중대형 망원경을 이용한 구상성단과 벌지의 항성종족 연구

이 영 욱 (연세대학교)

with 임동욱, 홍승수, 강이정, 김영로

1. MW globular clusters
2. MW bulge
3. SN Ia host galaxies

Image Credit: ESO

1. Multiple Stellar Populations in Globular Clusters

letters to nature

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

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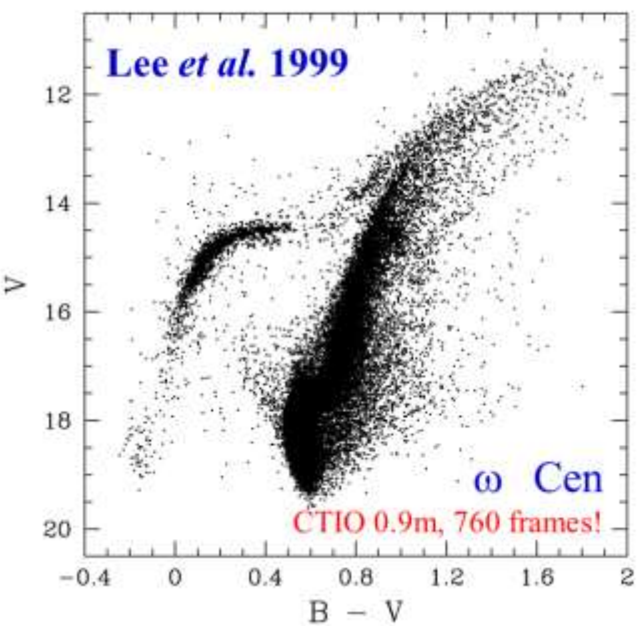
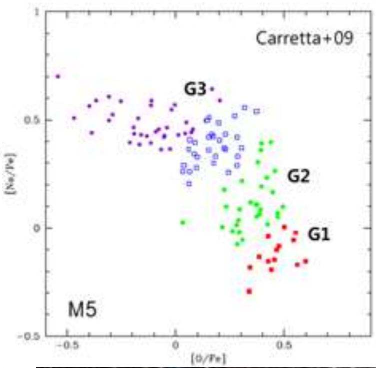
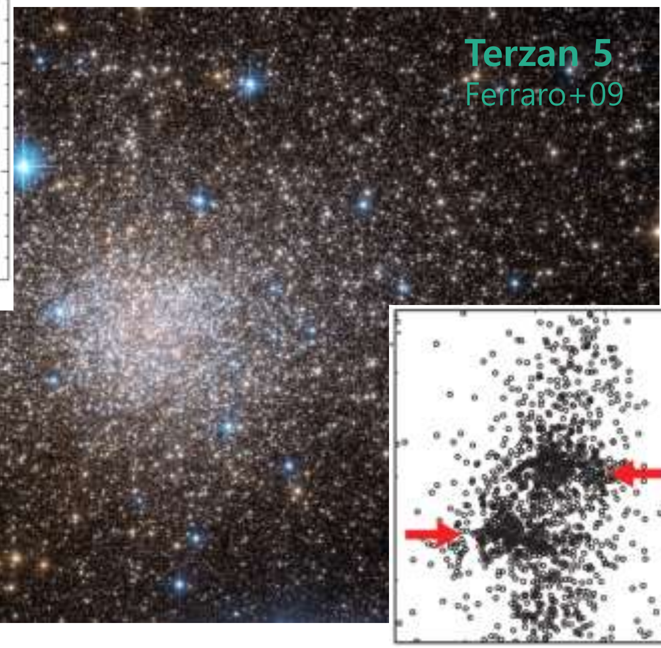






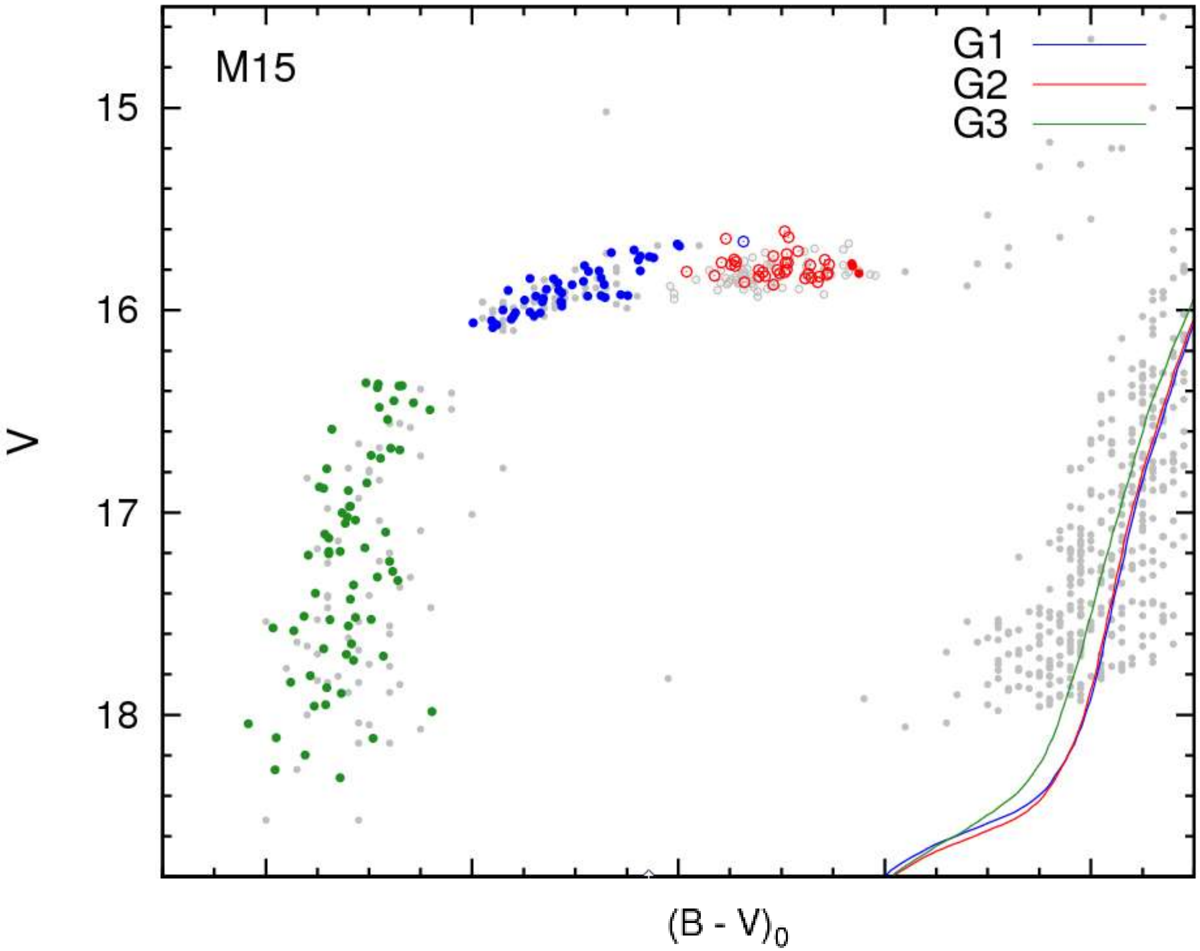
Lee+99; Pancino+00; Rey+04; Bedin+04; Norris 04; D'Antona+04; D'Antona+Caloi 04, 08; Lee+05; Piotto+05; Bekki+06; Decressin+08; D'Ercole+08; Renzini 08; Carretta+09; Ferraro+09; Johnson+Pilachowski+09, 15; Ventura+09; Han+09; JWLee+09; Vesperini+10, 13; Dalessandro+11; Gratton+11, 12, 13; Mucciarelli+12; 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) **& O, C, Mg depleted**

SNe의 기여가 (거의) 없는 환경에서의 독특한 현상!



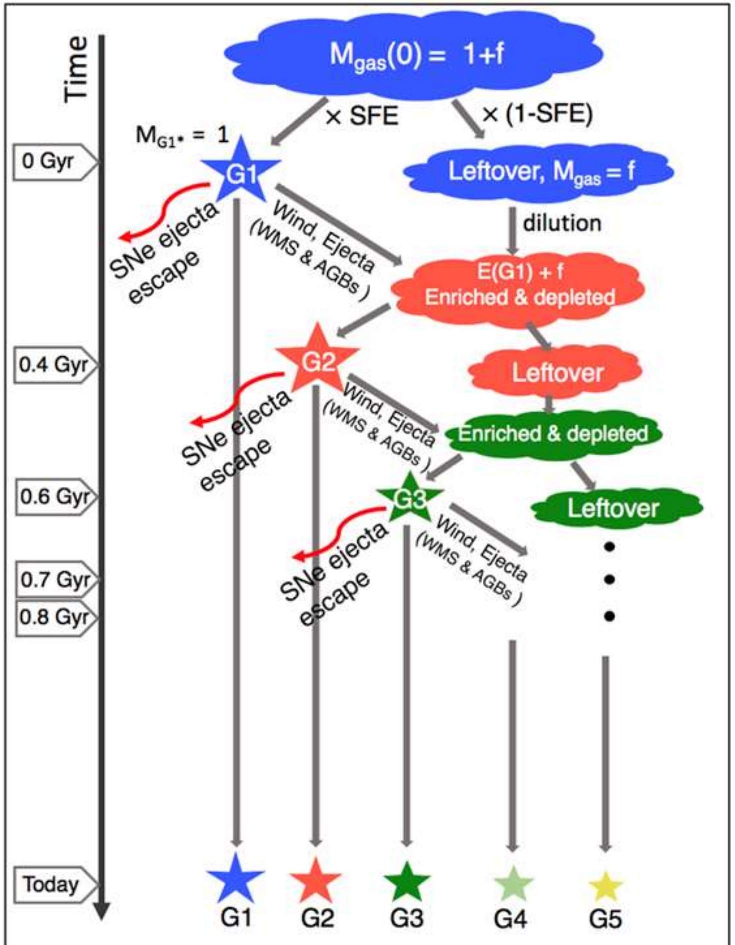
Jang, Lee+2014

He+CNO+age effects

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	0.327 ± 0.01	11.3 ± 0.2	0.129	0.589	0.42	-	-

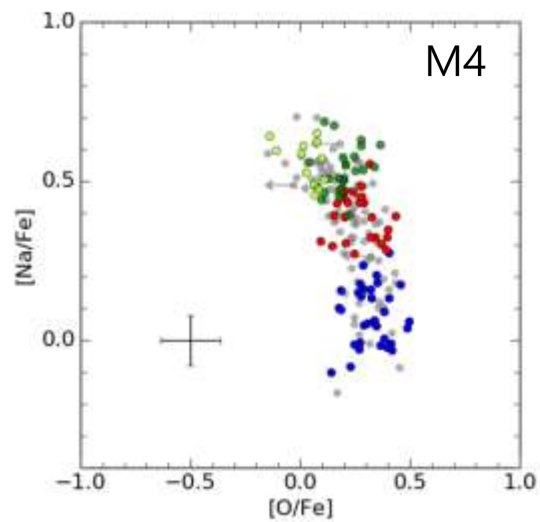
New insights on chemical evolution in proto-GCs

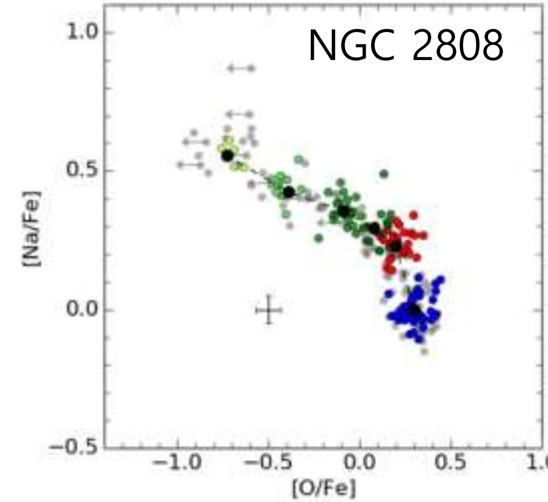


Na - O anticorrelation (24 year-old problem):

Reproduced by our new chemical evolution models, *if SN blast waves undergo blow-out without expelling the pre-enriched gas (Tenorio-Tagle+2015)*

→ Chemical evolution is dictated by AGB & WMS!





Kim & Lee 2017, in prep.

	Y	[N/Fe]	[O/Fe]	[Na/Fe]	dZ(CNO)	original	remaining	t (Gyr)
G1	0.234	0.000	0.000	0.000	0.0000	0.52	0.35	0.00
G2	0.258	0.792	-0.058	0.292	0.0004	0.27	0.26	0.50
G3	0.281	1.045	-0.163	0.457	0.0006	0.14	0.27	0.80
G4	0.303	1.143	-0.313	0.503	0.0006	0.07	0.13	0.90

Low-Resolution Multi-slit Spectroscopy

2.5m du Pont Telescope at LCO, Chile

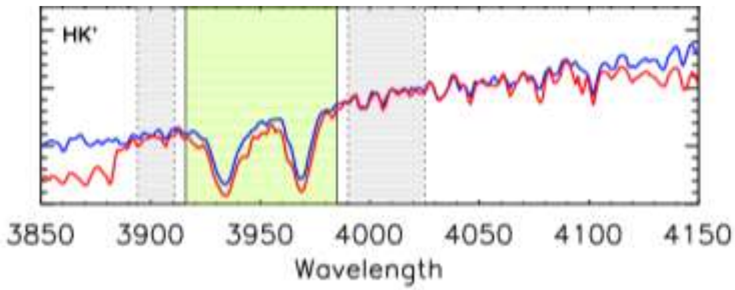
- **Multi-object spectroscopy**
- **WFCCD** (Wide Field Reimaging CCD camera)
- FOV ~ 25′ x 25′
- HK grism
- Pixel scale ~ 0.484 ″/pix
- Dispersion ~ 0.8 Å/pix
- Central wavelength ~ 3700Å

du Pont 2.5m telescope

Image credit: LCO homepage

Index Definition

Heavy element (Calcium)



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

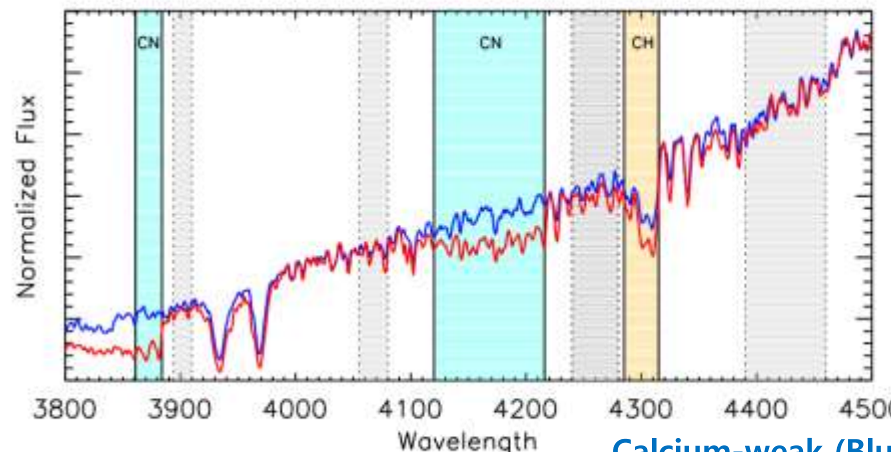
(Lim et al. 2015)

Light element (CN & CH)

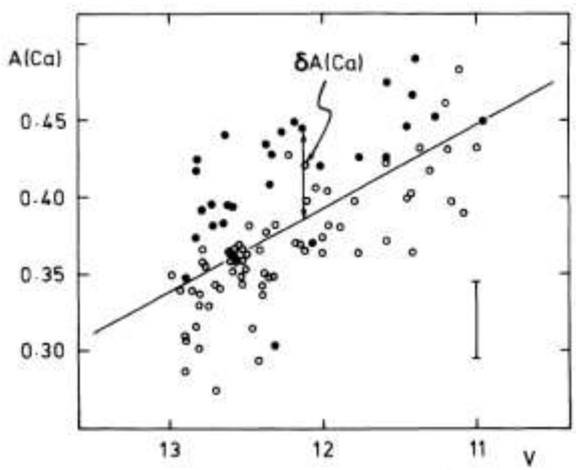
$$S(3839) = -2.5 \log \frac{F_{3861-3884}}{F_{3894-3910}},$$

$$S(4142) = -2.5 \log \frac{F_{4120-4216}}{0.4\,F_{4055-4080} + 0.6\,F_{4240-4280}}$$

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



Calcium-weak (Blue)
Calcium-strong (Red)



Delta (δ) Index

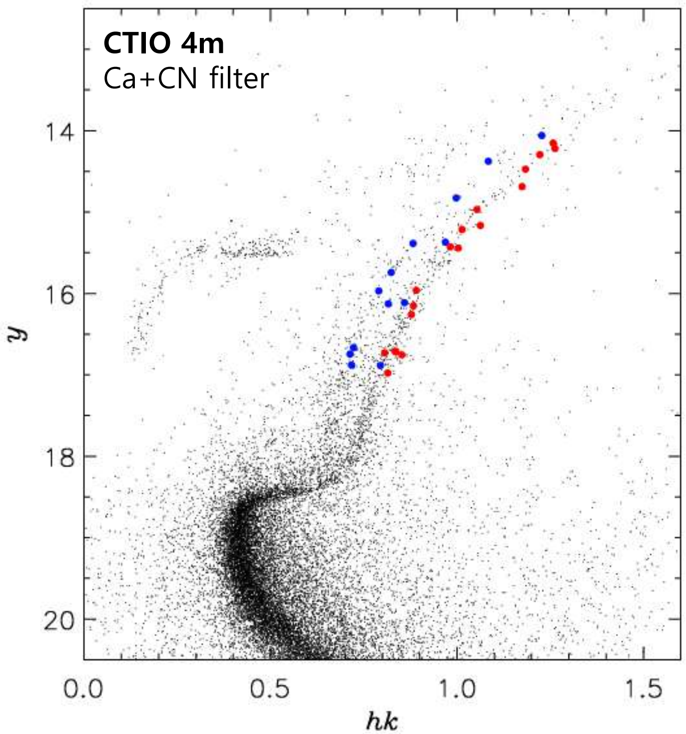
Absorption line = **Abundance** + T_{eff} + Surface Gravity

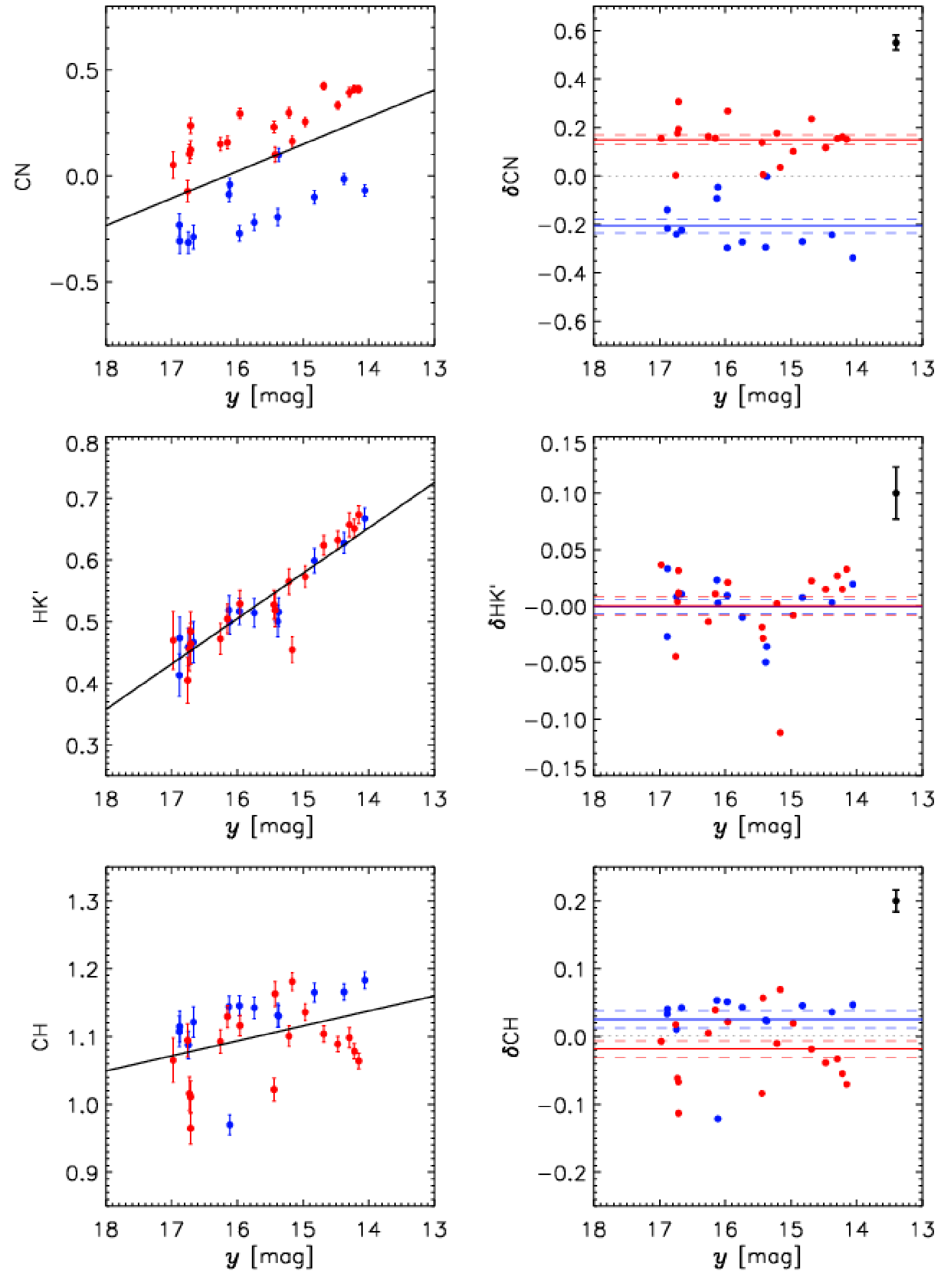
- We calculated delta indices (**δCN**, **δHK'**, and **δCH**) as the difference between original values and least square fitting line to minimize the effects of effective temperature and surface gravity.

Norris & Freeman 1983

δ*A(Ca)* index

NGC 6723





Blue: CN-weak subpopulation
Red: CN-strong subpopulation

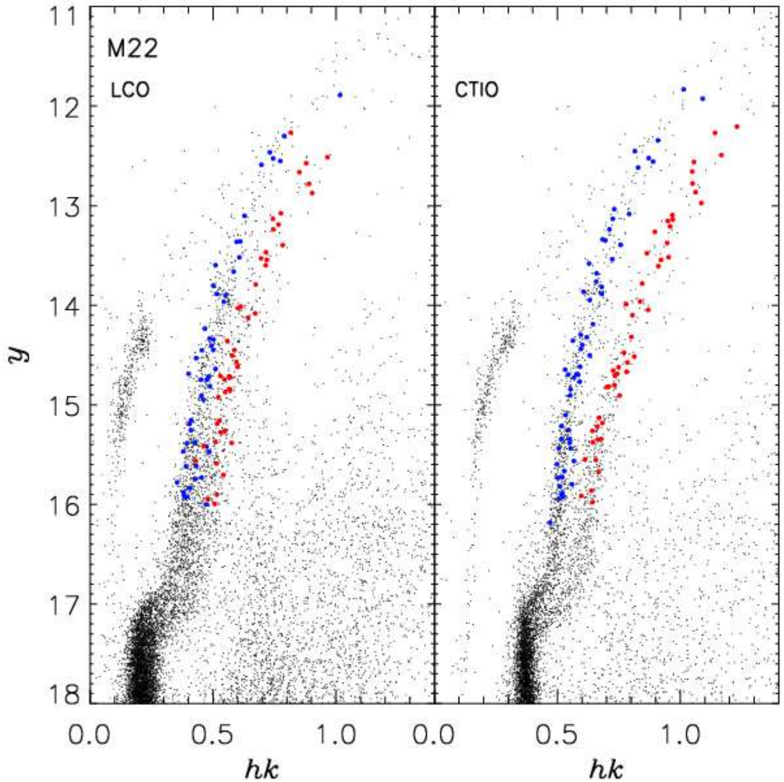
Difference between two subpopulations

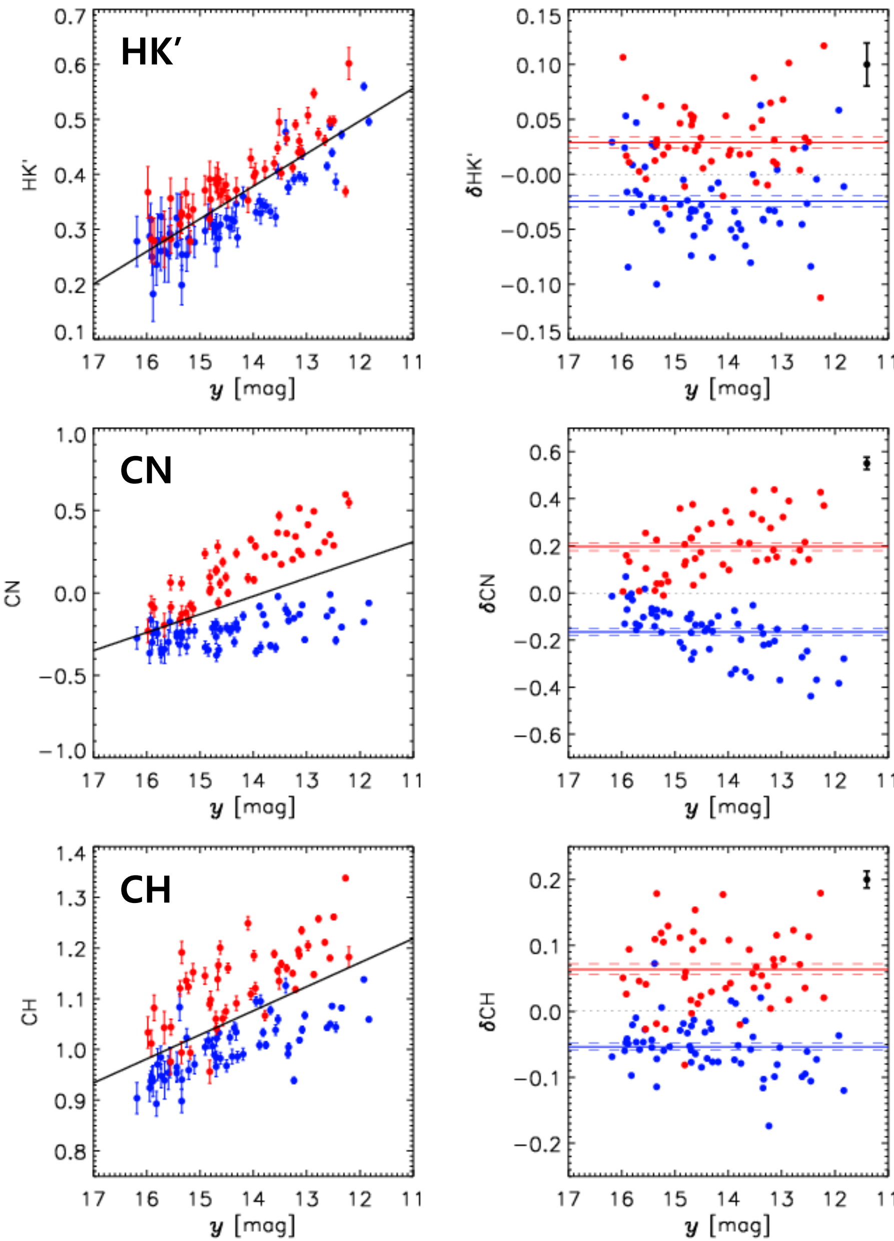
ΔδCN = 0.356 (10.4σ)

ΔδHK' = 0.001 (0.1σ)

ΔδCH = 0.044 (2.5σ)

M22





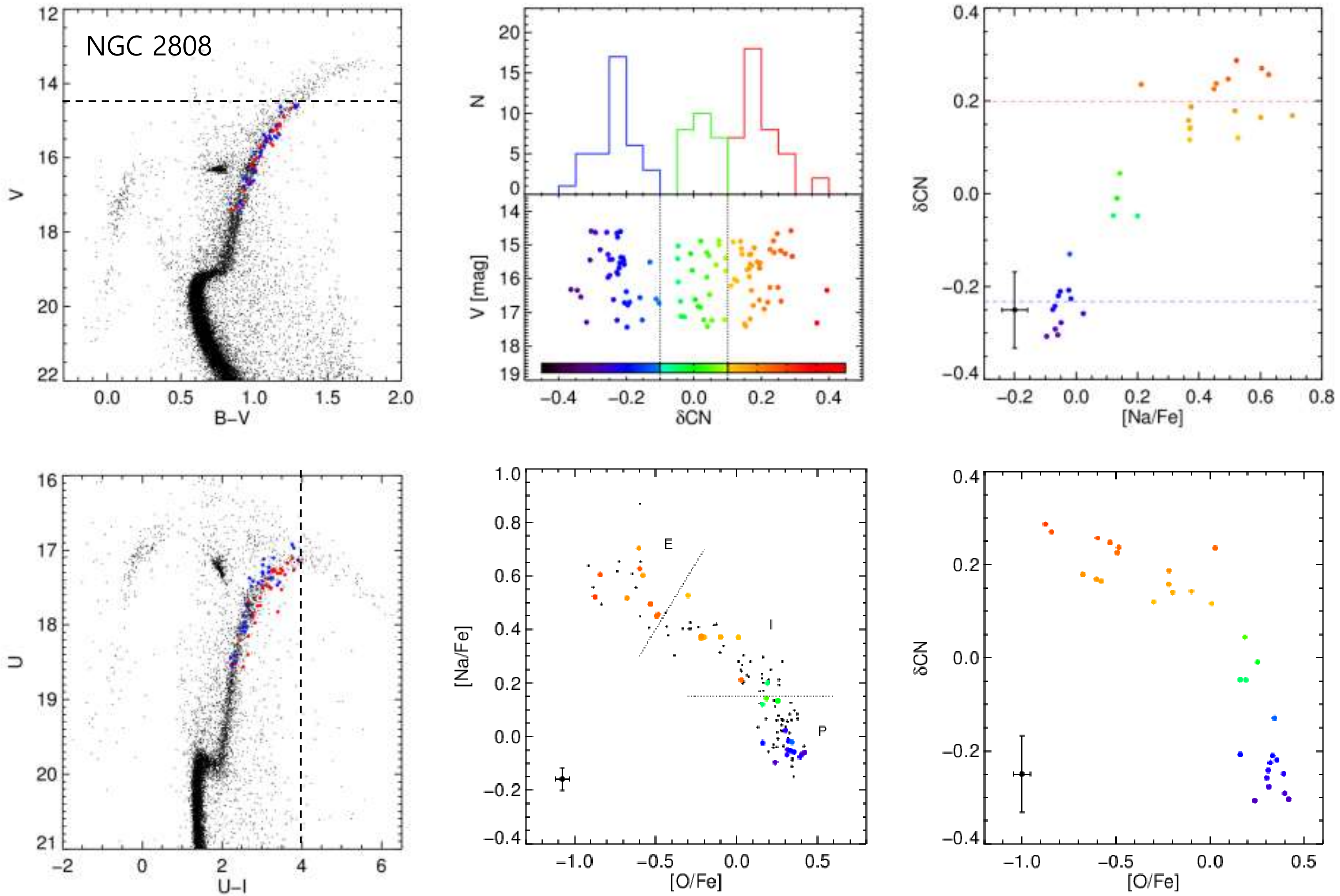
Difference between two subpopulations

ΔδHK' = 0.054 (7.5σ)

ΔδCN = 0.362 (15.9σ)

ΔδCH = 0.118 (12.1σ)

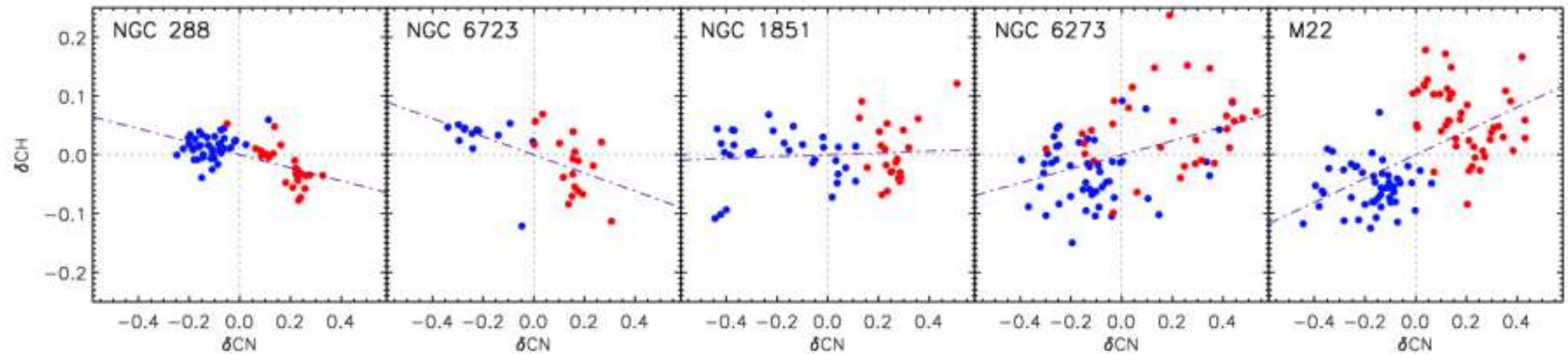
Lim, Han, Lee+2015, 2016
Han, Lim, Lee+2015



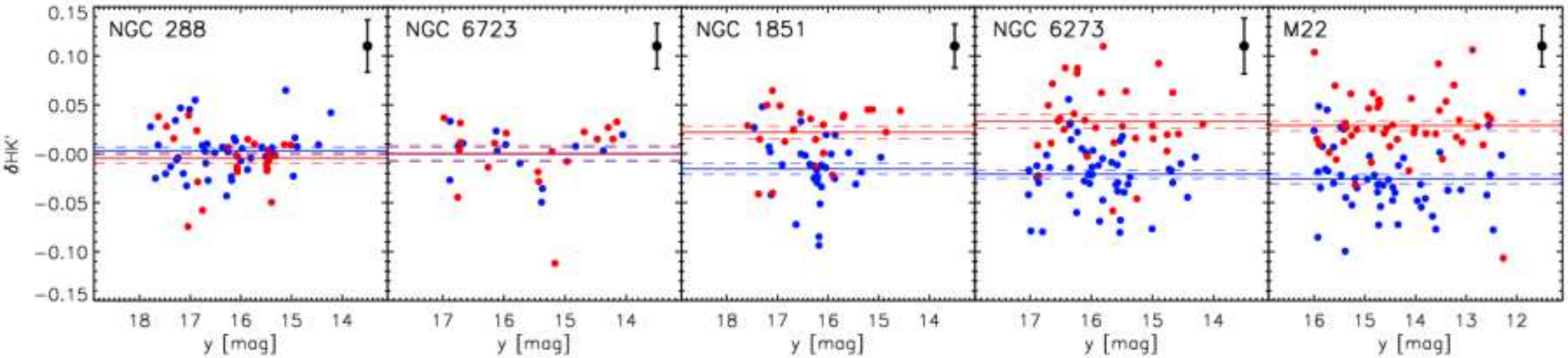
Low-resolution MOS can be as powerful as high-resolution spectroscopy!

Hong, Lee+2017, in prep.

CN-CH Correlation (Lim, Lee+2017)



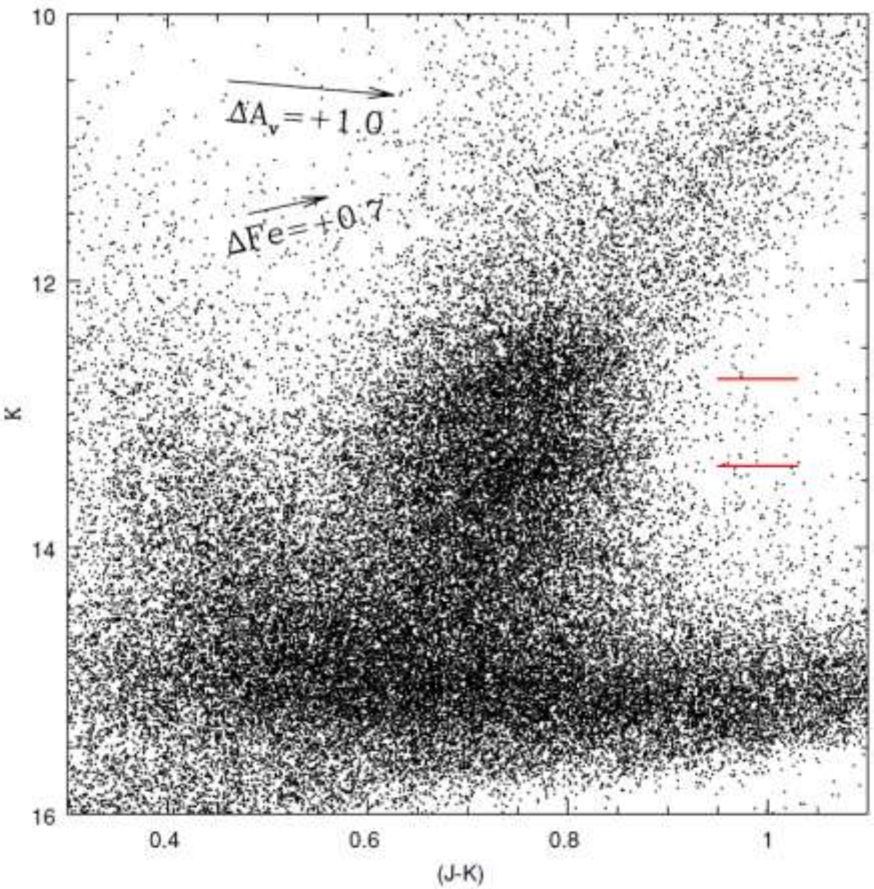
CN-CH anti-correlation ⟷ **CN-CH correlation**

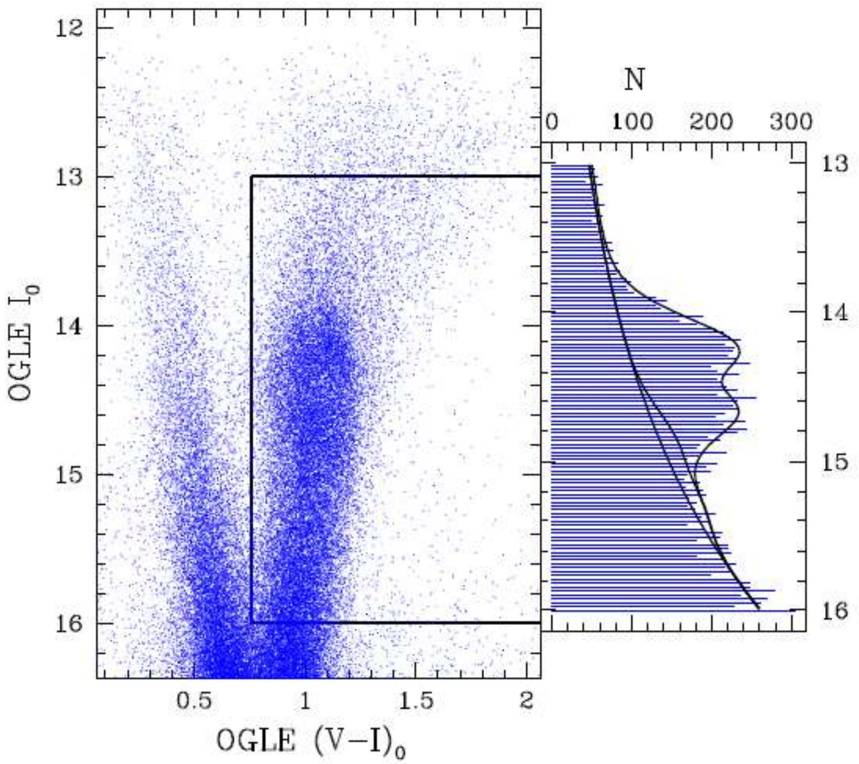


Light elements abundance variation ⟷ **Heavy & Light elements abundance variation**

Strength of SNe enrichment

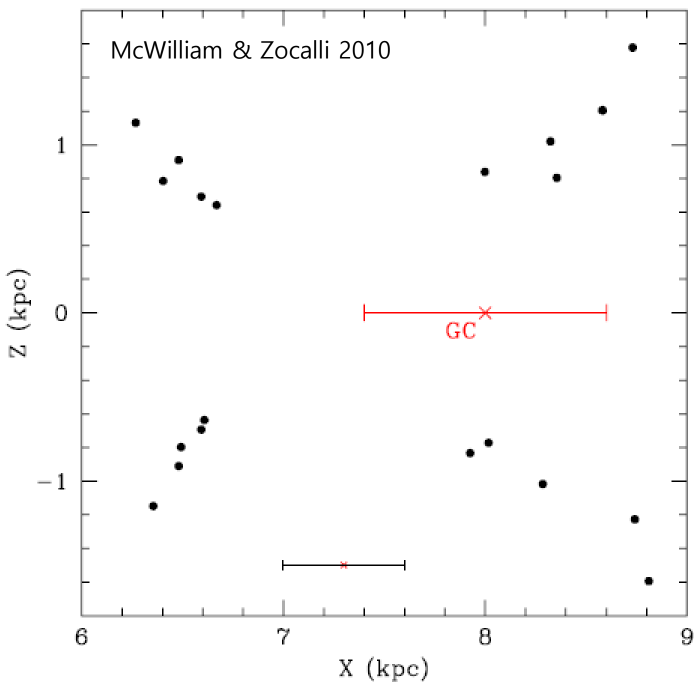
2. Double Red Clump in the Milky Way Bulge





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

The X-Shaped Bulge in the Milky Way



X-Shaped Bulge from disk & bar instability:

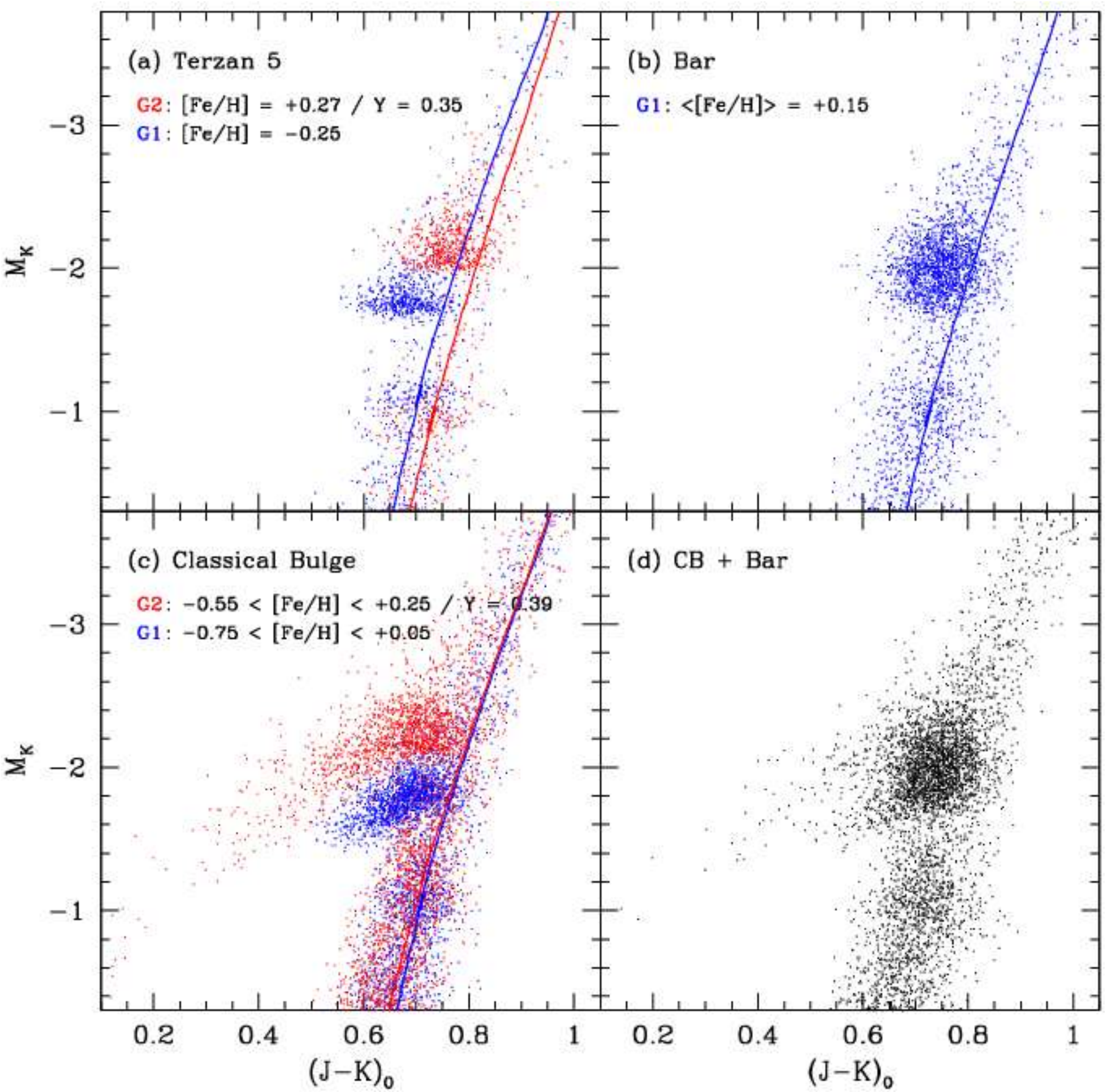
bright RC (foreground) + faint RC (background)

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...

110 papers (& 국제언론 보도)

→ 이후 pseudo bulge 이론이 국제학계의 표준모델로 자리 잡게 됨

→ 그러나 최근 우리 연구팀은 dRC 현상에 대해 완전히 새로운 이론을 발표!



Multiple Population Models for the Double RC in Bulge

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

G2: enhanced-He
$Y = 0.39$ ($\Delta Y/\Delta Z = 6$)
at [Fe/H] = -0.1

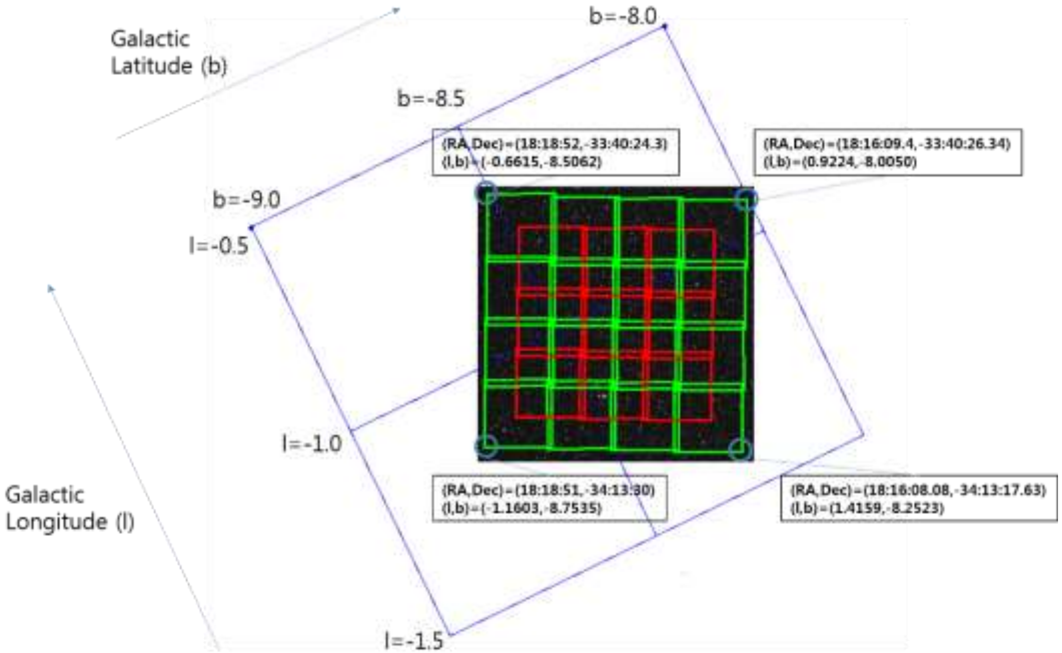
dRC 현상은 X 구조가 아닌 G1/G2의 고유 광도 차이!

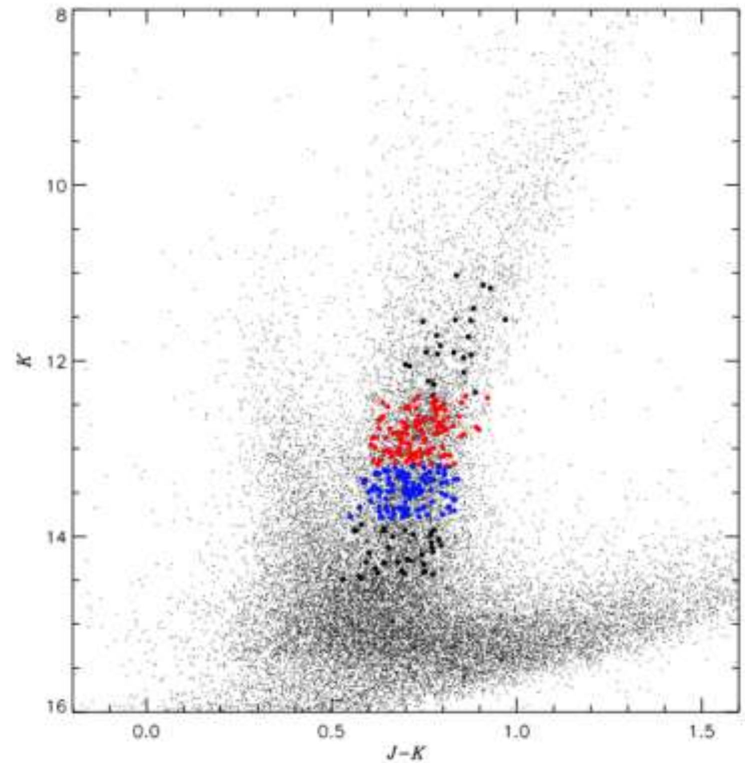
여러 관측적 특징을 보다 합리적으로 설명!

Lee, Joo & Chung 2015

Joo, Lee & Chung 2017

Spectroscopy of double RC stars in the Bulge



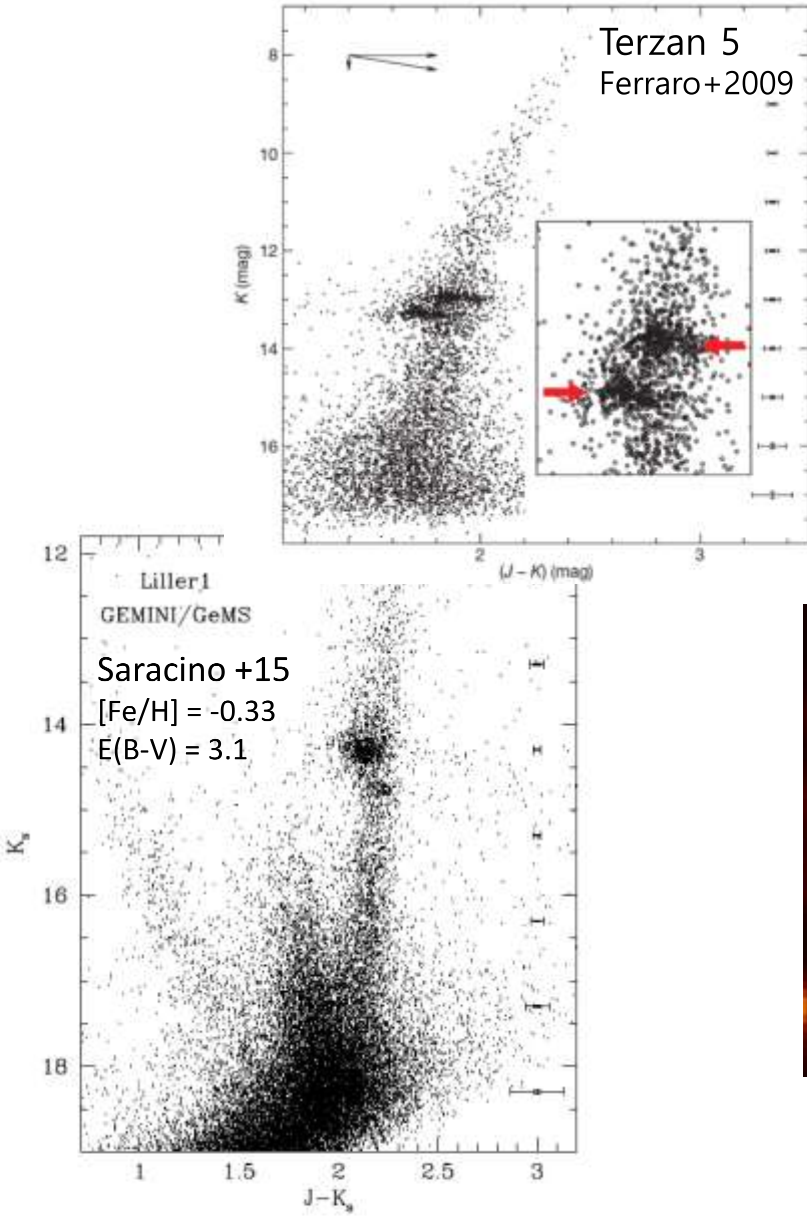


- du Pont 2.5m Bulge double RC survey (ongoing): CN, Ca
- Magellan M2FS/MIKE & Gemini high-resolution follow-up for Bulge field & Terzan 5: Na, N, O, Al, Mg, Fe
- Also, Magellan IMACS & Gemini GMOS!

- MS+SGB stars in Bulge & GCs → Good science for GMT GCLEF!

Image credit: S. Hong

Search for Terzan 5–like GCs with double RC

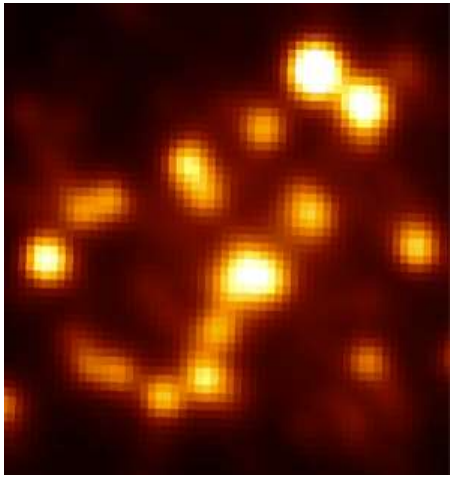


GEMINI/GSAOI :

Near Infrared & Adaptive Optics Imager

for heavily obscured bulge GCs

NTT 3.5m



GEMINI/GSAOI 8.1m

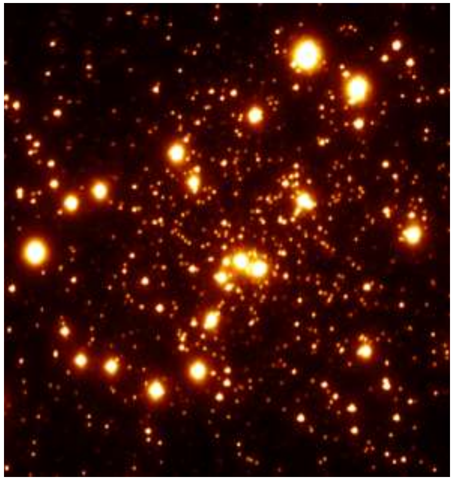


Image Credit: F. R. Ferraro/ E. Dalessandro

3. Project YONSEI:
Yonsei Nearby Supernovae Evolution Investigation

The major systematic uncertainty in "Supernova Cosmology" is a possible luminosity evolution of Type Ia SNe!

Low-resolution spectroscopy of ~70 nearby early-type host galaxies (since 2011)

→ du Pont 2.5m, MMT 6.5m, (Gemini 8m)

→ Direct age dating and metallicity measurement using Lick indices (e.g., H_β) & population synthesis models

→ ETGs preferred because of age dating & dust extinction

→ SNANA (Kessler+09) is used for the SNe LC analysis