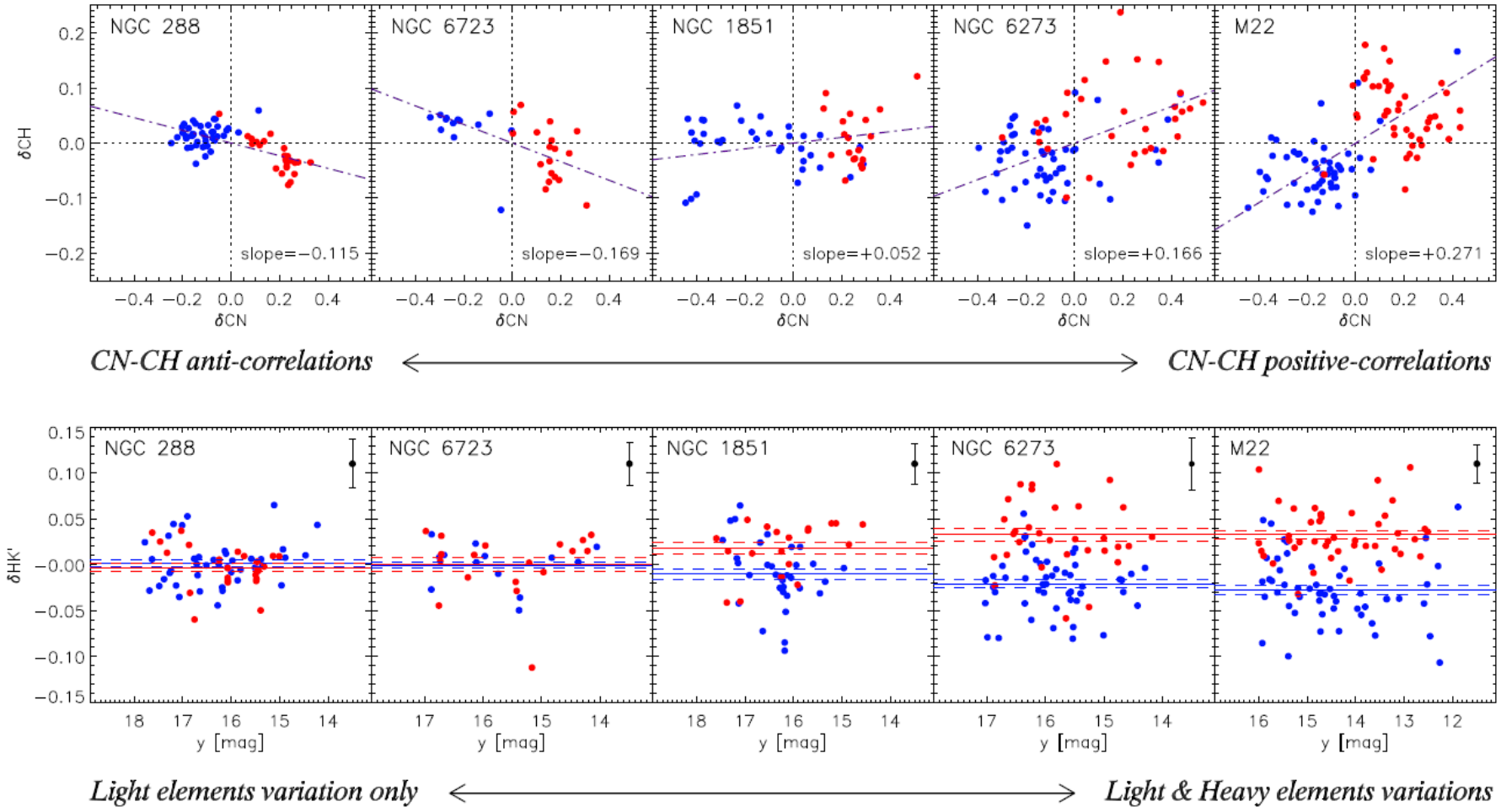


NGC 6273



✓ We find multiple stellar population with different Ca abundance in M22, NGC 1851, NGC 5286, and NGC 6273

3. CN-CH anti & positive correlation



NGC 288, NGC 362, NGC 6266, NGC 6723, and etc.

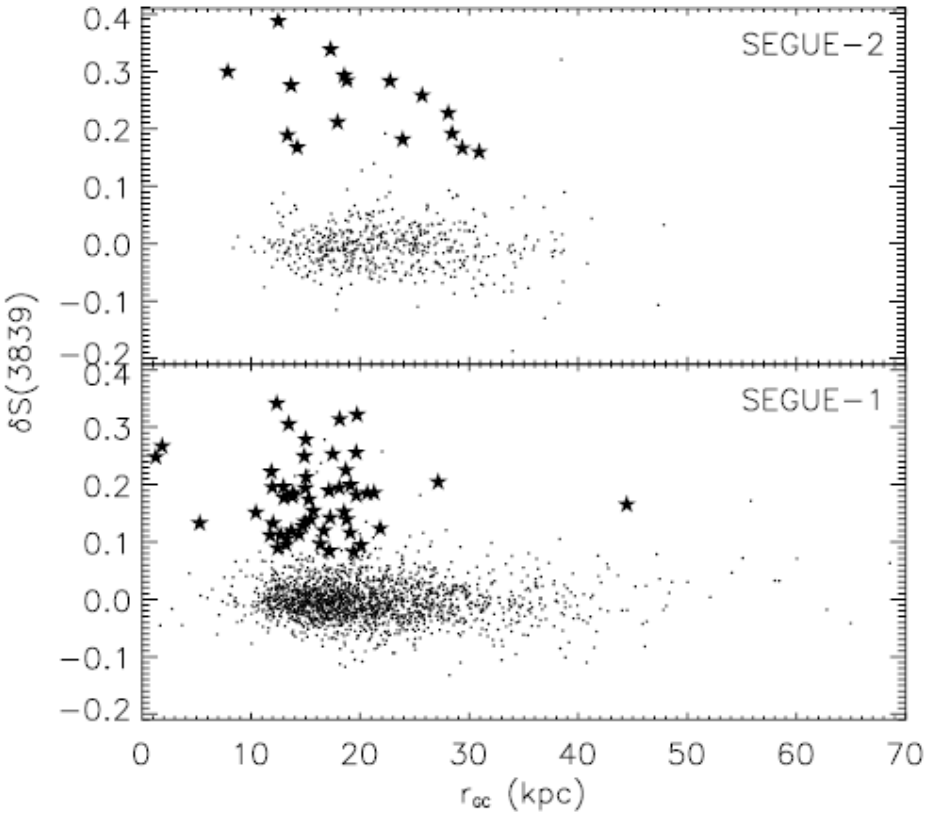
NGC 1851

M22, NGC 5286, NGC 6273

- ✓ The origin of the CN-CH positive correlation appears to be explicitly relevant to the heavy element variations.
- ✓ The CN-CH positive correlation can be a useful probe for the GCs with heavy element variations.

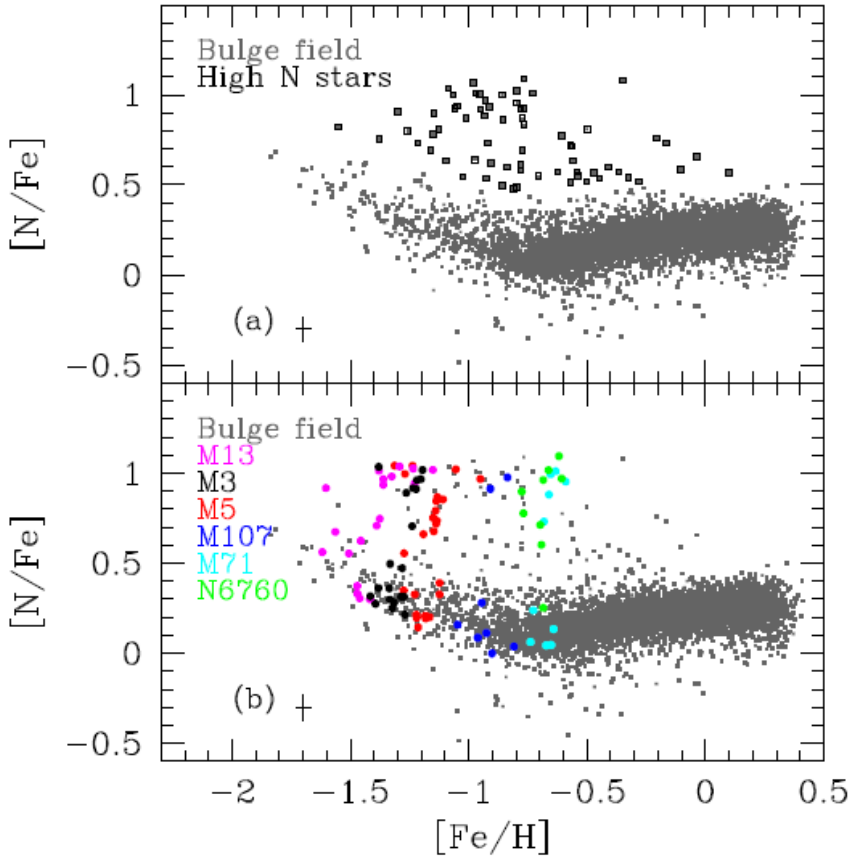
Contribution of GCs to the Milky Way formation

Halo



SDSS-III/SEGUE-2 Spectra
Martell et al. 2011

Inner Galaxy



Chemical tagging with APOGEE
Schiavon et al. 2017

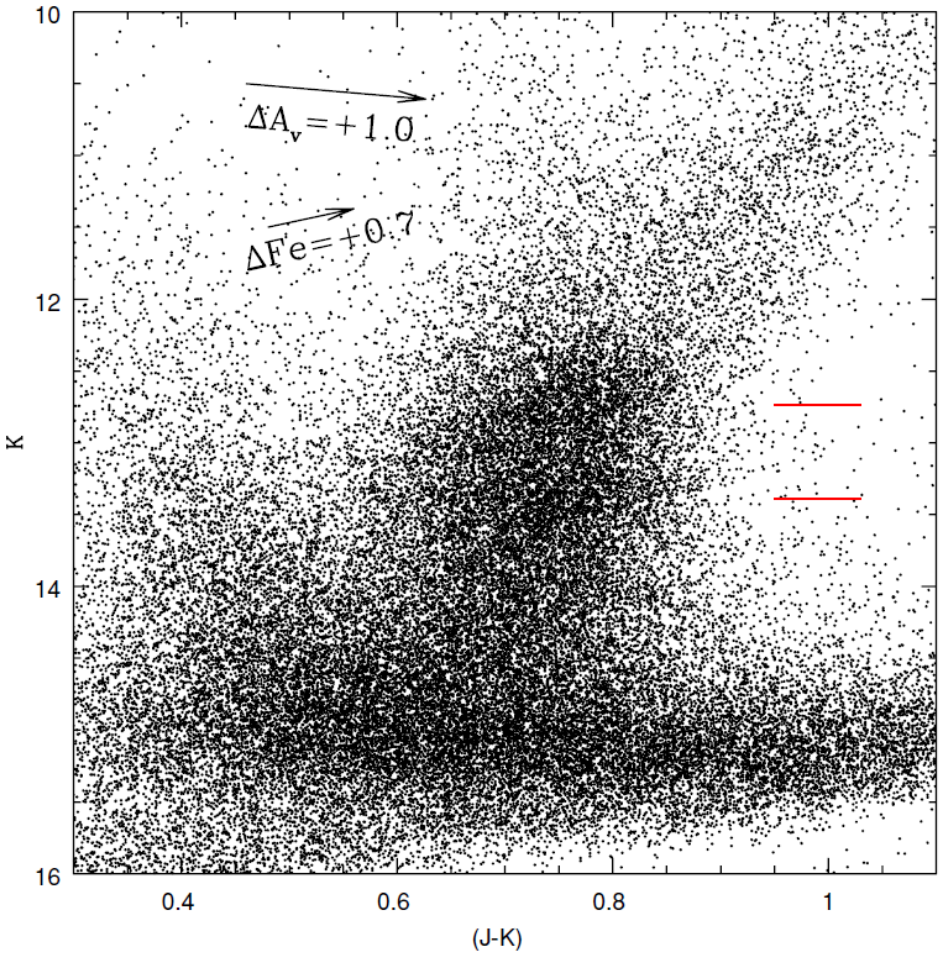
CN-strong / CH-weak stars

Originate from
Globular Cluster

High N stars

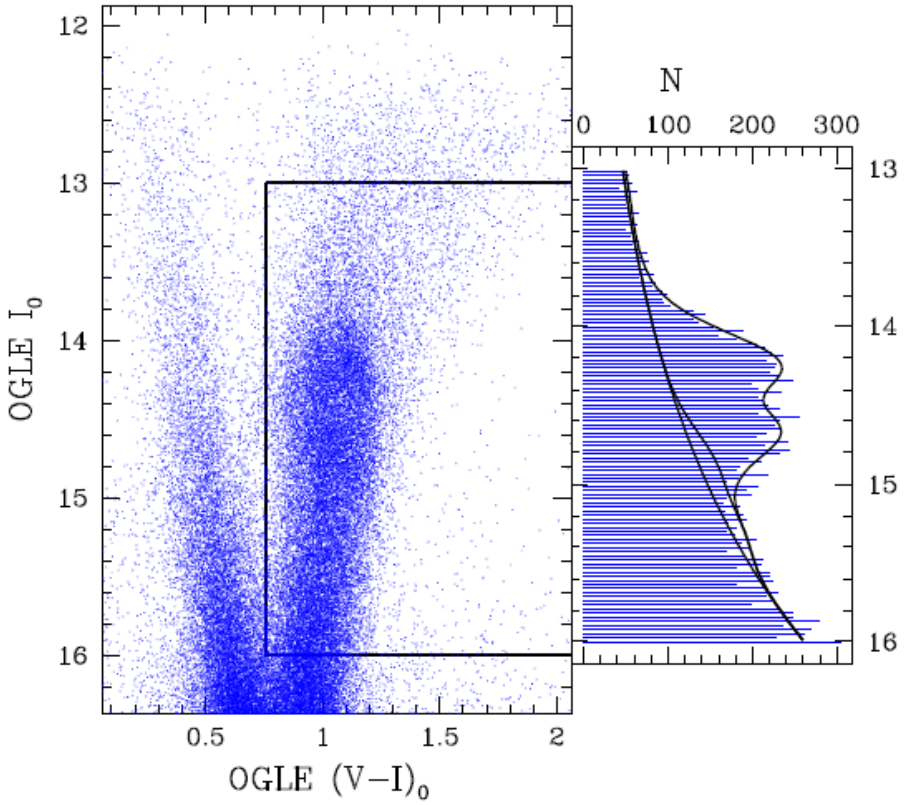
Double Red Clumps in the Bulge

(l, b) = (-1, -8)



2MASS (*K, J-K*) CMD
McWilliam & Zoccali 2010

(l, b) = (0.27, -6.31)

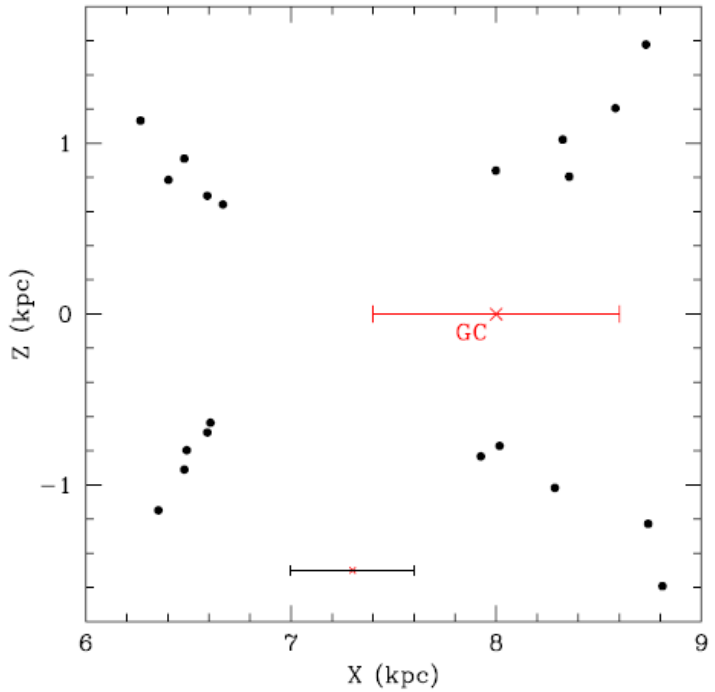


OGLE (*I, V-I*) CMD
Nataf et al. 2015

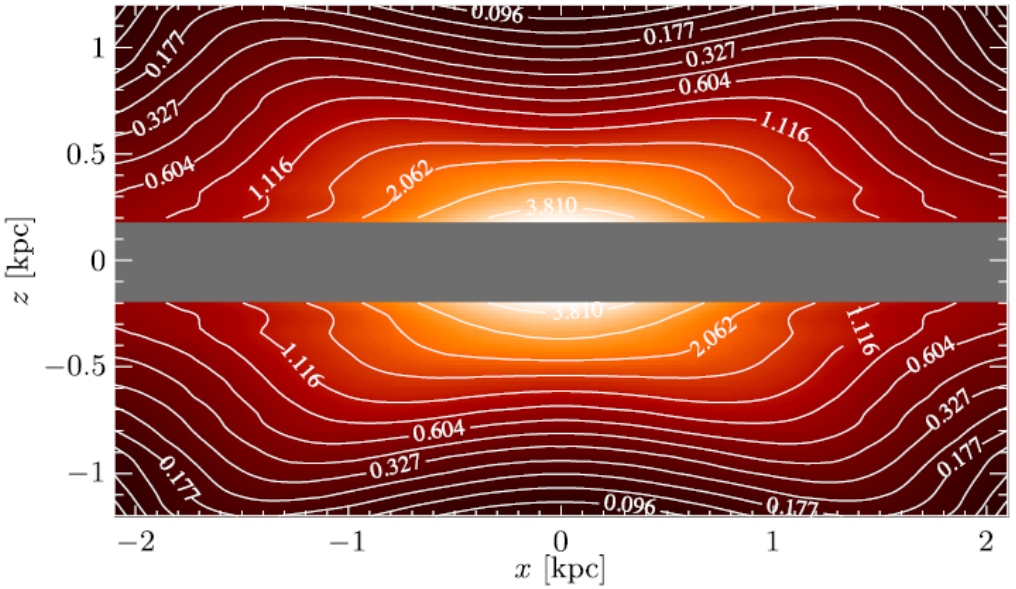
✓ **The presence of double red clumps was discovered in the higher latitude fields of the Milky Way bulge from the wide-field photometric survey (e.g., 2MASS, OGLE).**

X-Shaped Bulge Scenario (120+ papers)

McWilliam & Zoccali 2010



VVV survey - Wegg & Gerhard 2013

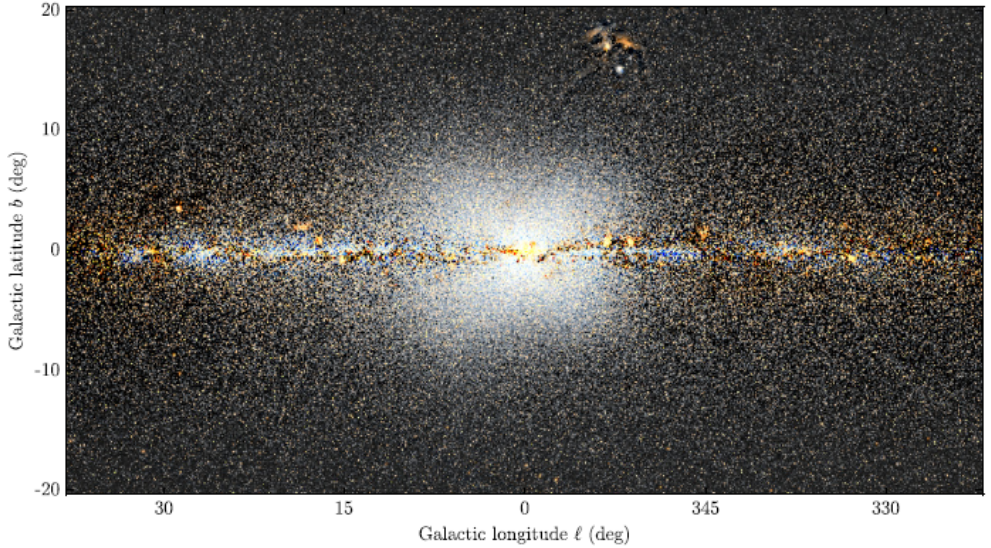


Bright RC ⇒ ***foreground***

Faint RC ⇒ ***background***

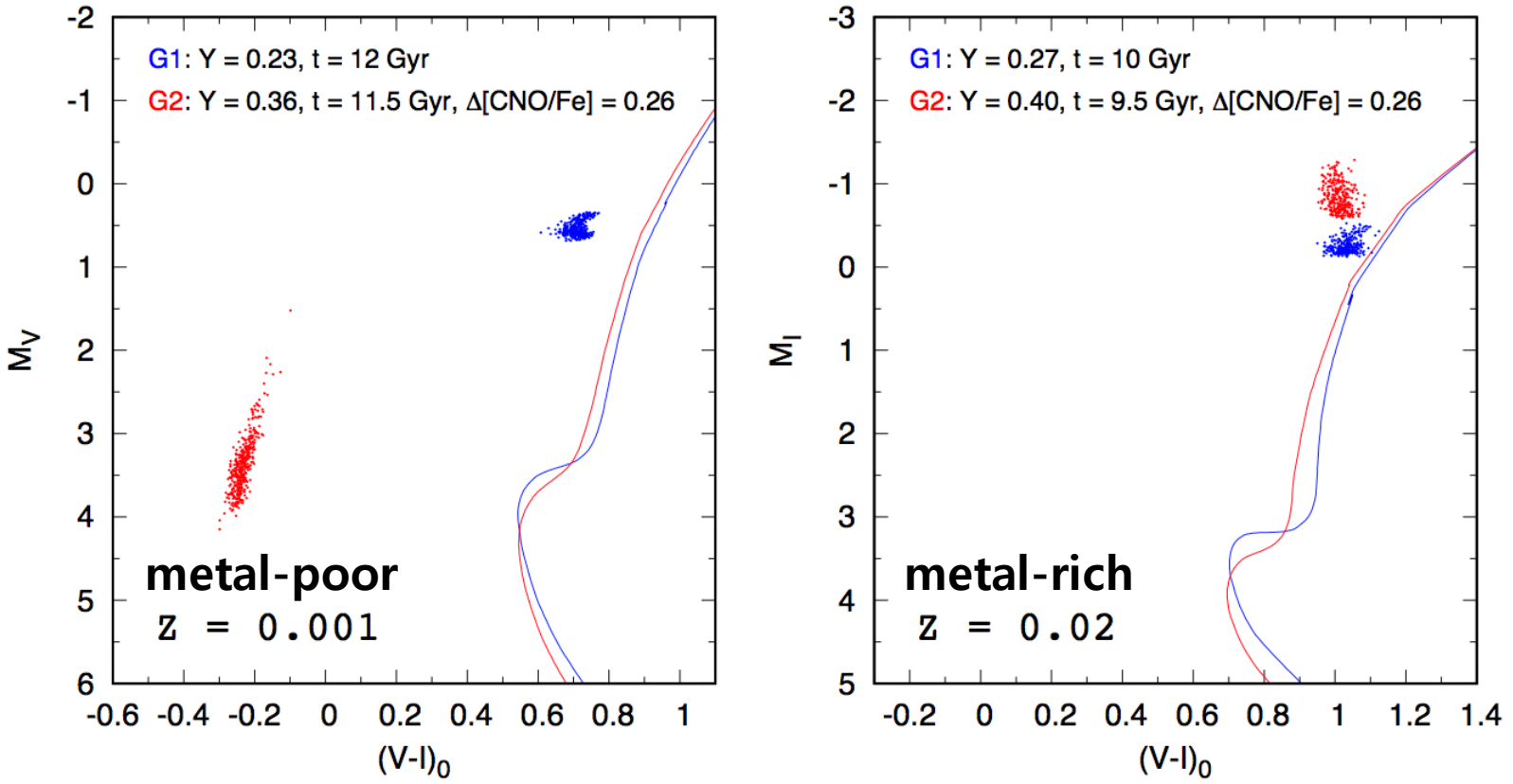
✓ The double RC is widely accepted as evidence for an **X-shaped structure** is originated from the **disc and bar instabilities**.

WISE image - Ness & Lang 2016



Multiple Populations Scenario

Lee et al. 2015; Joo et al. 2017



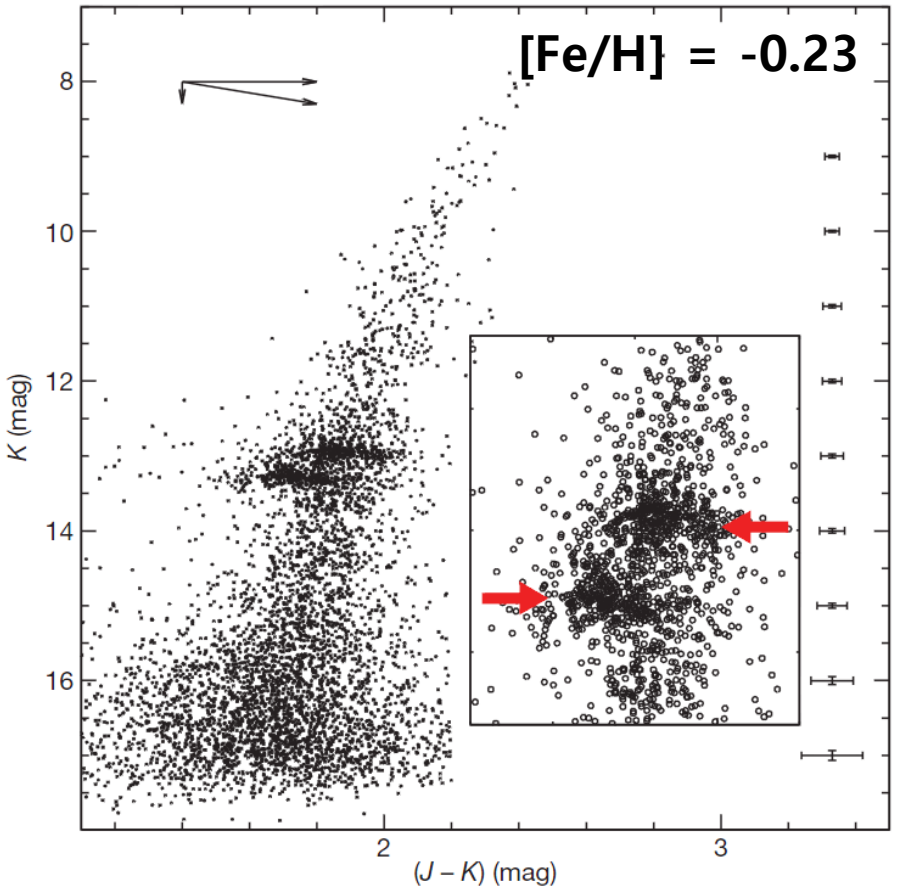
Bright RC ⇒ ***He-enhanced later generation stars (G2)***

Faint RC ⇒ ***He-normal earlier generation stars (G1)***

- ✓ In the metal-rich regime, He-rich HB stars are placed on the brighter RC.
- ✓ The double RC might be different manifestation of the **multiple populations phenomenon** in the **metal-rich regimes**.

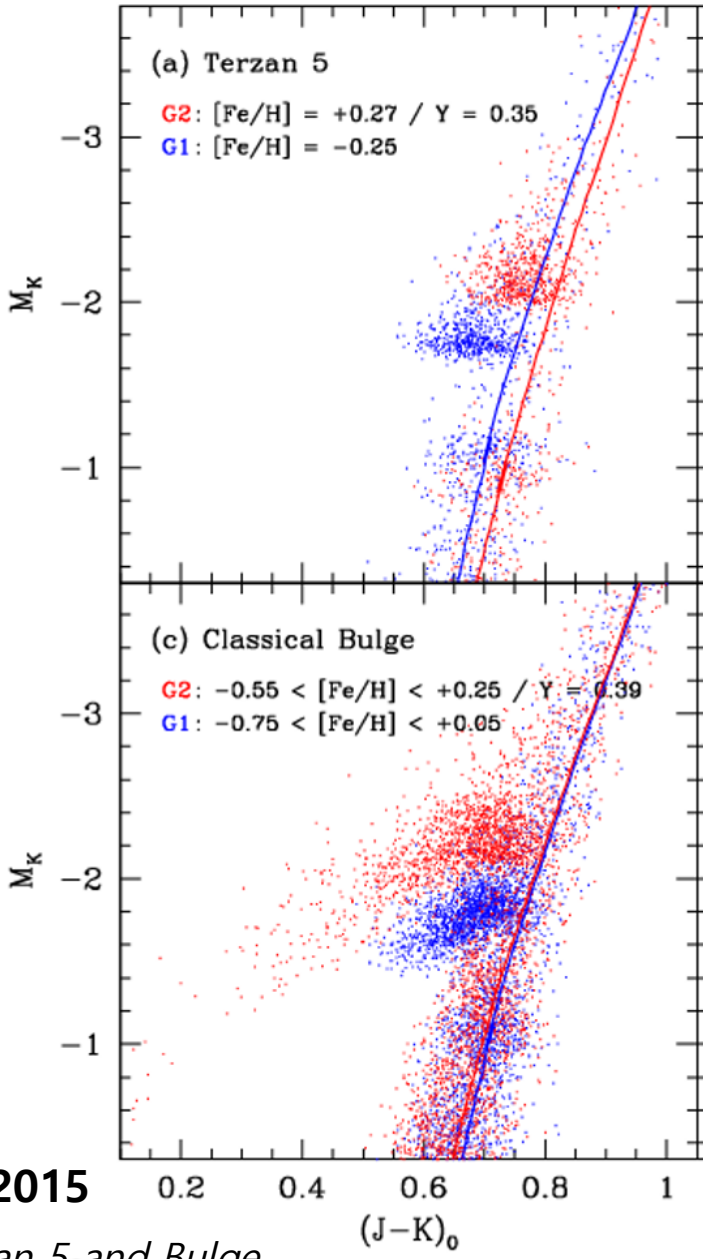
Metal-rich Bulge Globular Cluster: Terzan 5

Two HB clumps of Terzan 5



Ferraro et al. 2009

Age difference
and/or
He difference

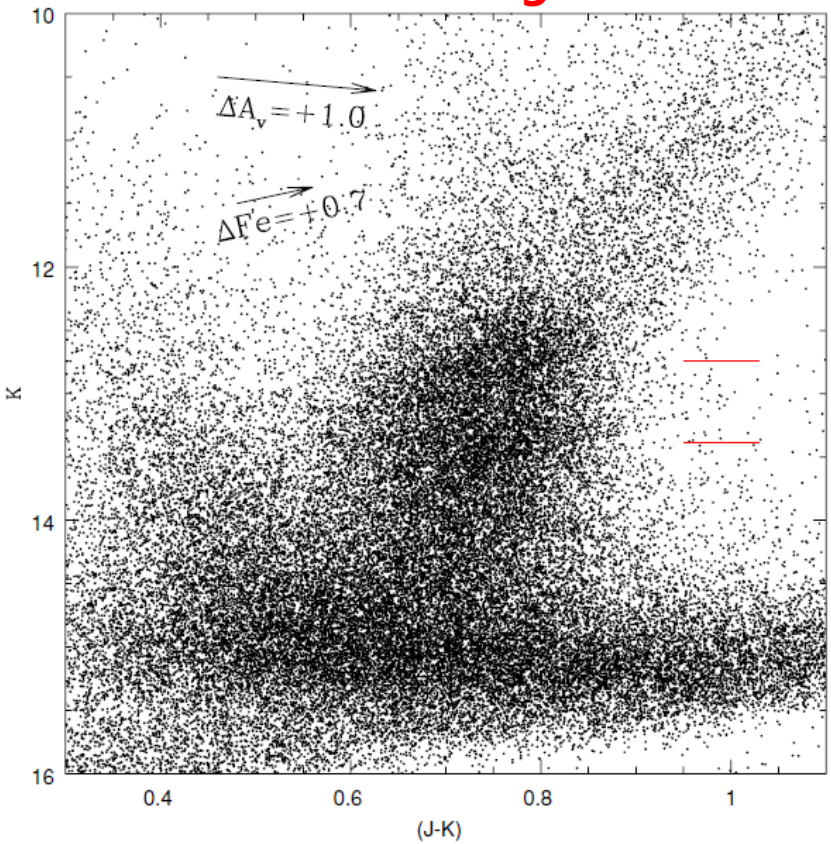


Lee et al. 2015

Synthetic CMDs for Terzan 5 and Bulge

Origin of double RC in the Galactic Bulge

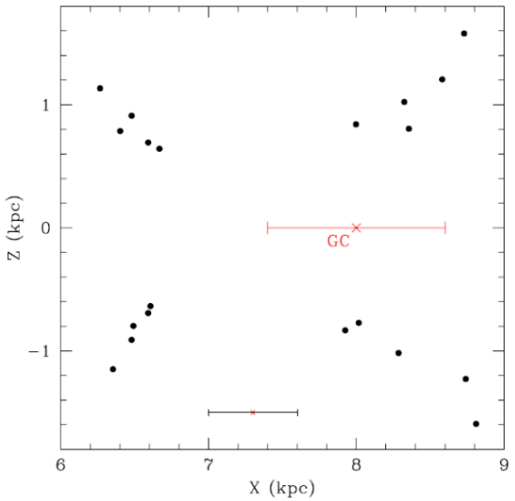
Double Red Clumps in the Galactic bulge



2MASS (*K*, *J-K*) CMD
McWilliam & Zoccali 2010

Distance

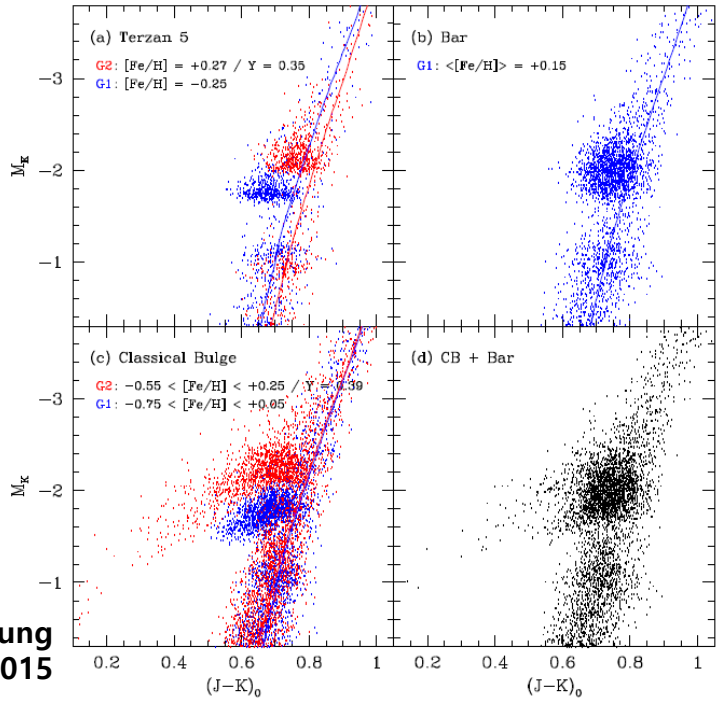
X-shaped bulge scenario



McWilliam & Zoccali 2010

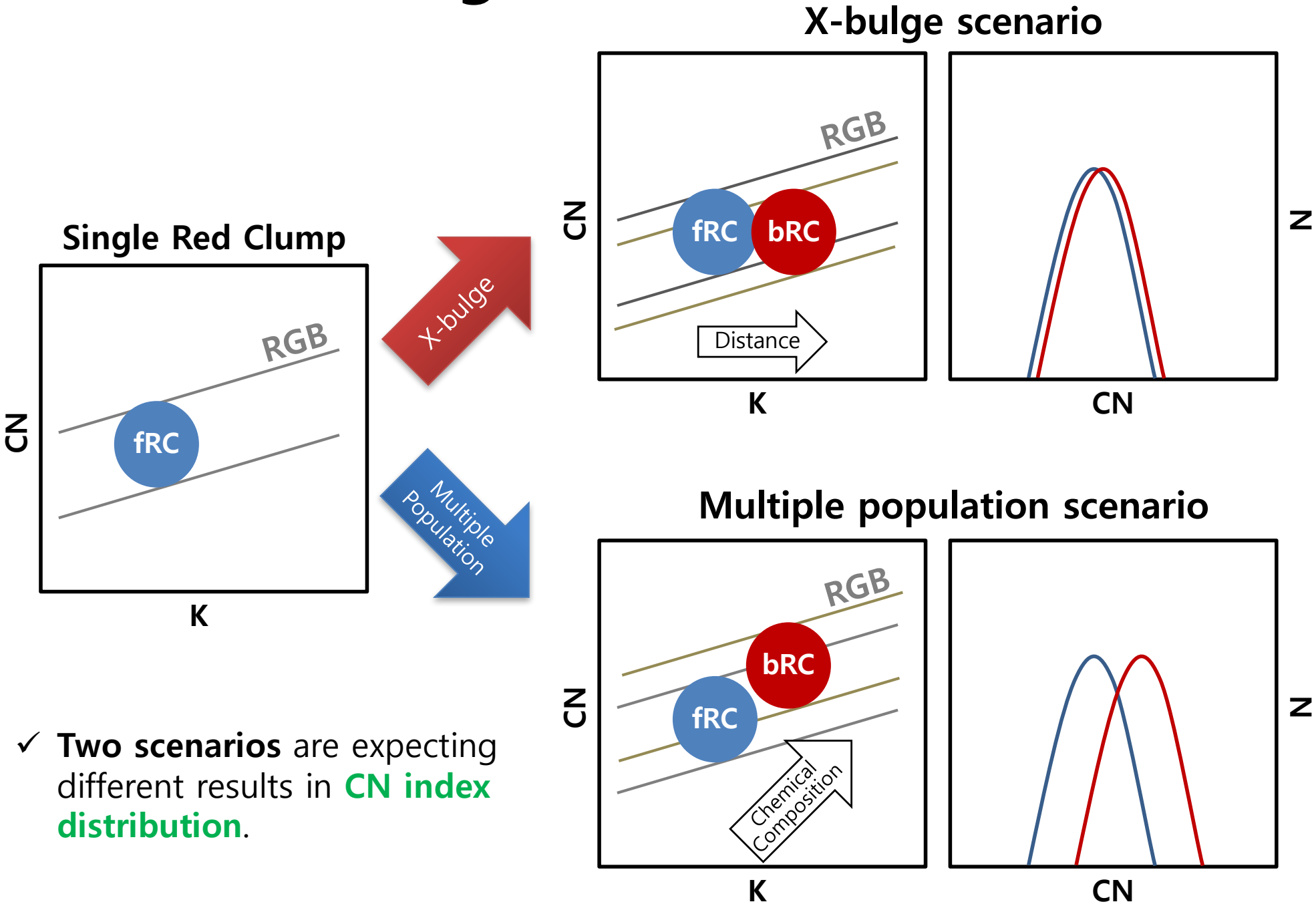
Chemical Composition

Multiple population scenario



Lee, Joo & Chung 2015

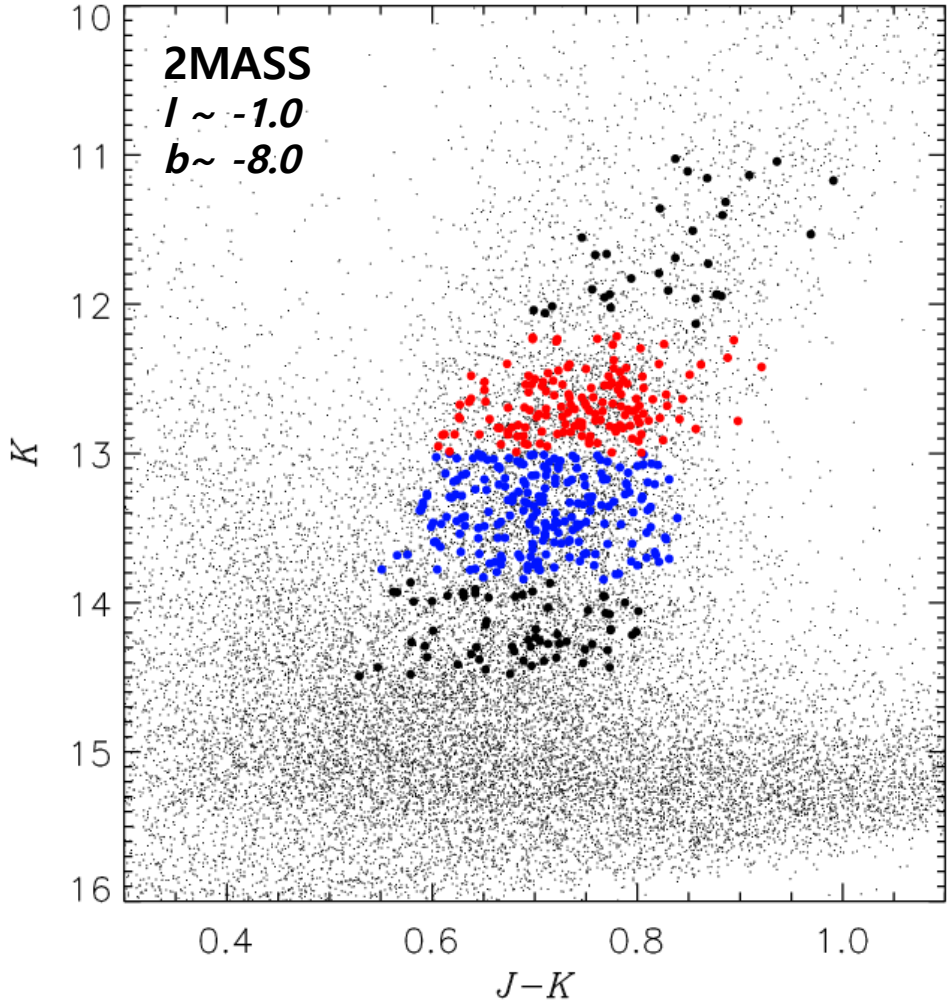
Schematic diagram

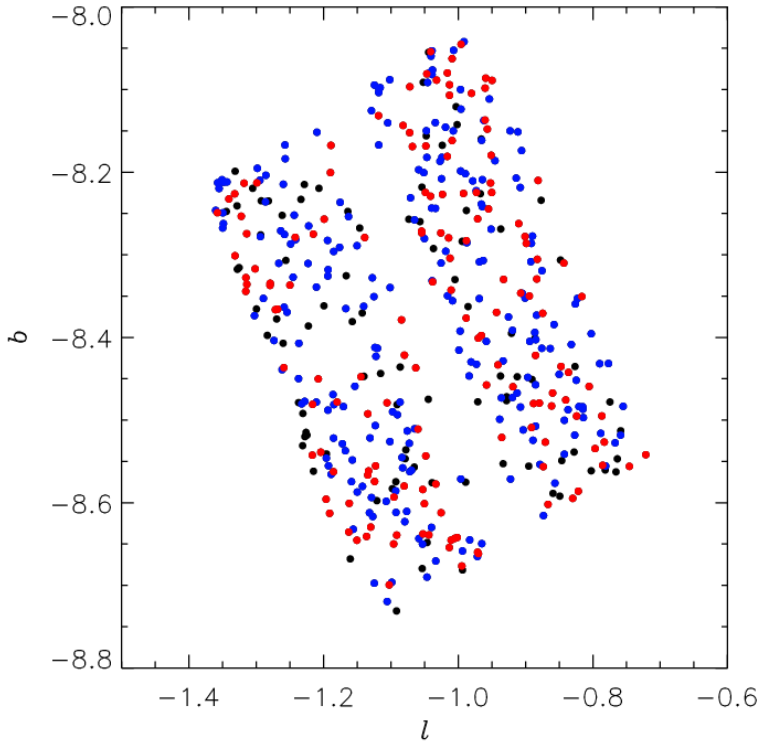


✓ **Two scenarios** are expecting different results in **CN index distribution**.

Low-resolution spectroscopy for Bulge field

WFCCD / du Pont 2.5m telescope @ LCO



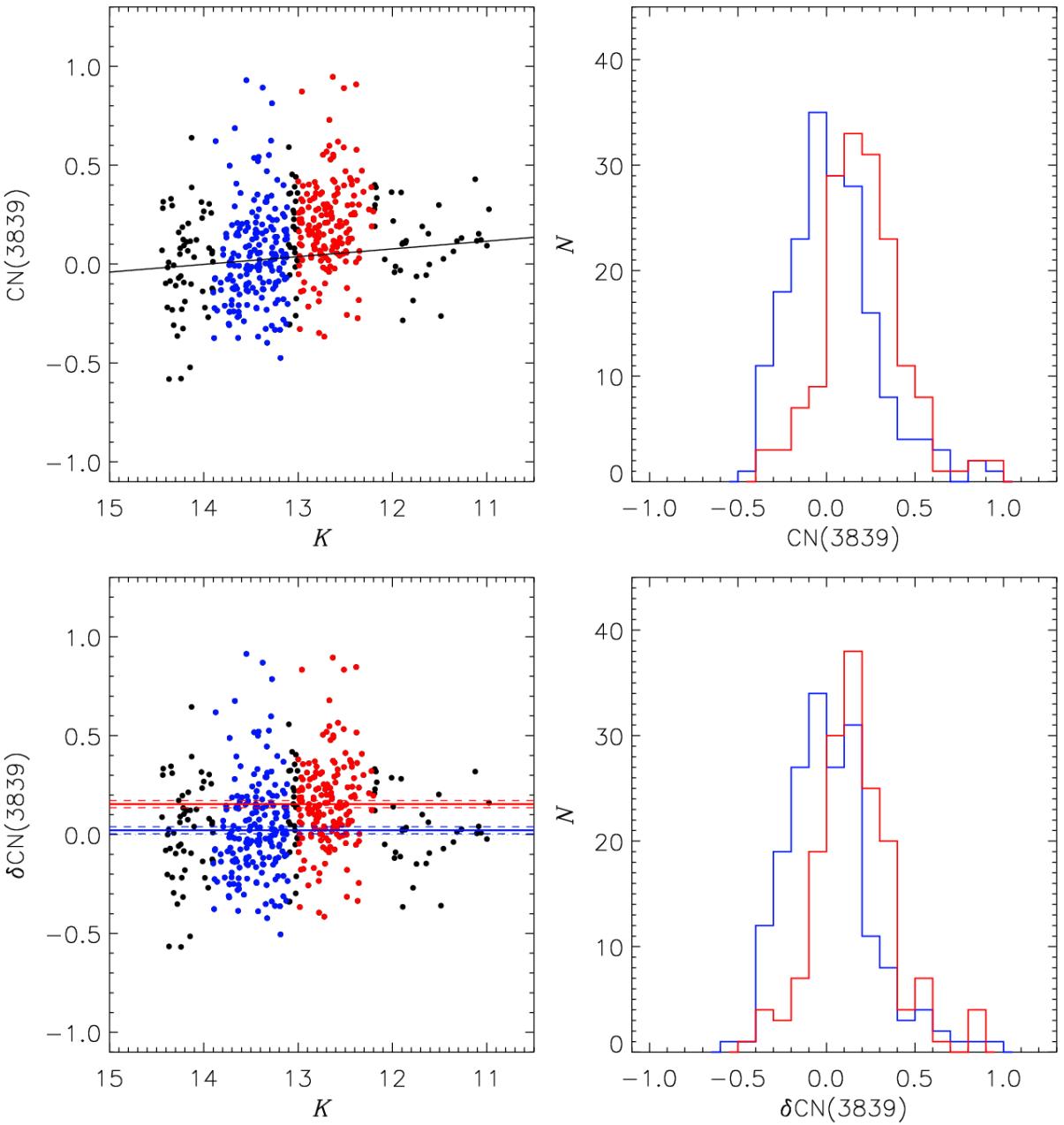


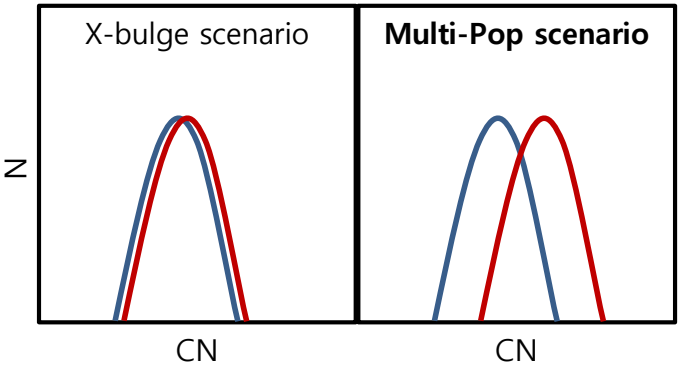
Faint RC (221) 13.0 < K_{mag} < 13.85
Bright RC (149) 12.15 < K_{mag} < 13.0
RGB (92) K_{mag} < 12.15 / 13.85 < K_{mag}

Telescope	du Pont 2.5m @ LCO
Instrument	WFCCD
Period	June 2016 ~ June 2017
Targets	RC & RGB stars (N=462)
Region	Galactic longitude (*l*): -1.5 ~ -0.5 Galactic latitude (*b*): -9.0 ~ -8.0

CN index distribution

G1 (Faint RC) / G2 (Bright RC) / RGB





Bright RC stars are more enhanced than faint RC stars in **CN band strength!**

ΔδCN = 0.13

number ratio

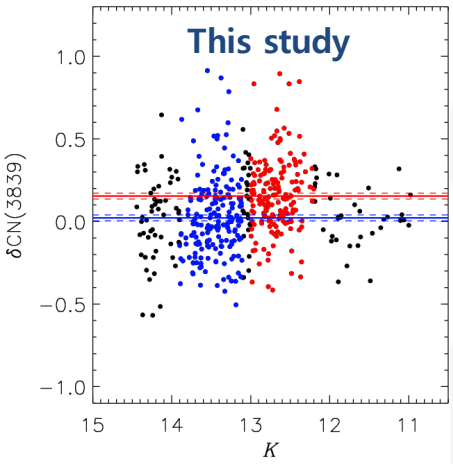
$$\frac{N_{fRC}}{N_{total}} = 0.220 \qquad \frac{N_{bRC}}{N_{total}} = 0.342$$

ΔδCN (G1-G2) ~ 0.43

similar to GCs

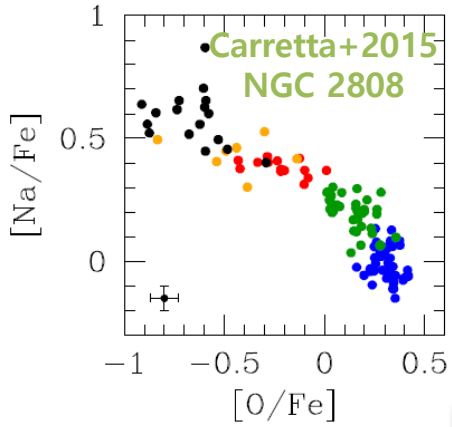
Evidence for the multiple population scenario in bulge!

Implication

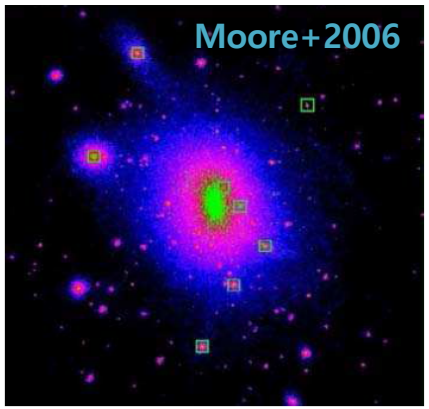


Brighter RC stars are enhanced in **CN index**

CN band strength is correlated with ***N*** **&** ***Na*** **elements** abundances

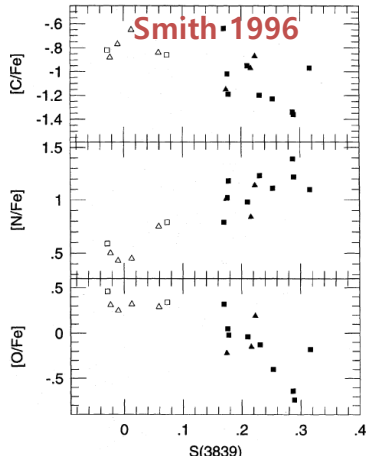


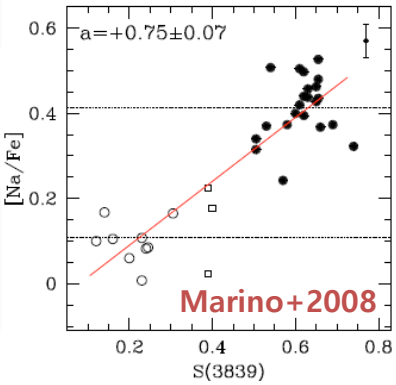
CN-strong / *N*, *Na*-rich stars (bRC) are **later generation stars originated from GCs**

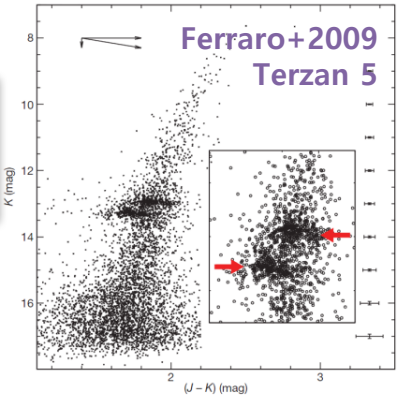


Double RC in MW bulge is **metal-rich manifestation** of **multiple populations** in GCs

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

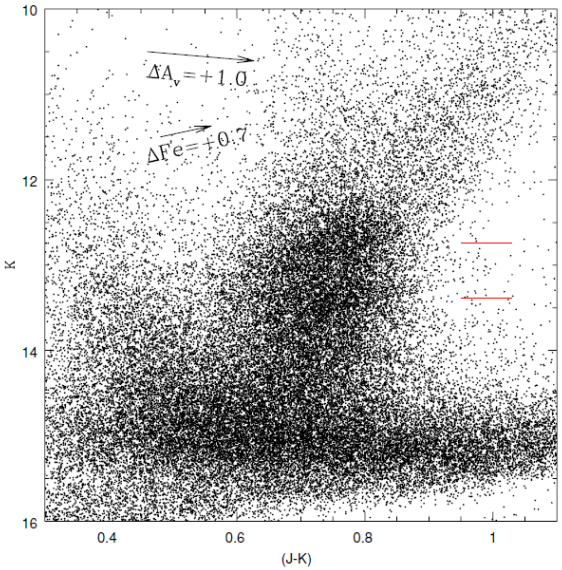




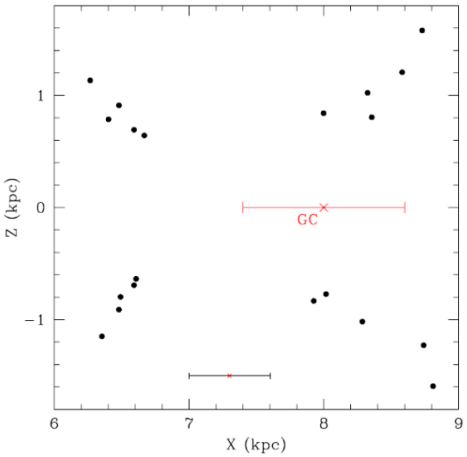


In the era of large survey

Double Red Clumps



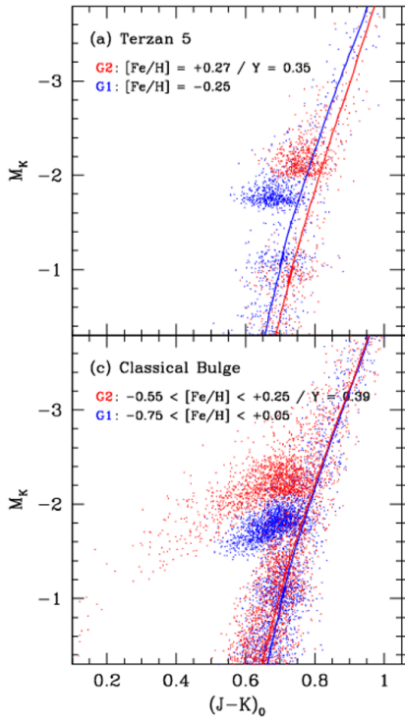
X-bulge Scenario



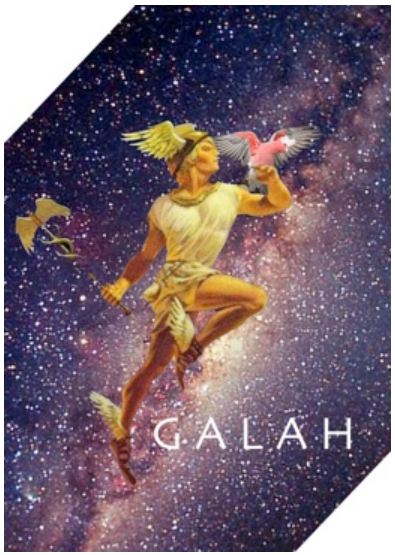
Distance

gaia

Multi-Pop Scenario

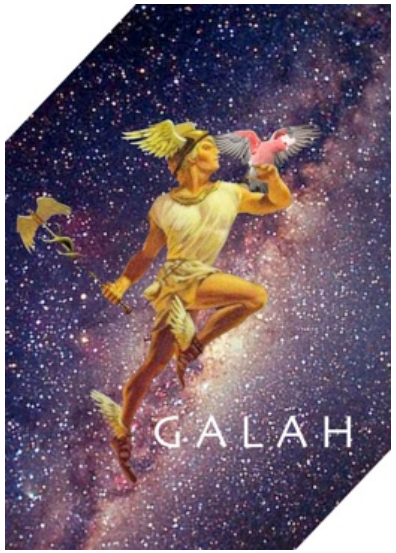


Chemical Tagging



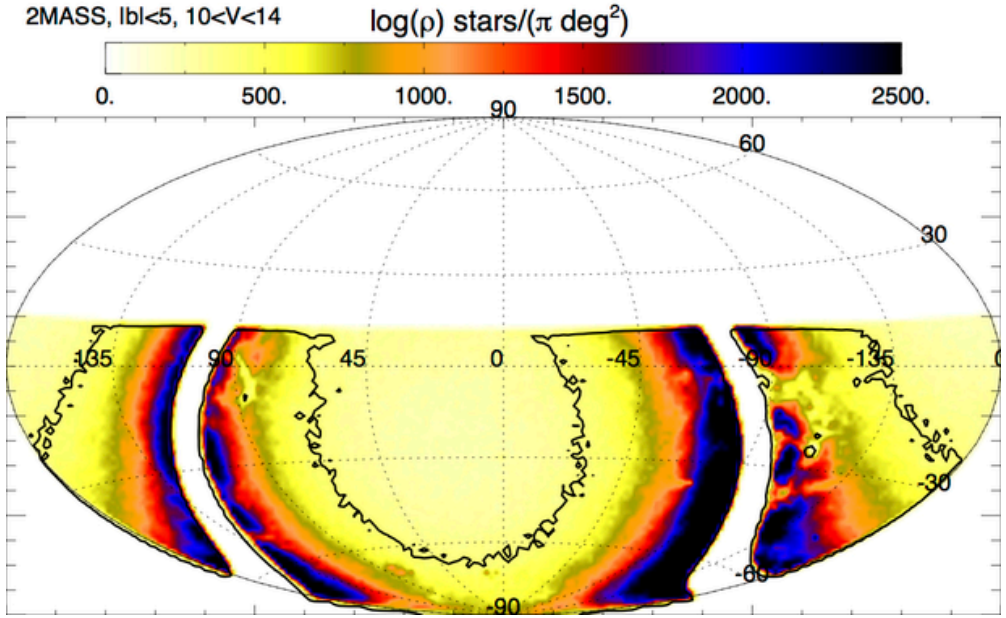
✓ **A huge amount of survey data would provide a crucial test as to the origin of double RCs in the Milky Way bulge!**

GALAH GALACTIC ARCHAEOLOGY WITH HERMES



high resolution spectra of one million stars for chemical tagging

spectra for 1,000,000 stars
Resolution ~ 28,000
Elements: Li, C, **O**, **Na**, Al, K, Mg, Si, Ca, Ti, Sc, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Y, Zr, Ba, La, Nd, Ce, Dy, and Eu



Target Selection
$|b|$< 5 10 < V < 14

77% thin-disk
22% thick-disk
0.8% bulge
0.2% halo

✓ **GALAH survey** will be useful to investigate stellar populations in the Milky Way, especially on the **Na-O** plane.