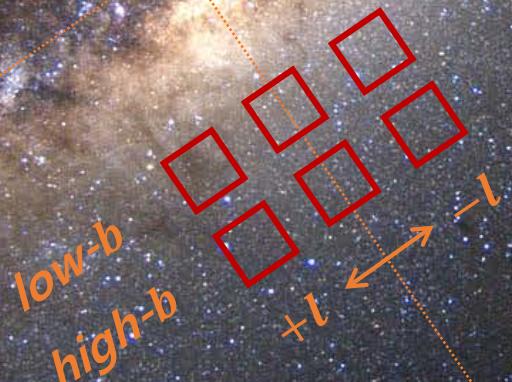


The CN Survey for Bulge

Red Clump Stars:

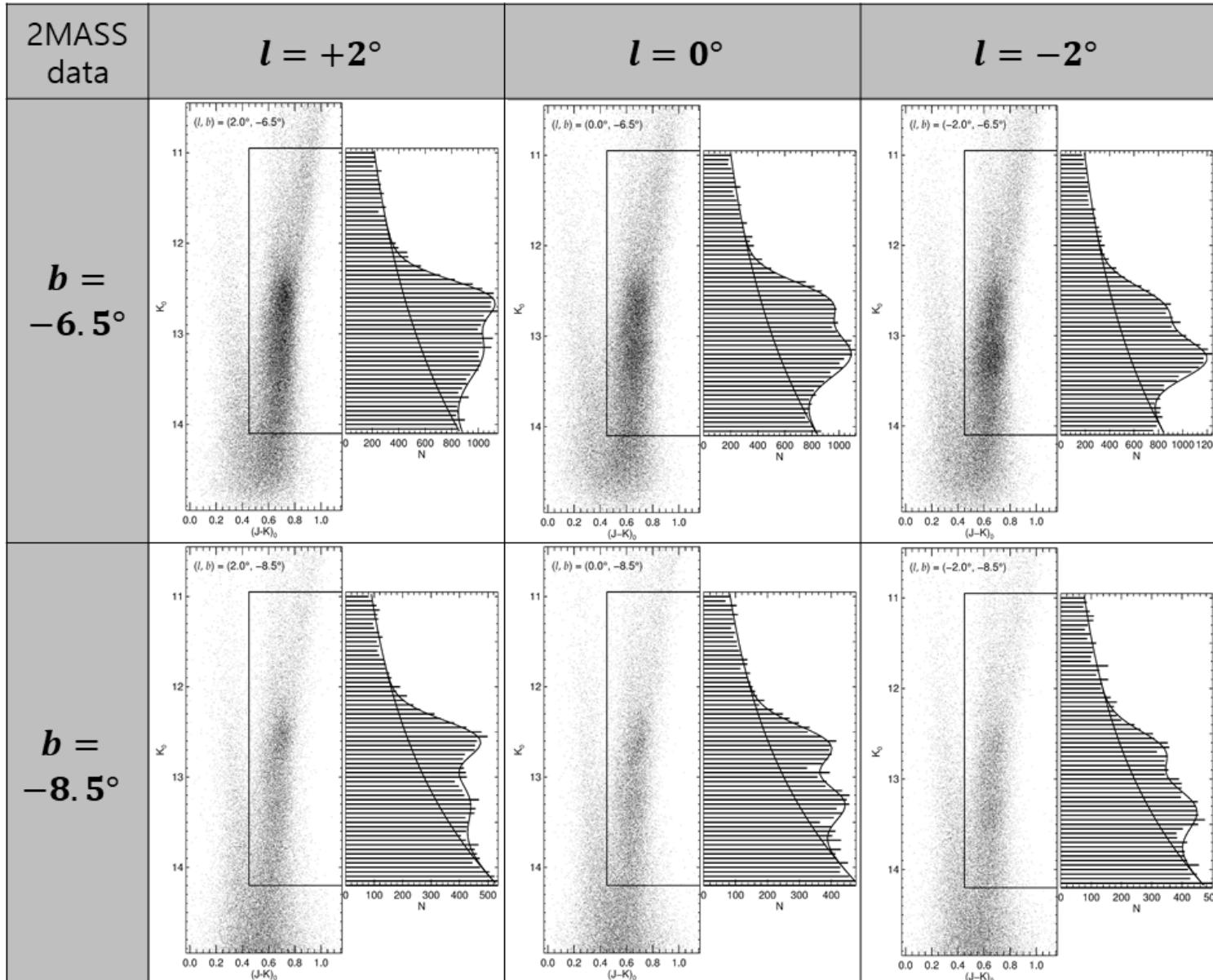
New Insights on the
Structure and Formation of
the Milky Way Bulge



Seungsoo Hong
(Yonsei University)

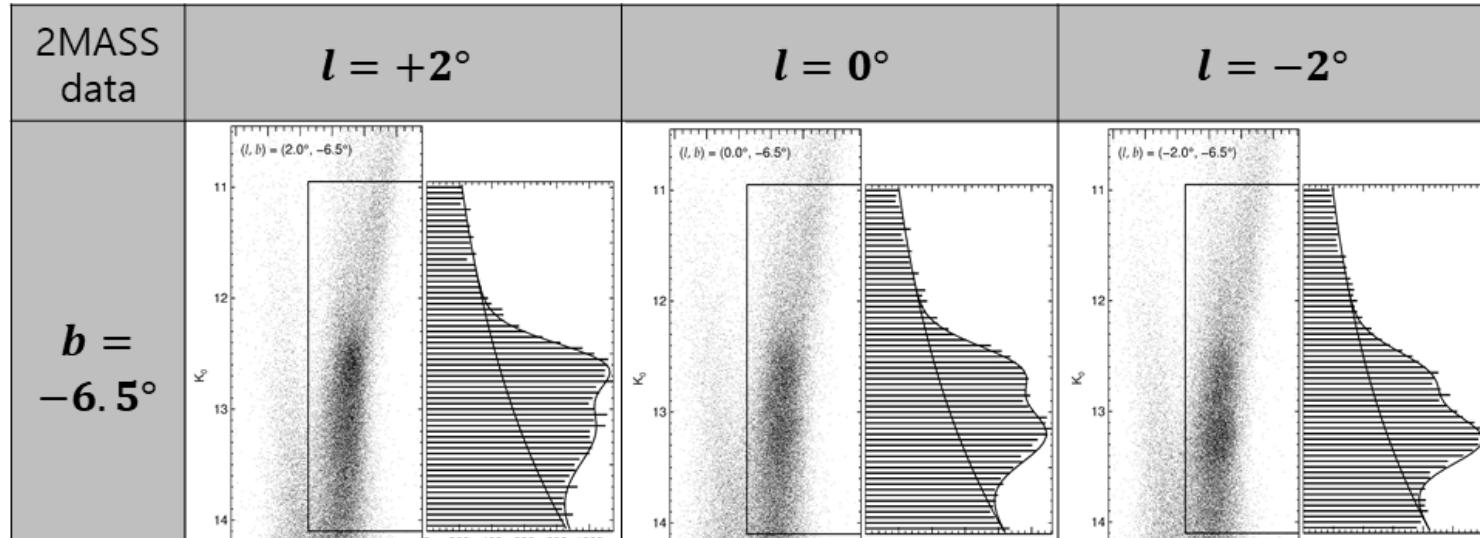
Young-Wook Lee (Yonsei University)
Dongwook Lim (ARI, Universität Heidelberg)

Double Red Clump in the Milky Way Bulge

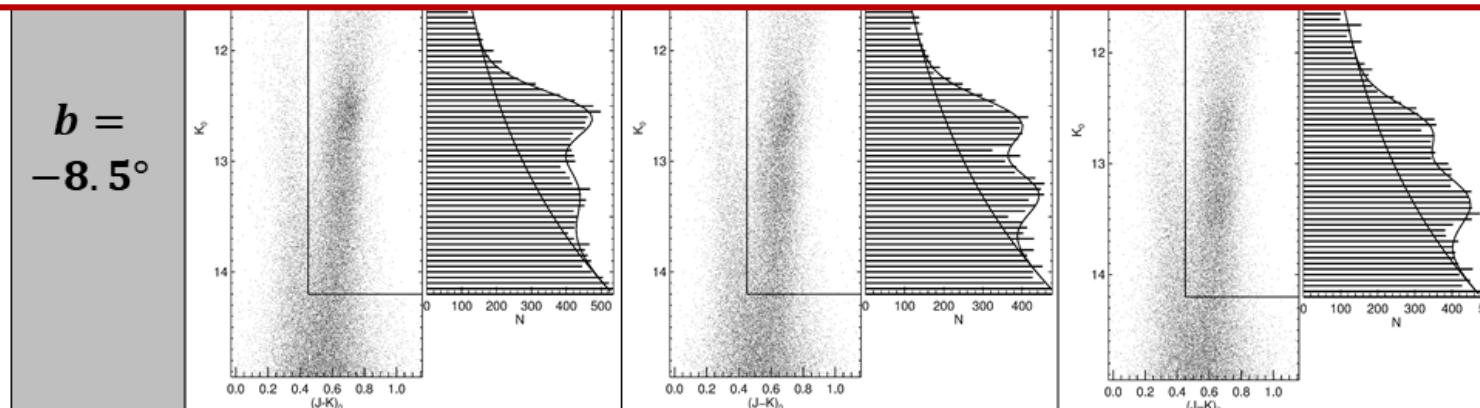


* Red clump (RC) = metal-rich counterpart of core-He-burning HB stars

Double Red Clump in the Milky Way Bulge



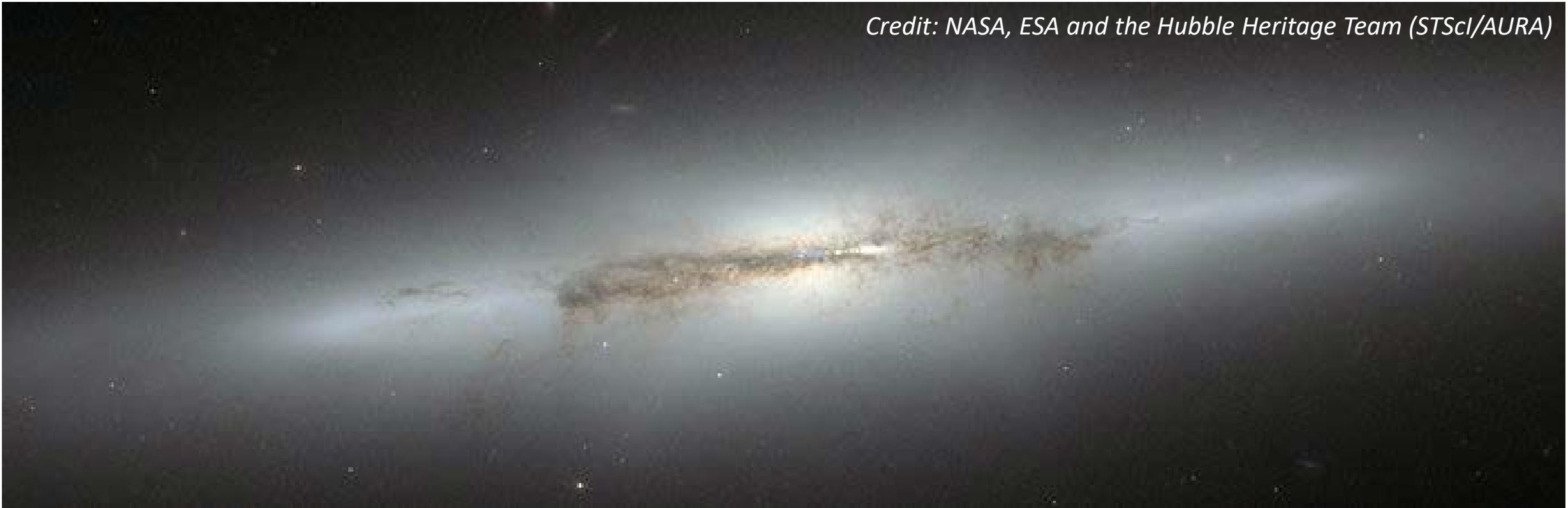
- 1. Why it is *double*?**
- 2. Why it is $f(l, b)$?**



* Red clump (RC) = metal-rich counterpart of core-He-burning HB stars

Scenario 1: The X-shaped Bulge

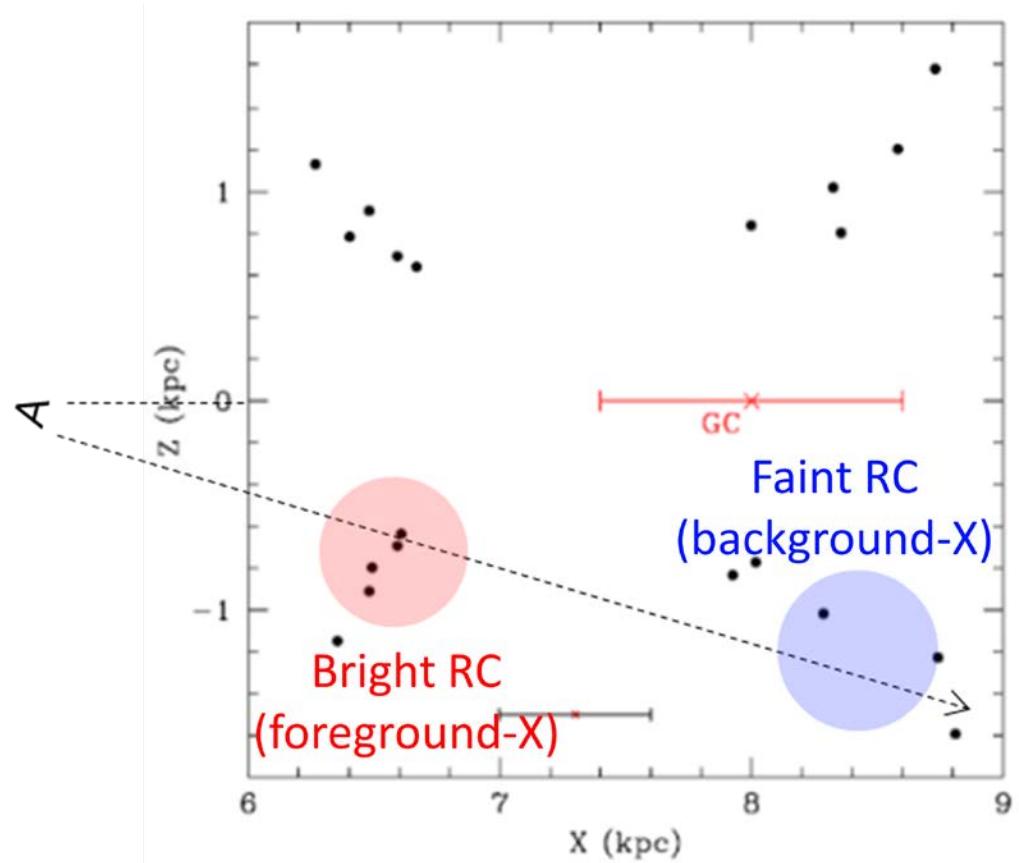
Credit: NASA, ESA and the Hubble Heritage Team (STScI/AURA)



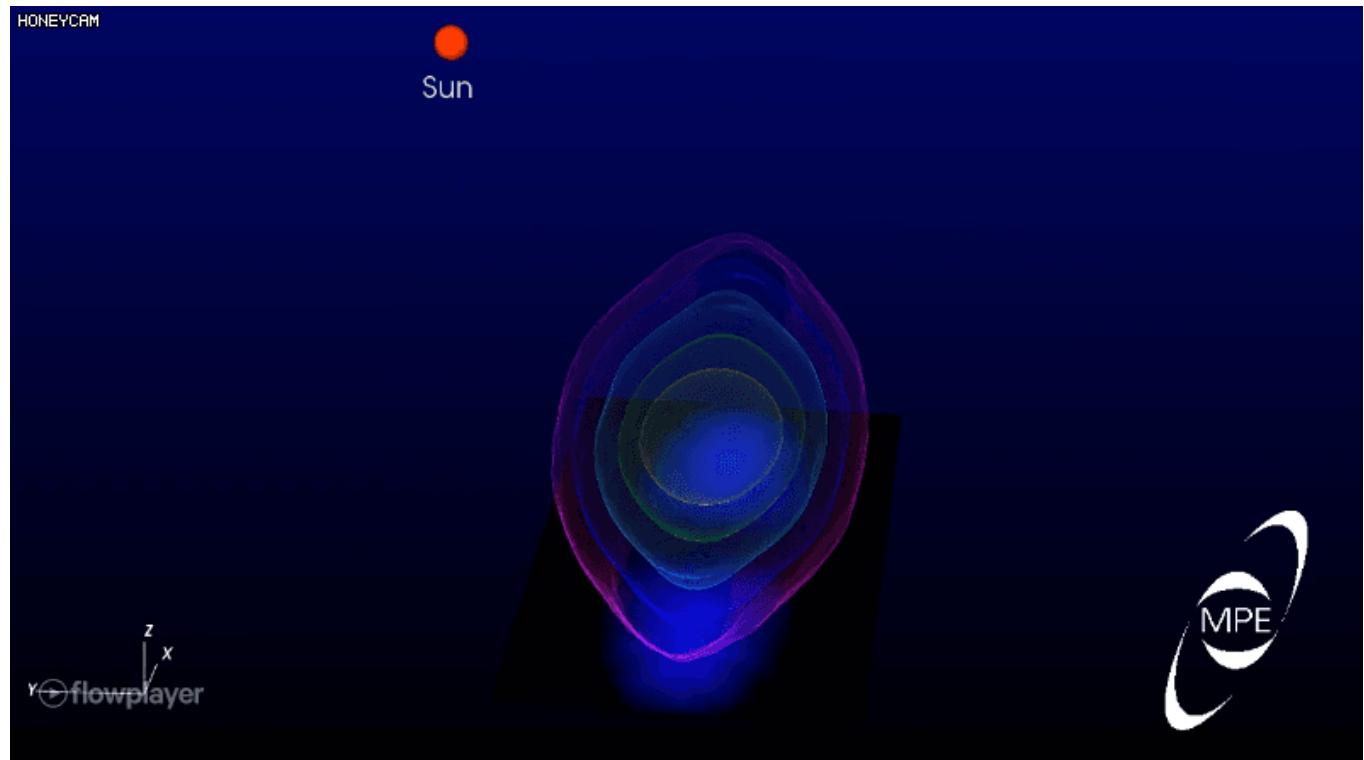
NGC 4710: An extreme case of X-shaped (pseudo) bulge

Scenario 1: The X-shaped Bulge

1. Why it is double?
2. Why it is $f(l, b)$?



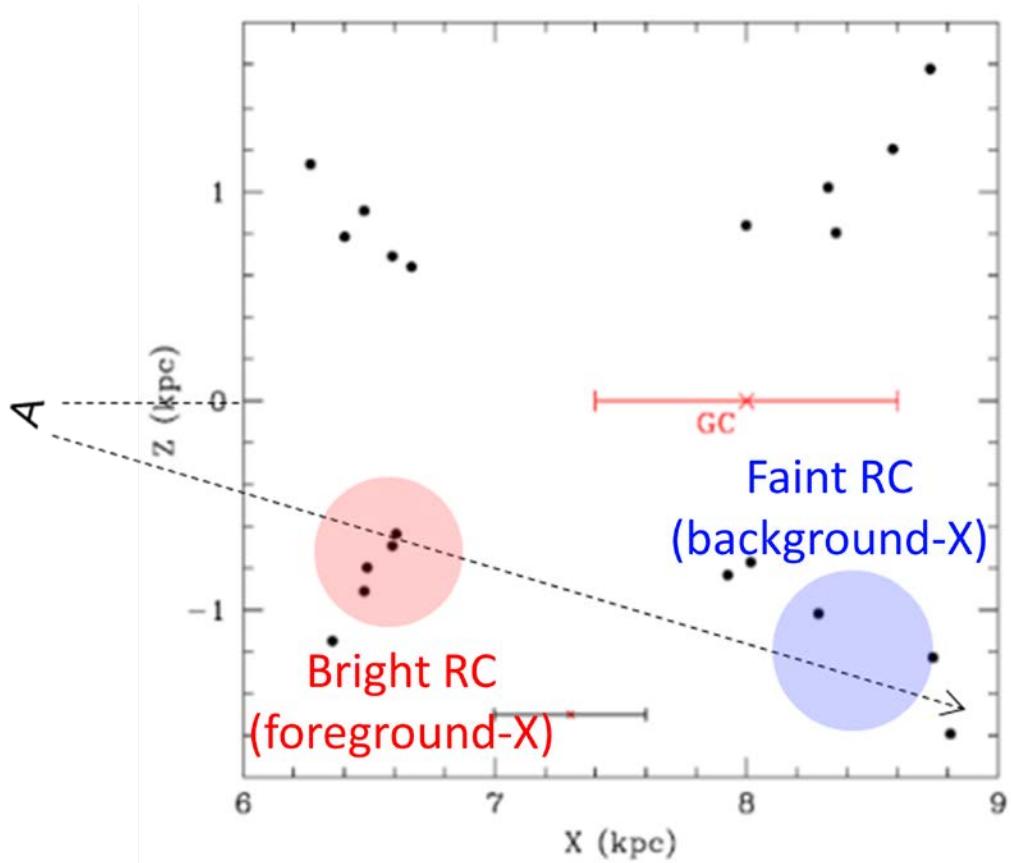
McWilliam & Zocalli 2010



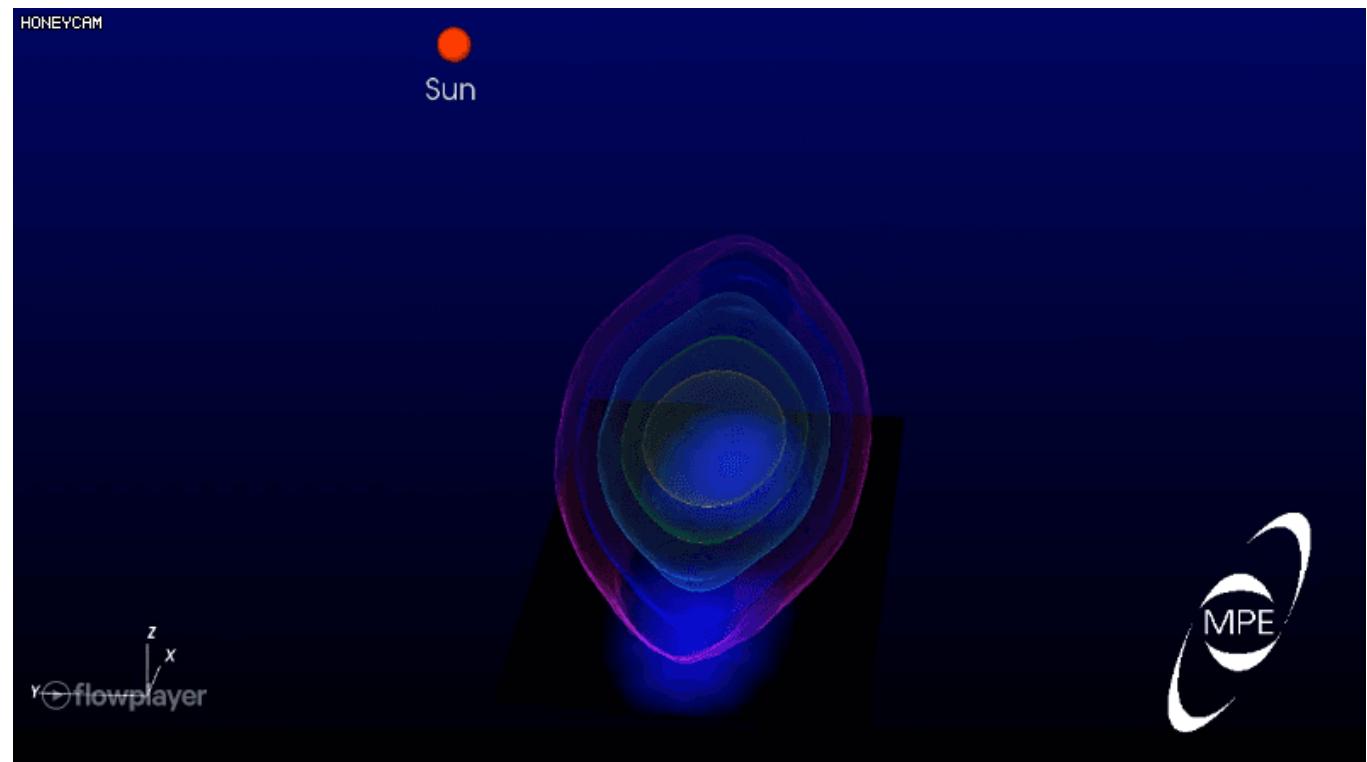
Wegg & Gerhard 2013

Scenario 1: The X-shaped Bulge

1. Why it is double?
2. Why it is $f(l, b)$?



McWilliam & Zocalli 2010

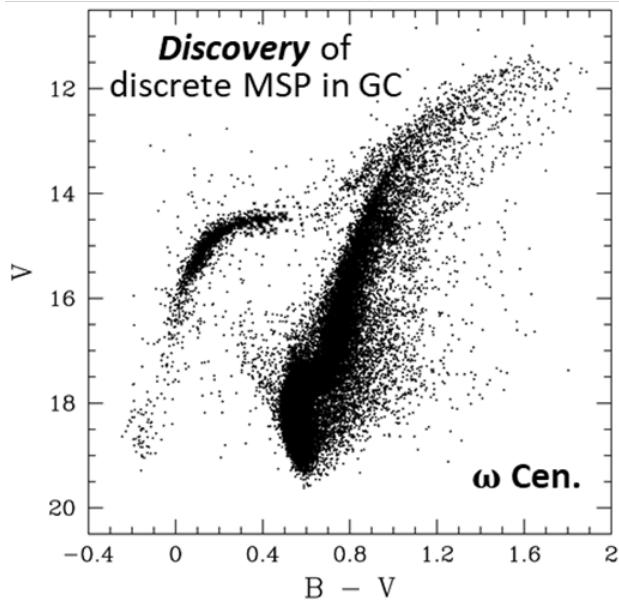


Wegg & Gerhard 2013

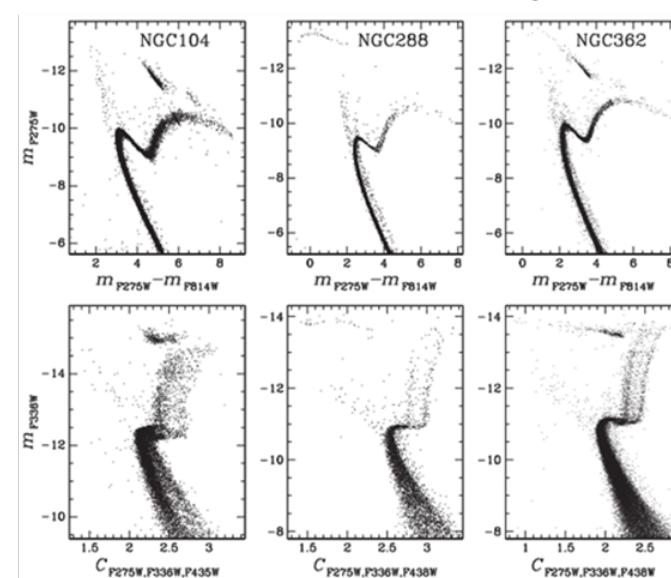
But, an alternative interpretation has been suggested based on the multiple population phenomenon (Y.-W. Lee et al. 2015)

Multiple Stellar Populations in Globular Clusters

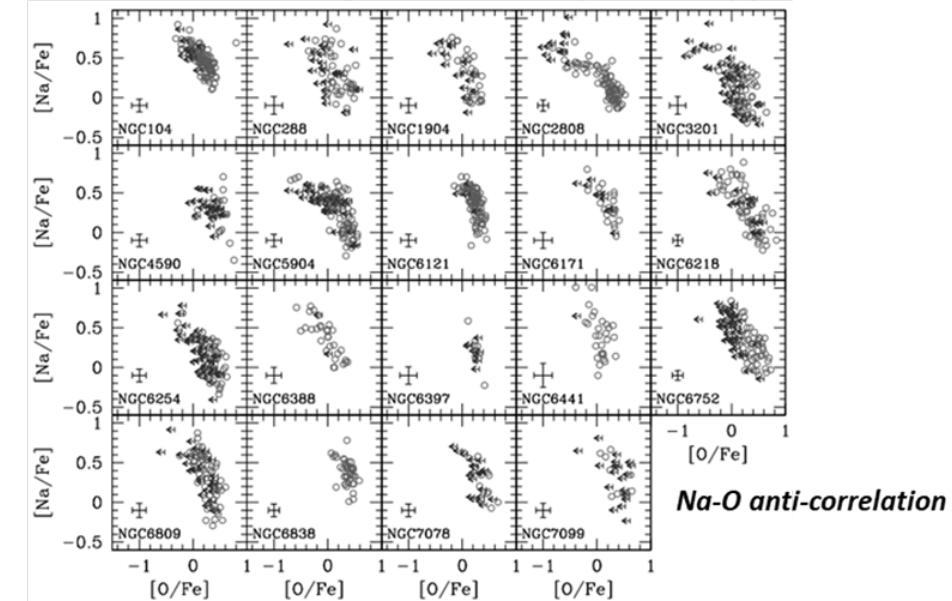
Lee et al. 1999 / CTIO 0.9m



Piotto et al. 2015 / *HST UV-band photometry*



Carretta et al. 2009 / *High-resolution spectroscopy with VLT*



Na-O anti-correlation

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; 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; Renzini 15;
Bastian+Lardo 18; ... 700+ papers!

Multiple Stellar Populations in Globular Clusters

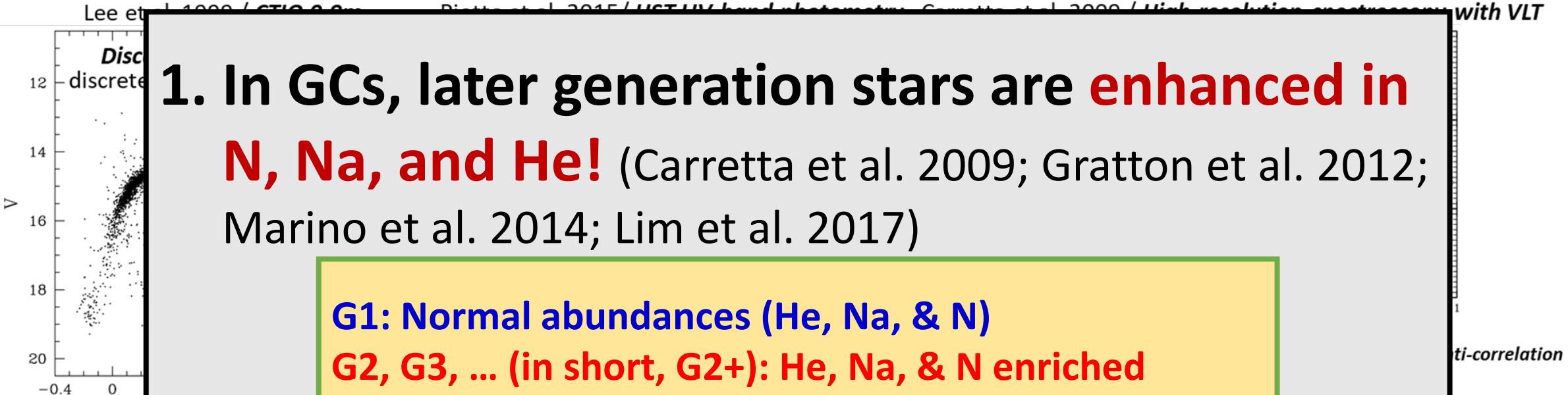
1. In GCs, later generation stars are **enhanced in N, Na, and He!** (Carretta et al. 2009; Gratton et al. 2012; Marino et al. 2014; Lim et al. 2017)

G1: Normal abundances (He, Na, & N)

G2, G3, ... (in short, G2+): He, Na, & N enriched
O & C depleted or invariant

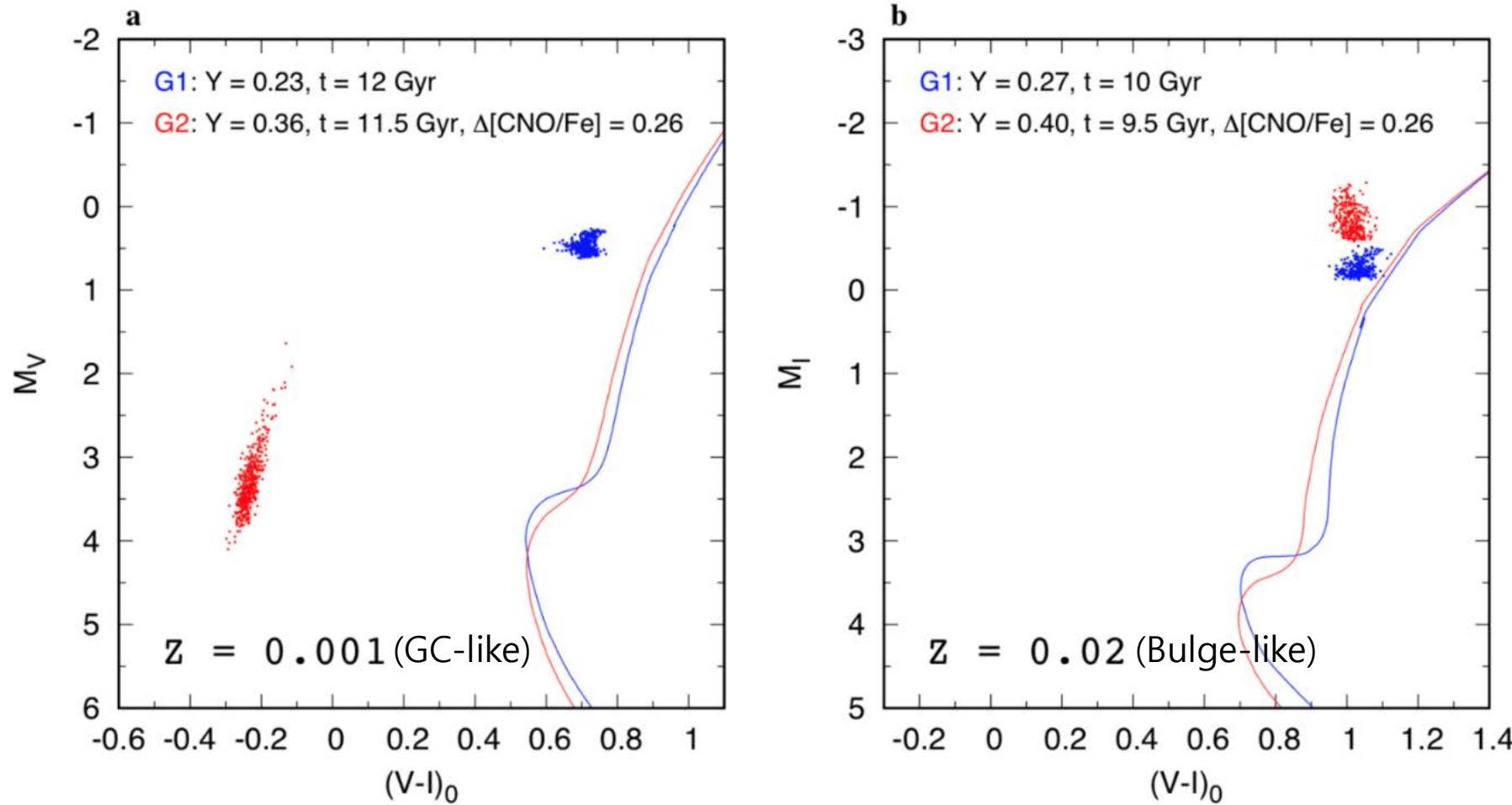
2. Stars enhanced in N, Na, and He are produced **only in GC(-like) environment!** (Martell et al. 2011; Renzini et al. 2015; Lardo et al. 2016; Bastian & Lardo 2018)

Lee+99
Lee+00
Johnson+00
Gratton+00
Da Costa+00
Bastian+Lardo 10...



Scenario 2: Multiple Populations in the Bulge

In the metal-rich regime, **He-rich HB stars are on the brighter RC!**



Lee et al. 2019

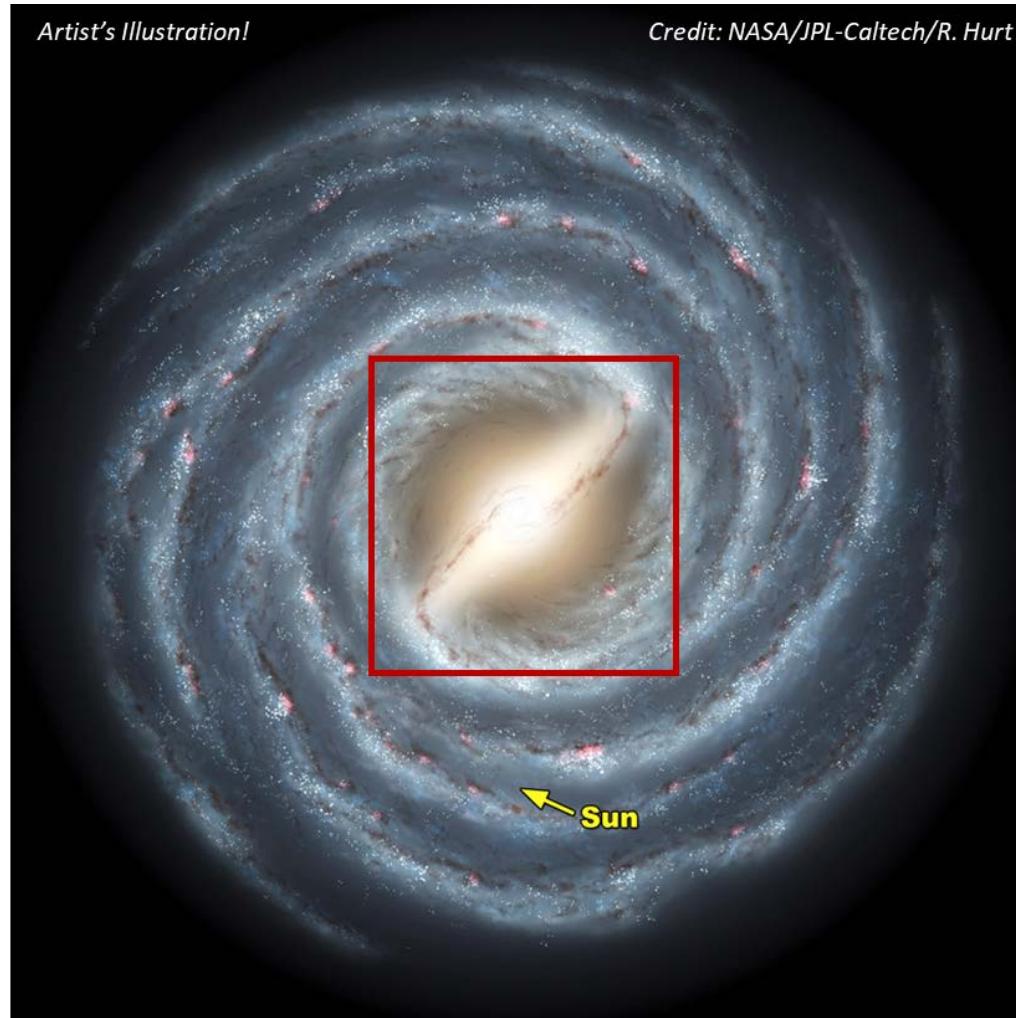
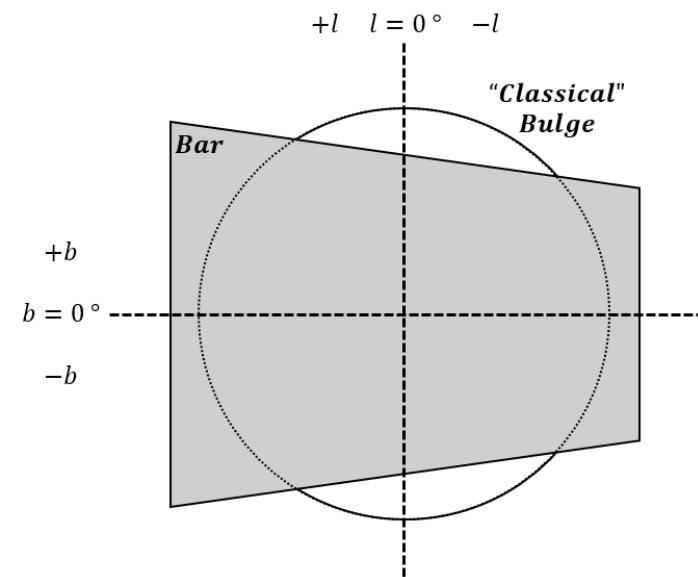
- **Faint RC (fRC): *He,N-normal* earlier generation (**G1**)**
- **Bright RC (bRC): *He,N-enhanced* later generations (**G2+**)**

Scenario 2: Multiple Populations in the Bulge

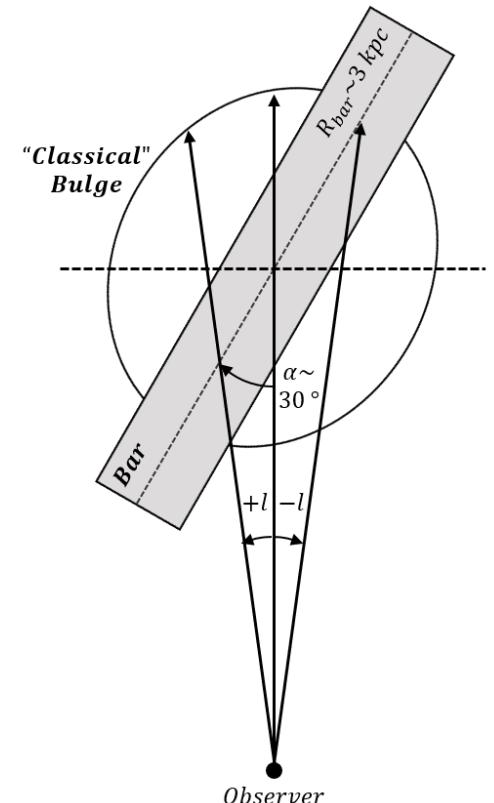
Tilted Bar embedded in a “Classical” Bulge

i.e. Composite Bulge (Babusiaux et al. 2010; Hill et al. 2011; Erwin et al. 2014;
Rojas-Arriagada et al. 2014; Saha 2015; Lee et al. 2015; Joo et al. 2017; Zoccali et al. 2018)

side (edge-on) view



top (face-on) view

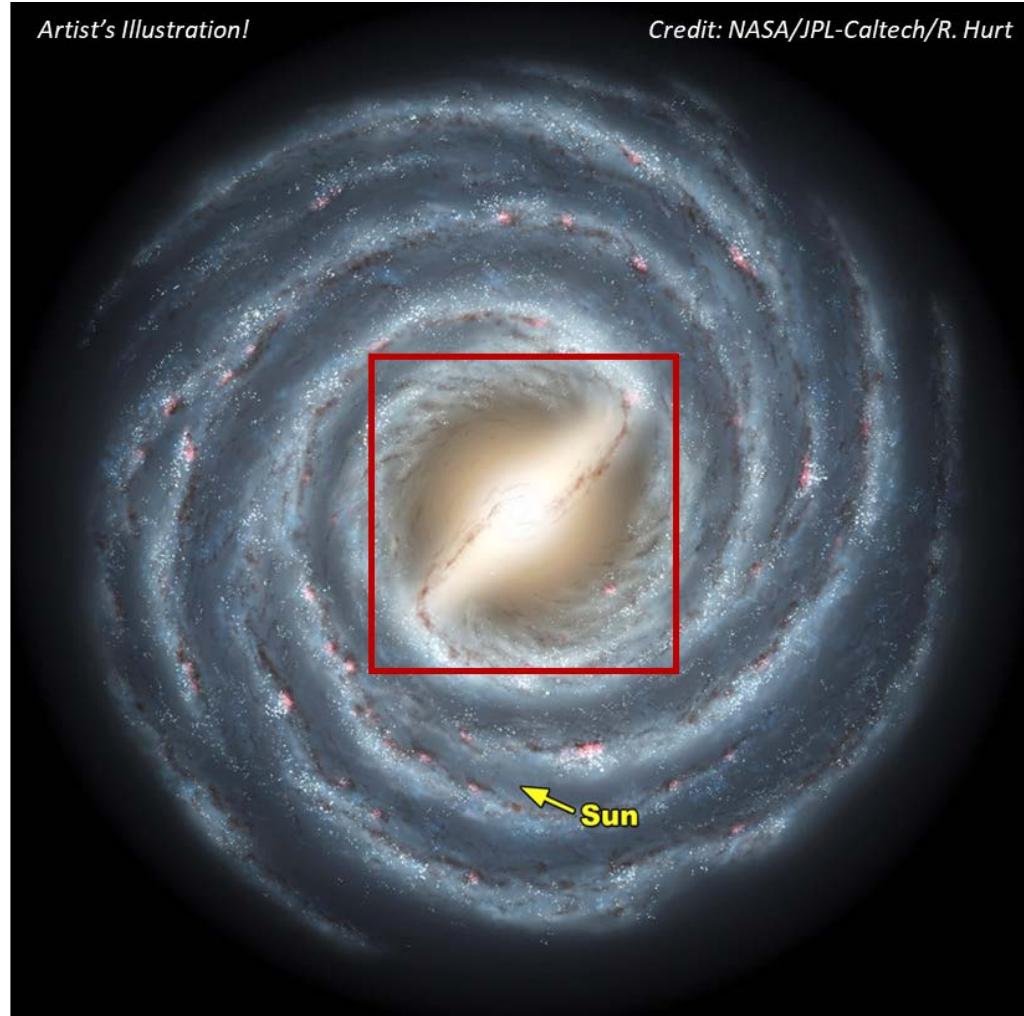
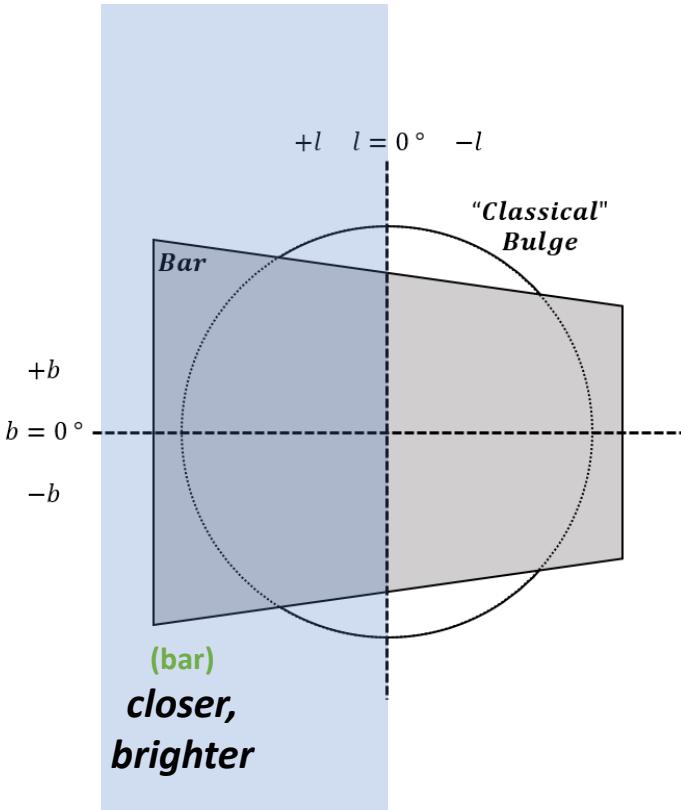


Scenario 2: Multiple Populations in the Bulge

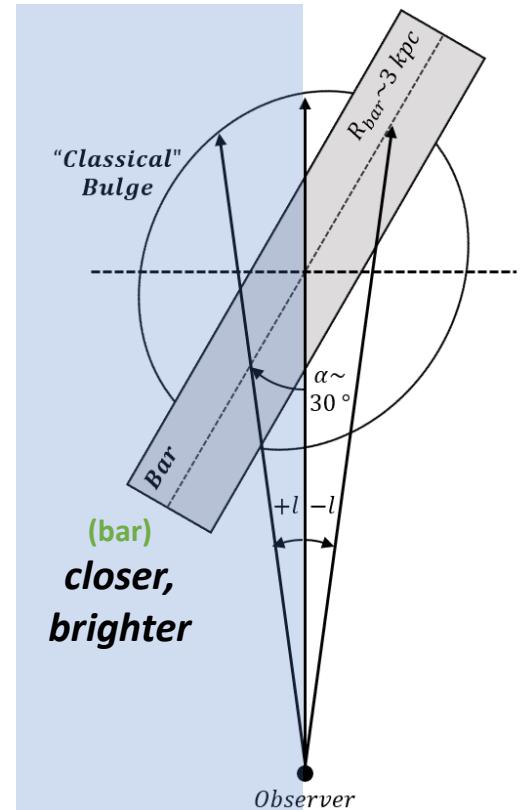
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side (edge-on) view



top (face-on) view

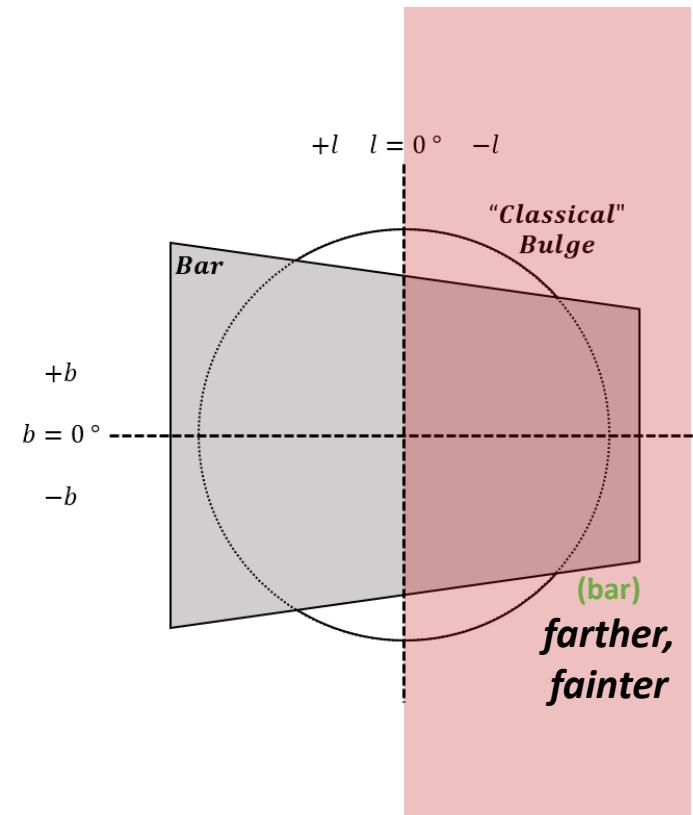


Scenario 2: Multiple Populations in the Bulge

Tilted Bar embedded in a “Classical” Bulge

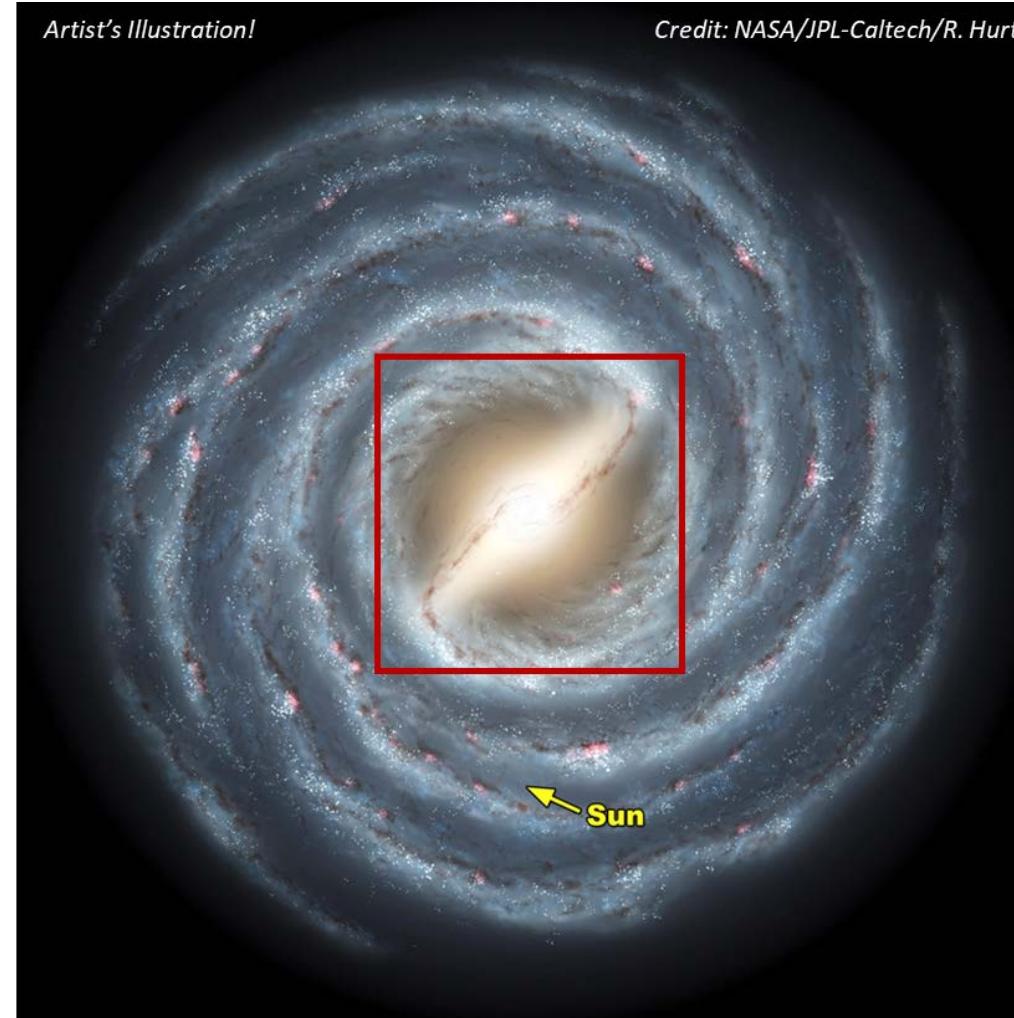
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Rojas-Arriagada et al. 2014; Saha 2015; Lee et al. 2015; Joo et al. 2017; Zoccali et al. 2018)

side (edge-on) view

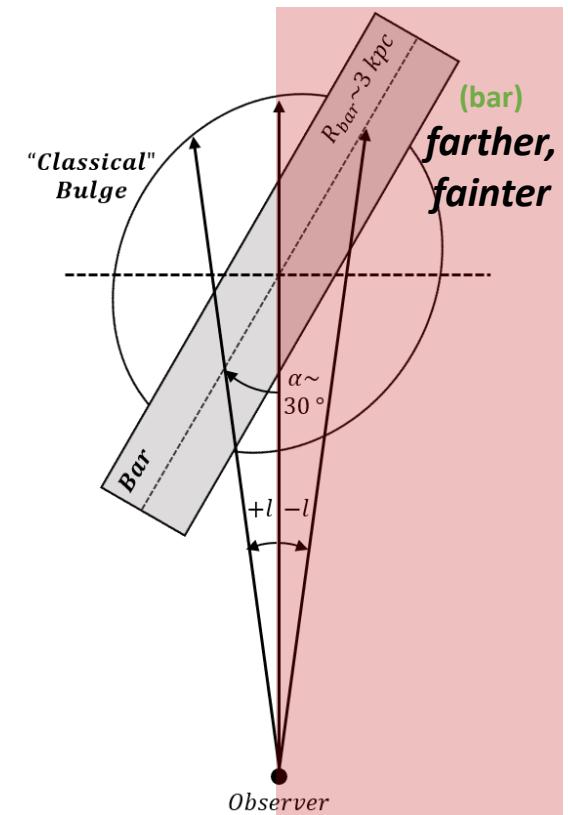


Artist's Illustration!

Credit: NASA/JPL-Caltech/R. Hurt

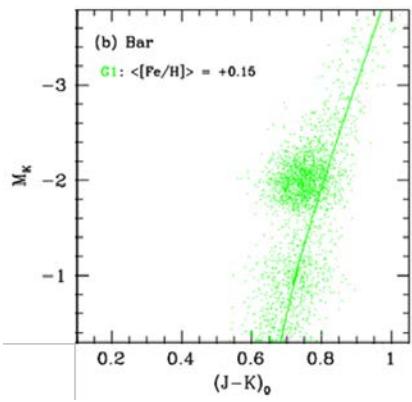


top (face-on) view

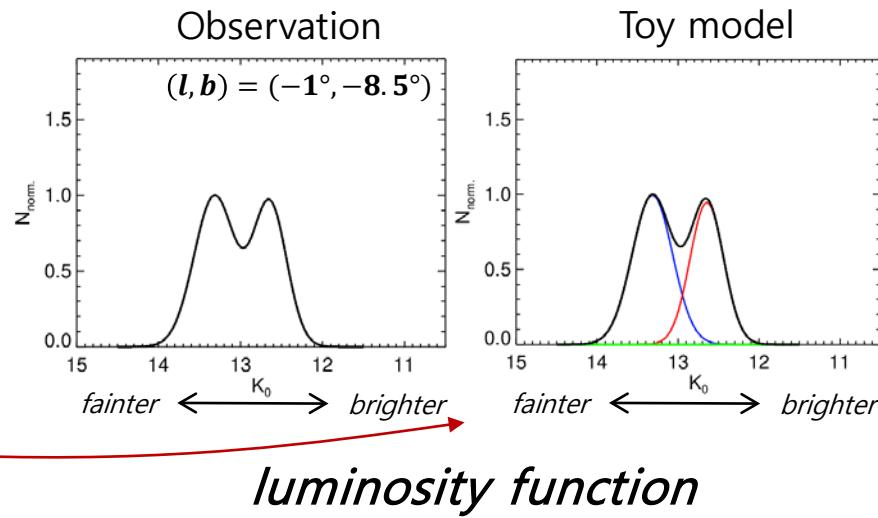
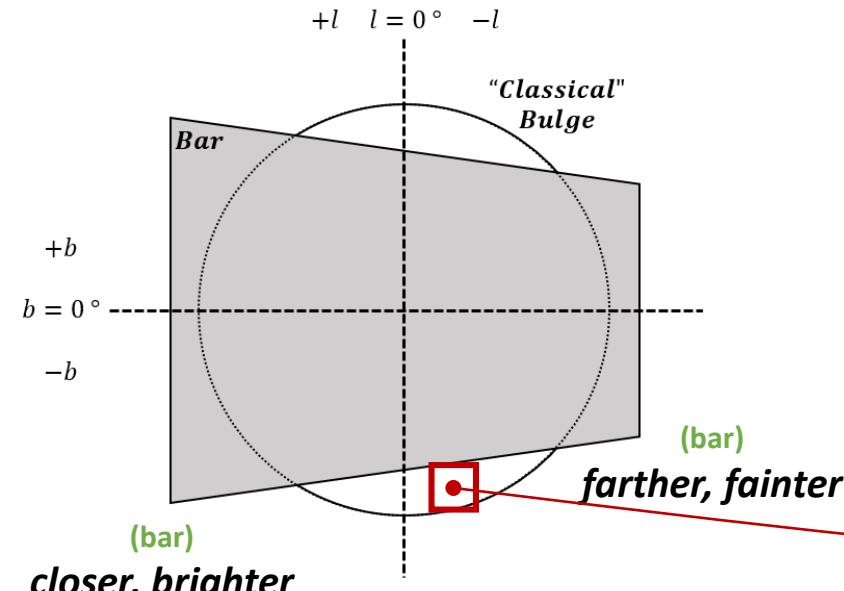
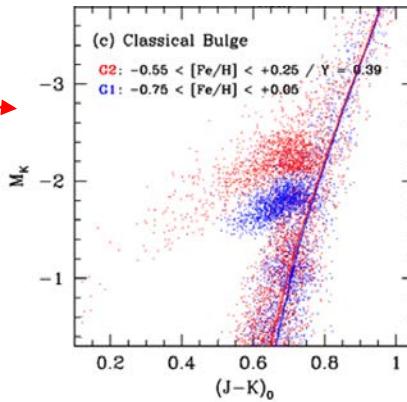


2. Why it is $f(l, b)$?

Scenario 2: Multiple Populations in the Bulge

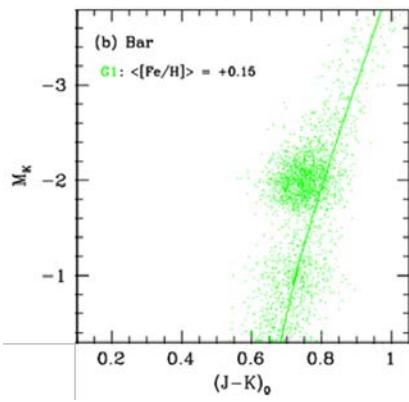


Tilted Bar embedded in a “Classical” Bulge

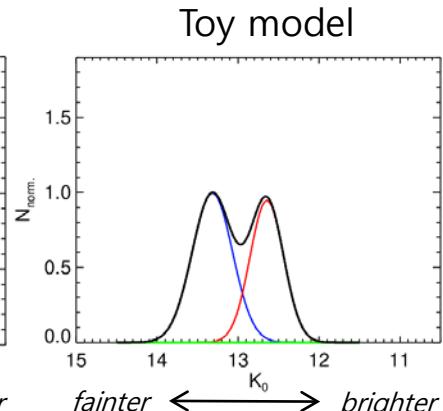
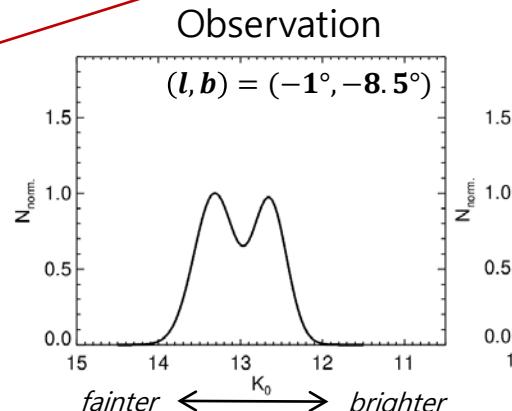
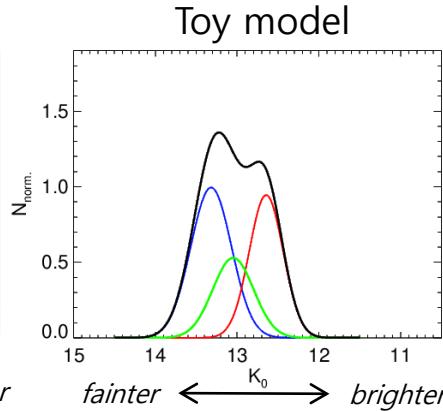
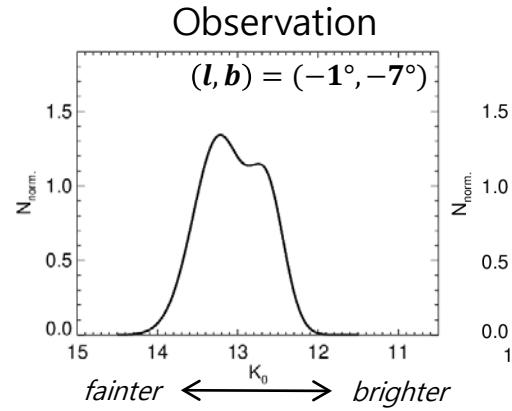
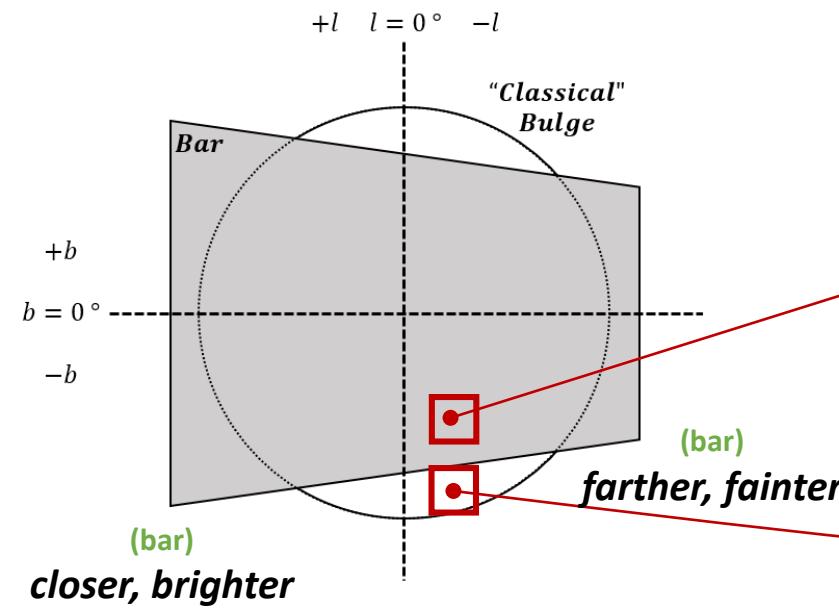
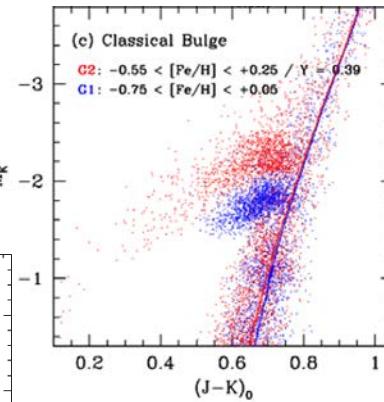


2. Why it is $f(l, b)$?

Scenario 2: Multiple Populations in the Bulge



Tilted Bar embedded in a “Classical” Bulge

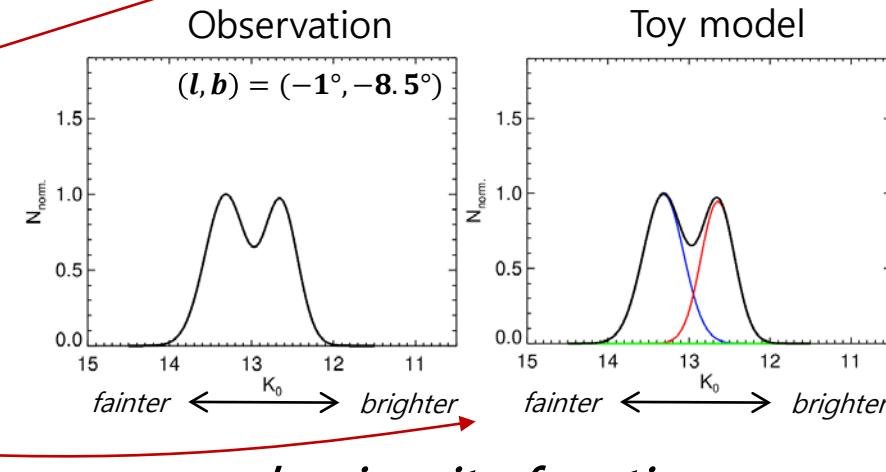
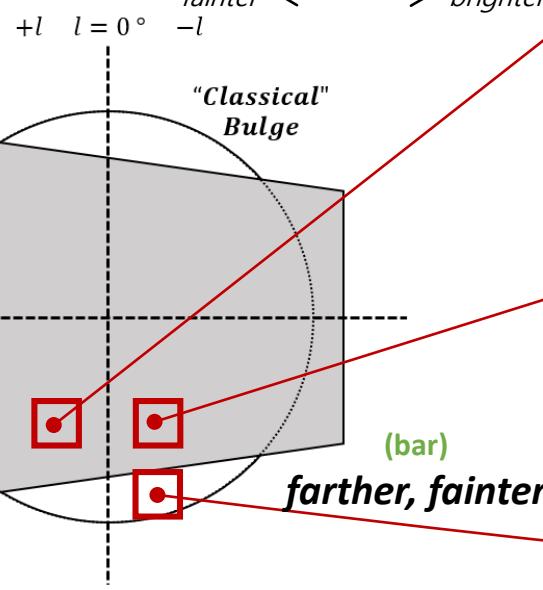
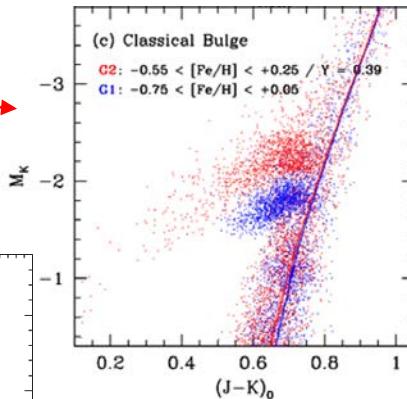
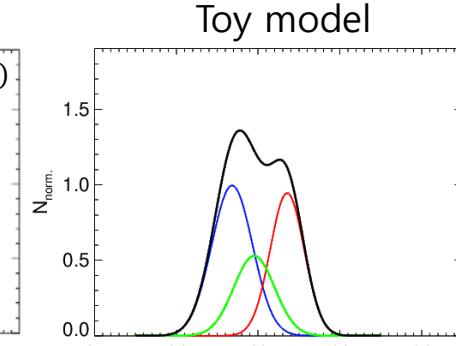
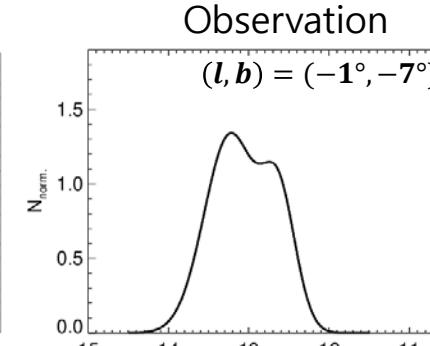
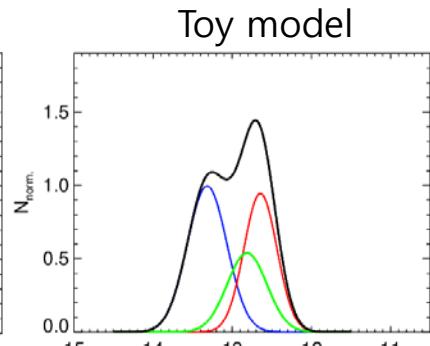
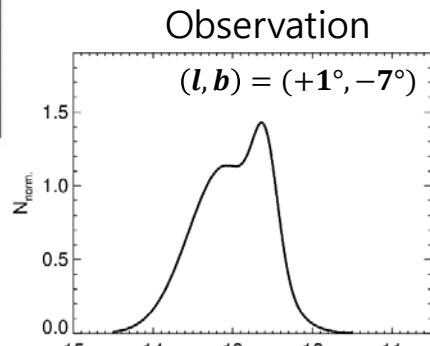
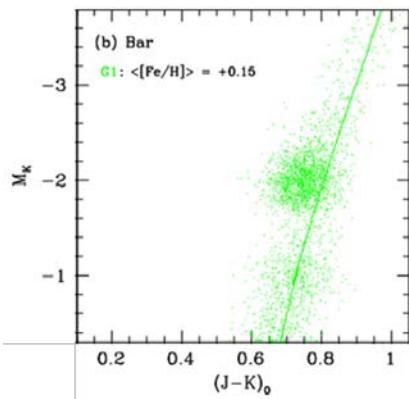


luminosity function

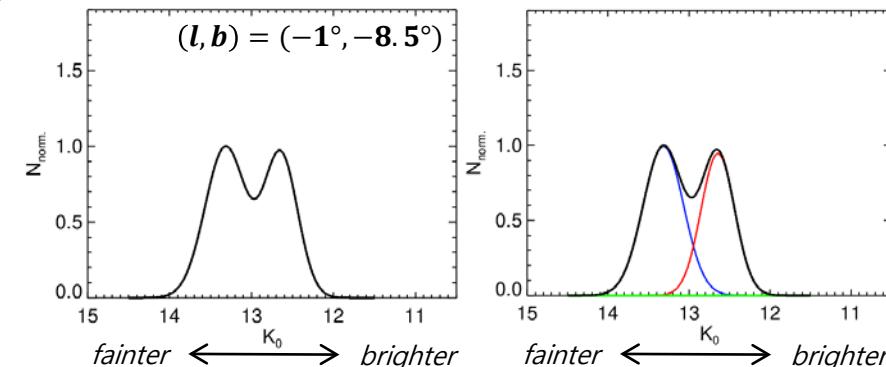
2. Why it is $f(l, b)$?

Scenario 2: Multiple Populations in the Bulge

Tilted Bar embedded in a “Classical” Bulge



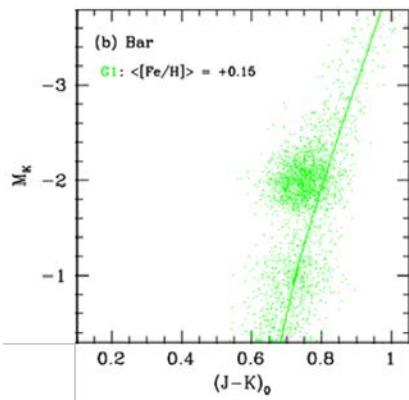
luminosity function



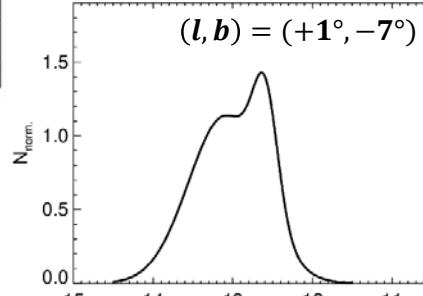
2. Why it is $f(l, b)$?

Scenario 2: Multiple Populations in the Bulge

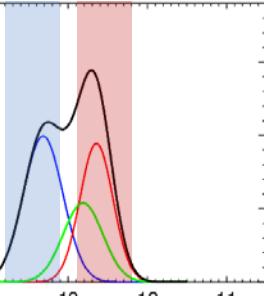
Tilted Bar embedded in a “Classical” Bulge



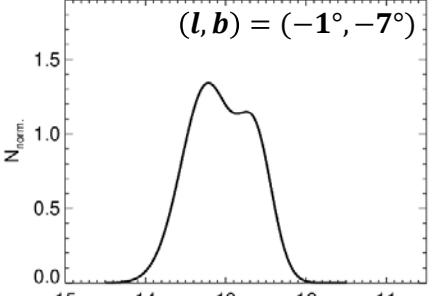
Observation



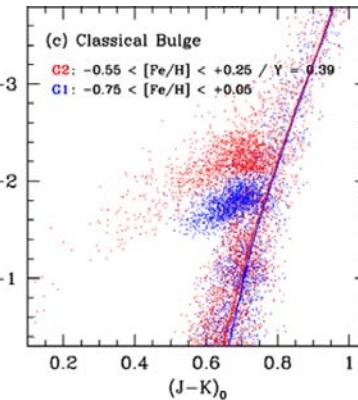
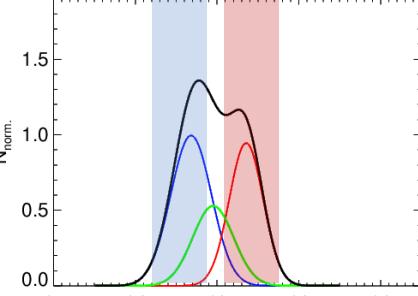
Toy model



Observation

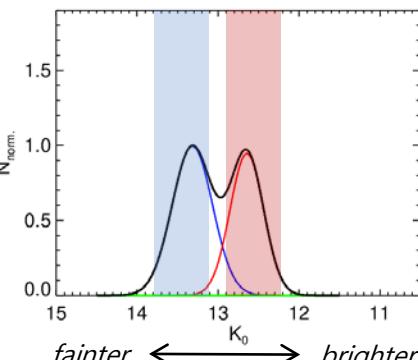
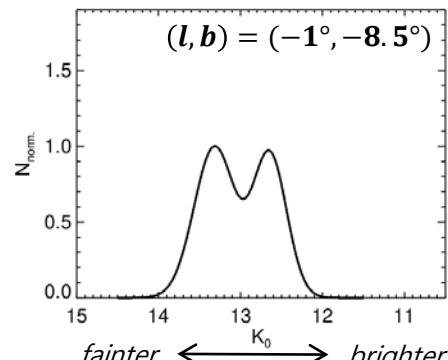
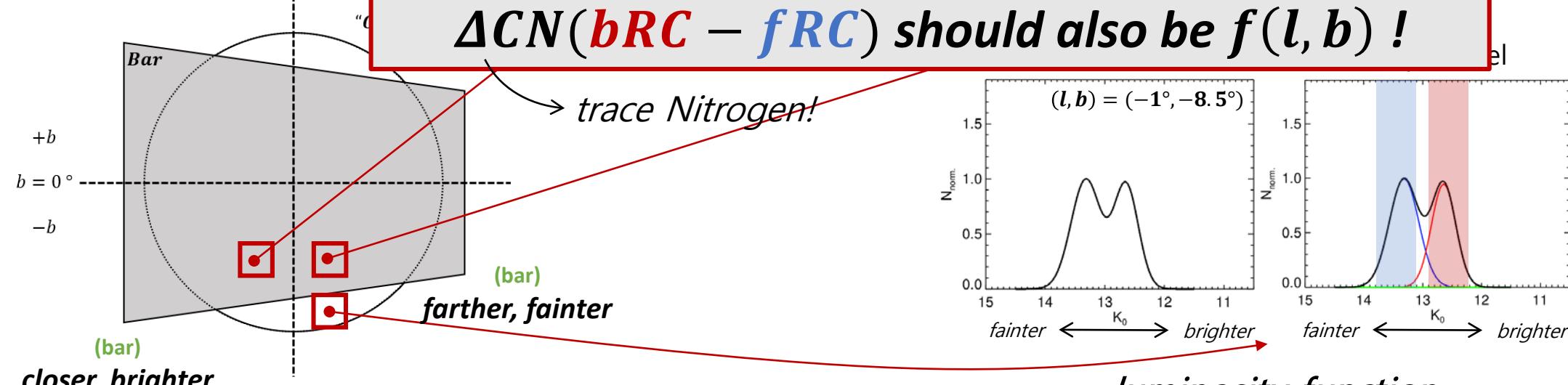


Toy model



$+l \quad l = 0^\circ \quad -l$

$\Delta CN(bRC - fRC)$ should also be $f(l, b)$!



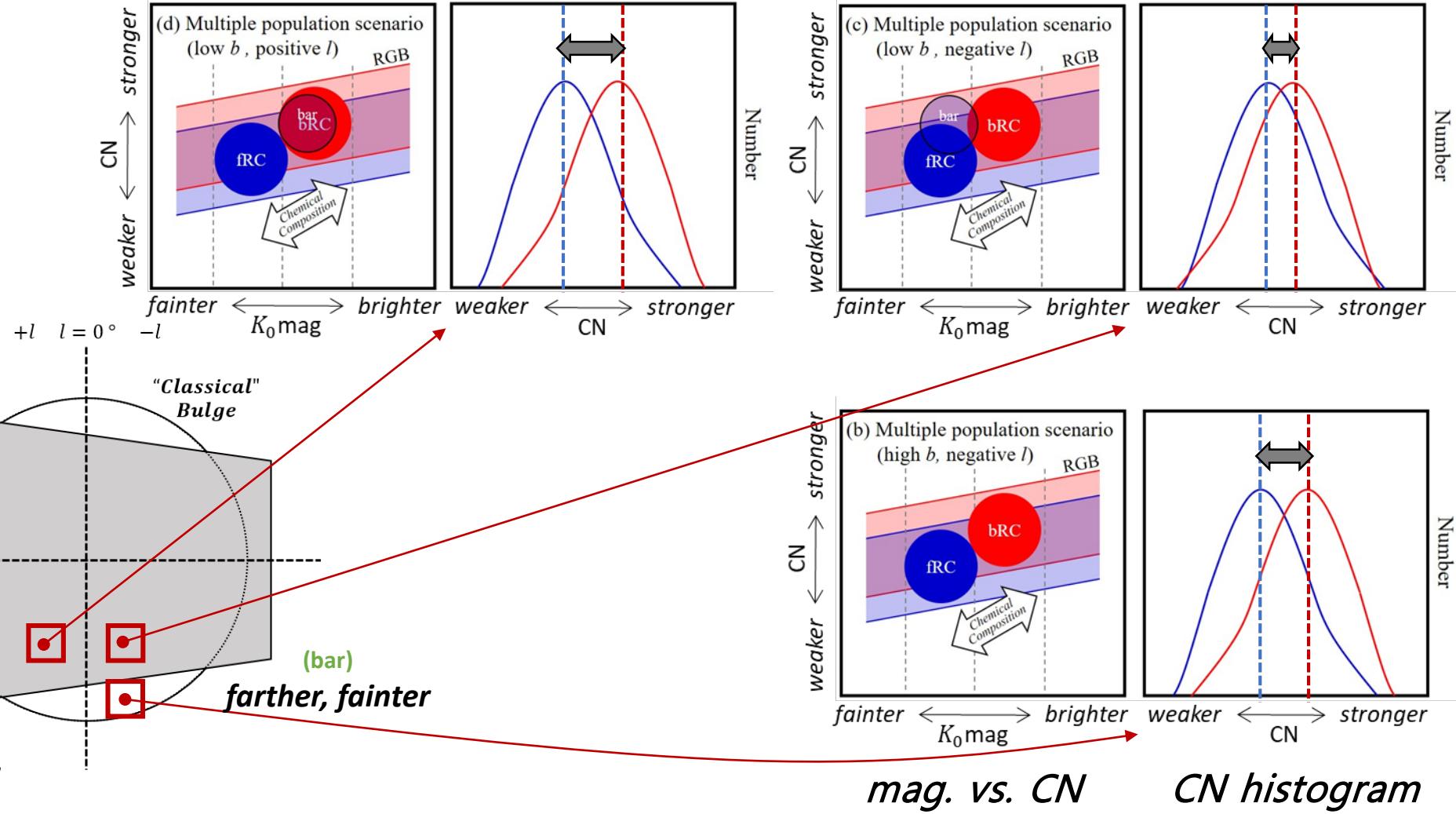
luminosity function

Scenario 2: Multiple Populations in the Bulge

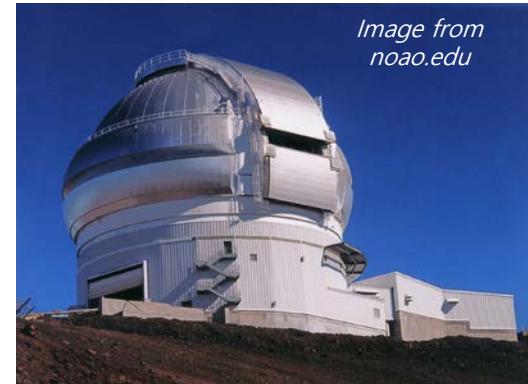
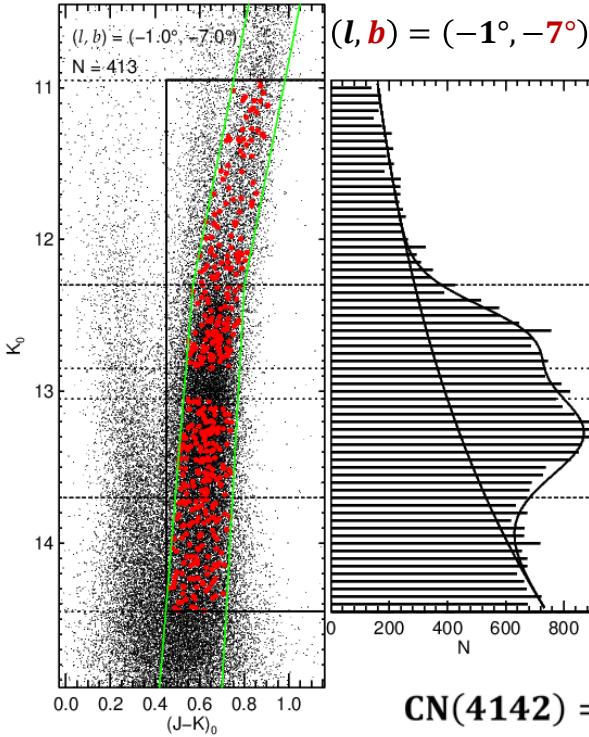
- $[\text{Fe}/\text{H}] > 0.0$ (most metal-rich)
- G1 (He-rich, CN-strong)

Tilted Bar embedded in a “Classical” Bulge

- $[\text{Fe}/\text{H}] < 0.0$
- G1 (He-normal, CN-weak)
- G2+ (super He-rich, CN-strong)



Low-Resolution Spectroscopy for the RC & RGB stars in the *various l & b fields* of the bulge

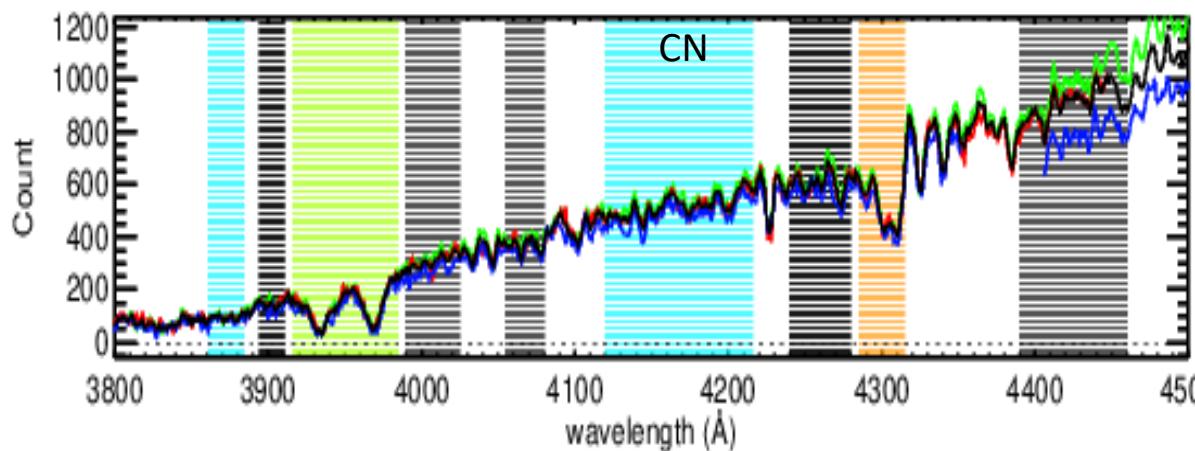


Gemini-South Multi-Object Spectrographs

GS-2018B-Q-211

GS-2019A-Q-118&223

GS-2020A-Q-126&227

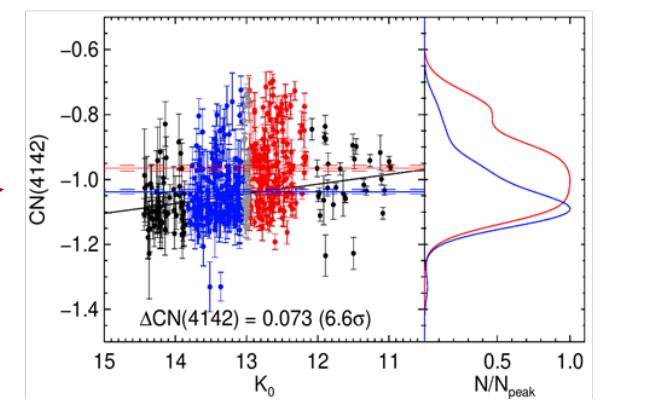
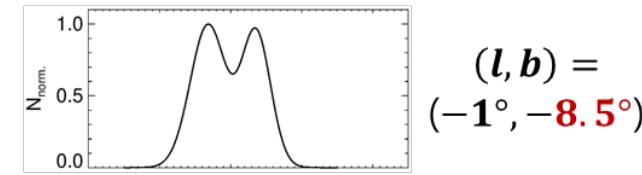
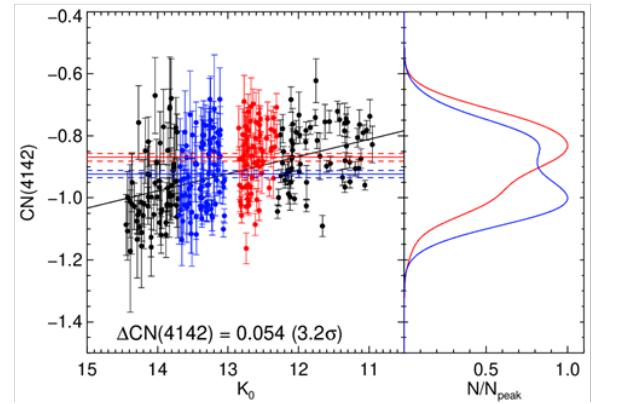
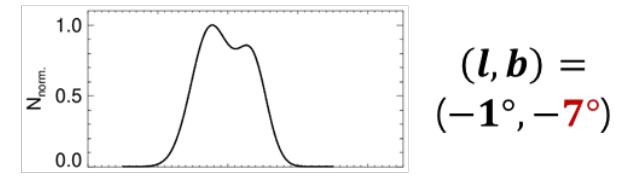
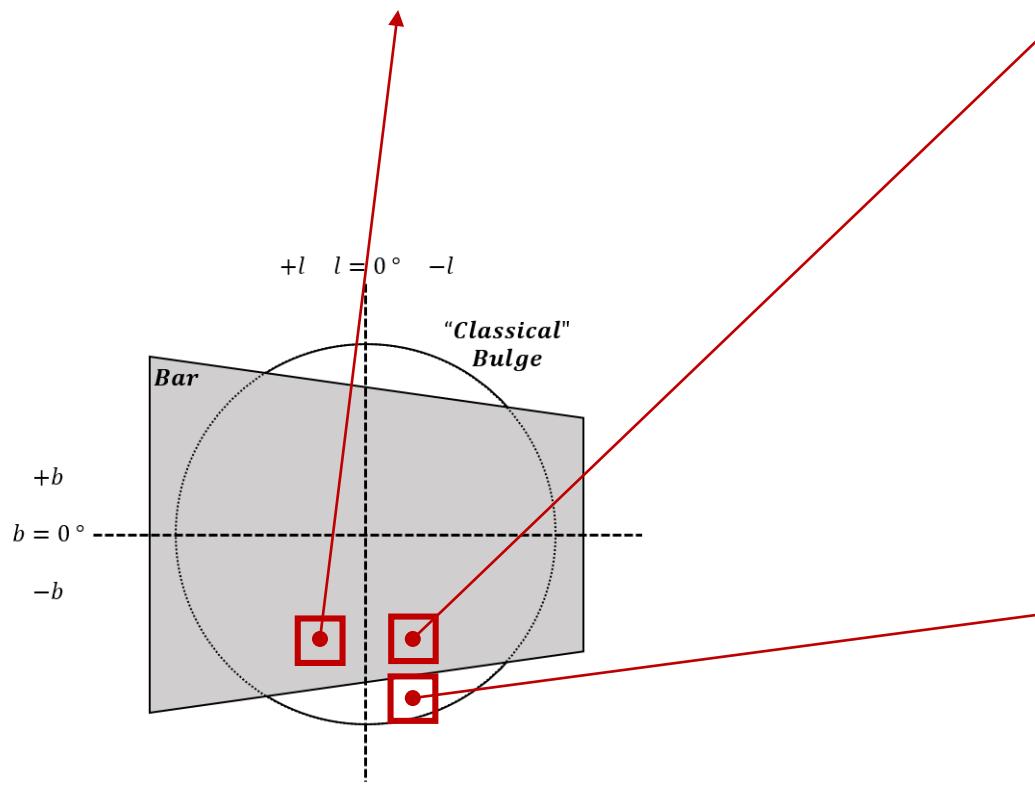


Thanks to the K-GMT Science Program

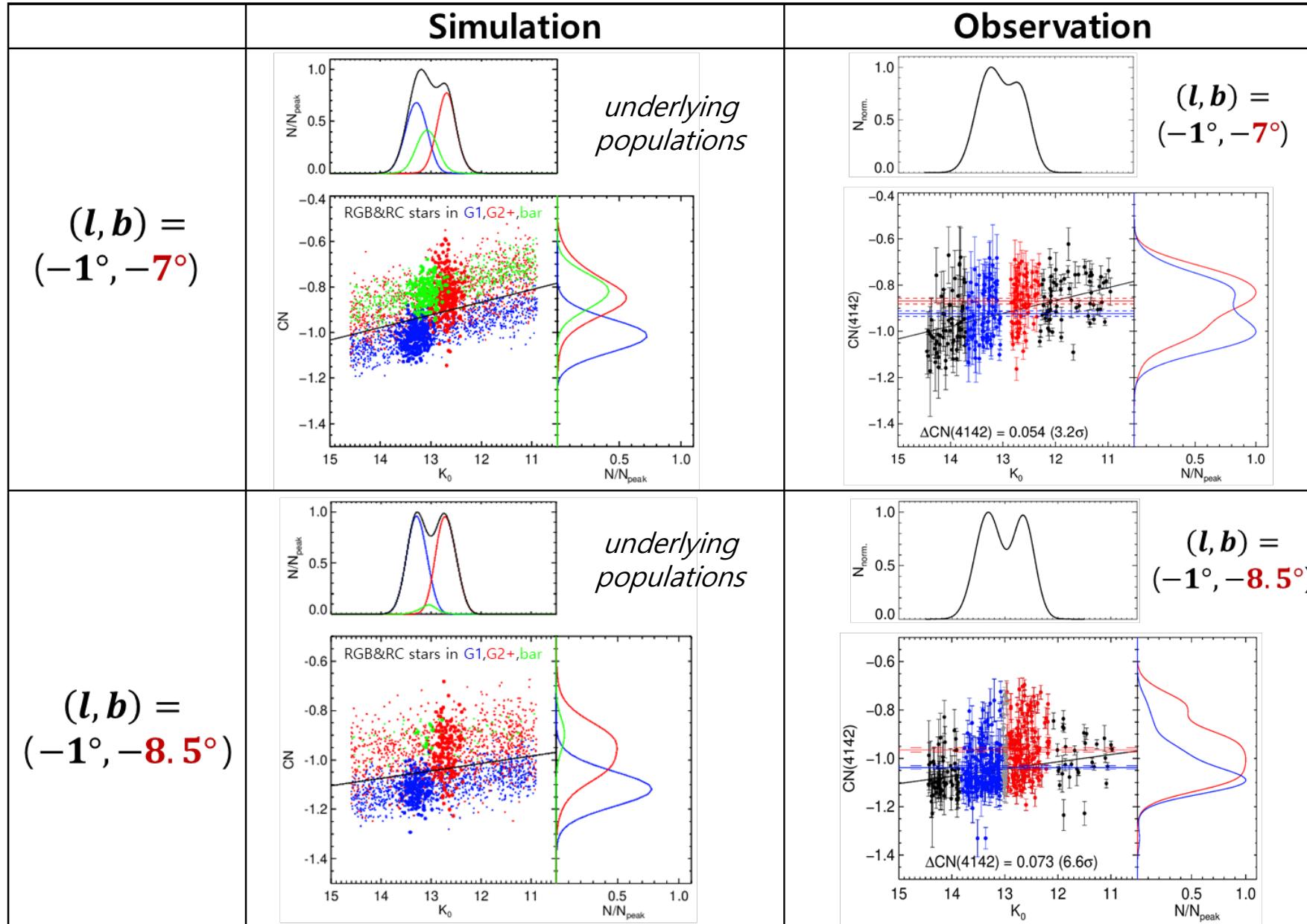
- 1. Bright RC stars are enhanced in CN !**
- 2. $\Delta CN(bRC - fRC)$ varies with latitude !**

$$(l, b) = (+1^\circ, -7^\circ)$$

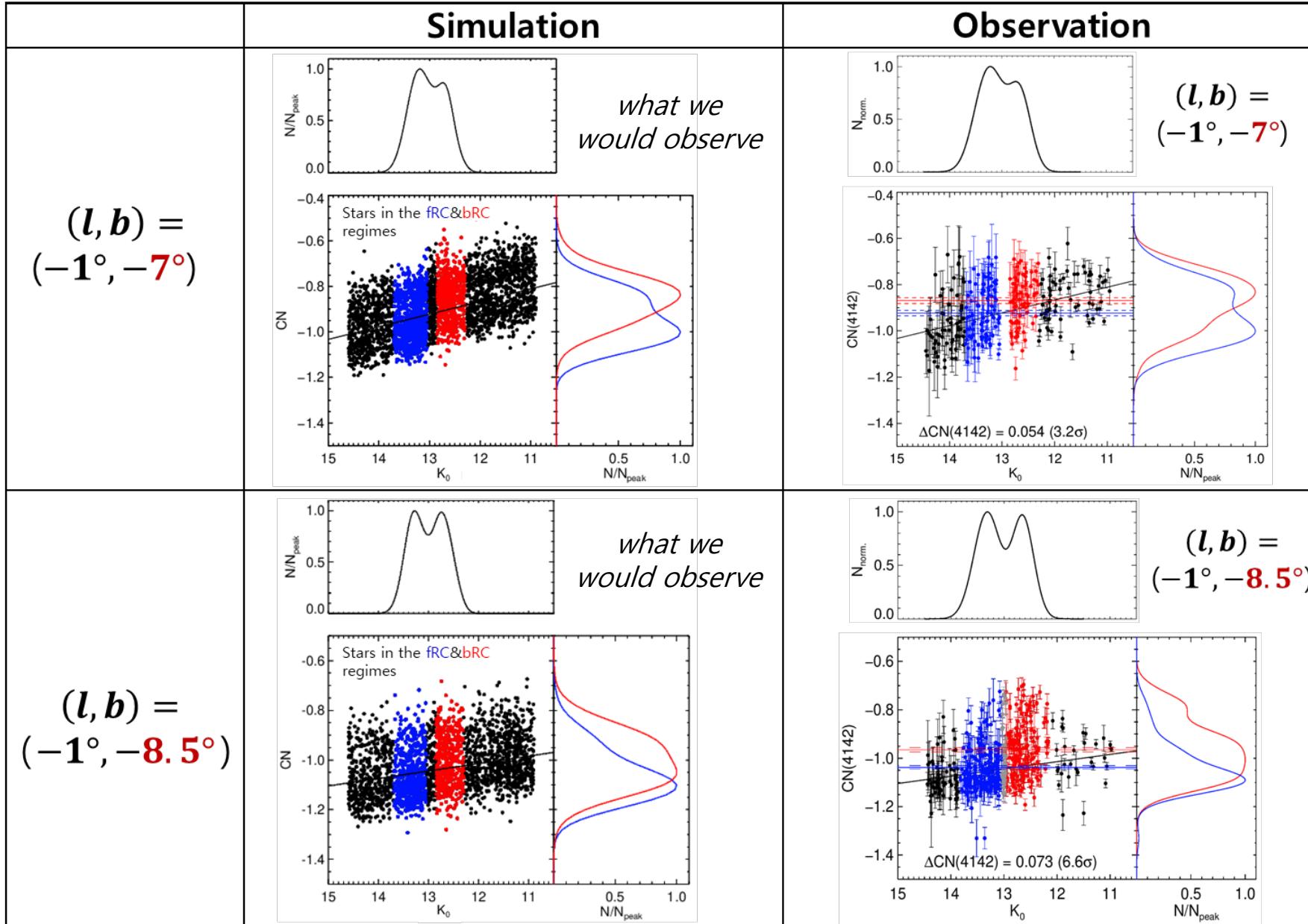
Observations in progress



- 1. Bright RC stars are enhanced in CN !**
- 2. $\Delta CN(bRC - fRC)$ varies with latitude !**

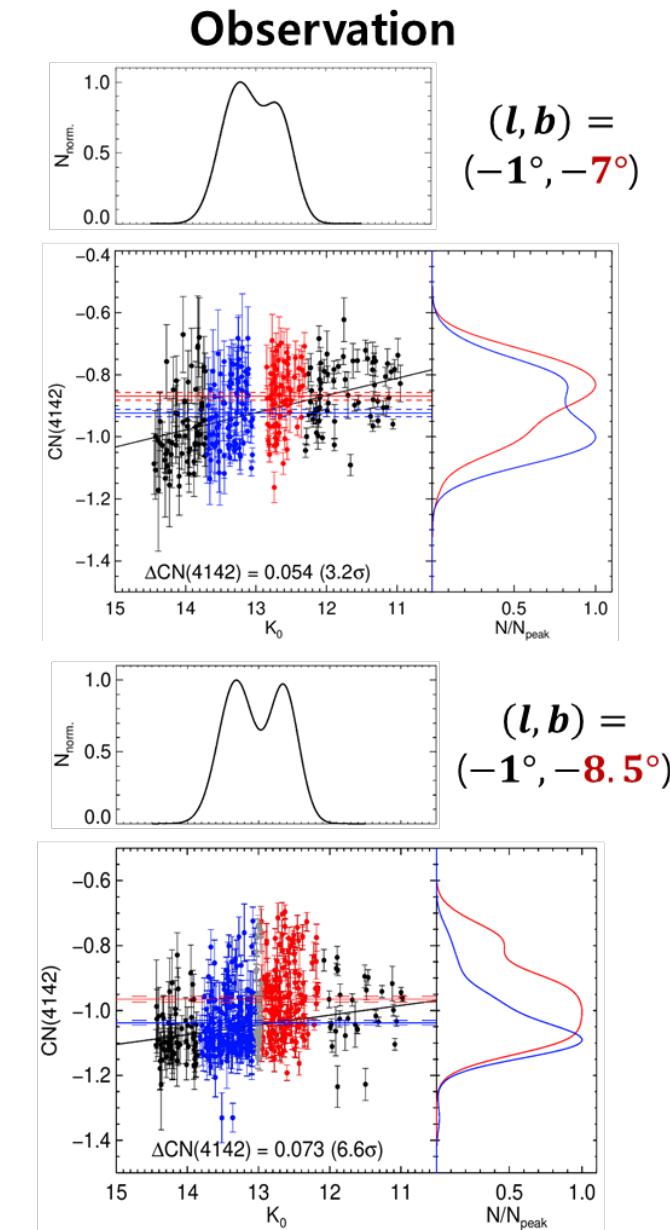
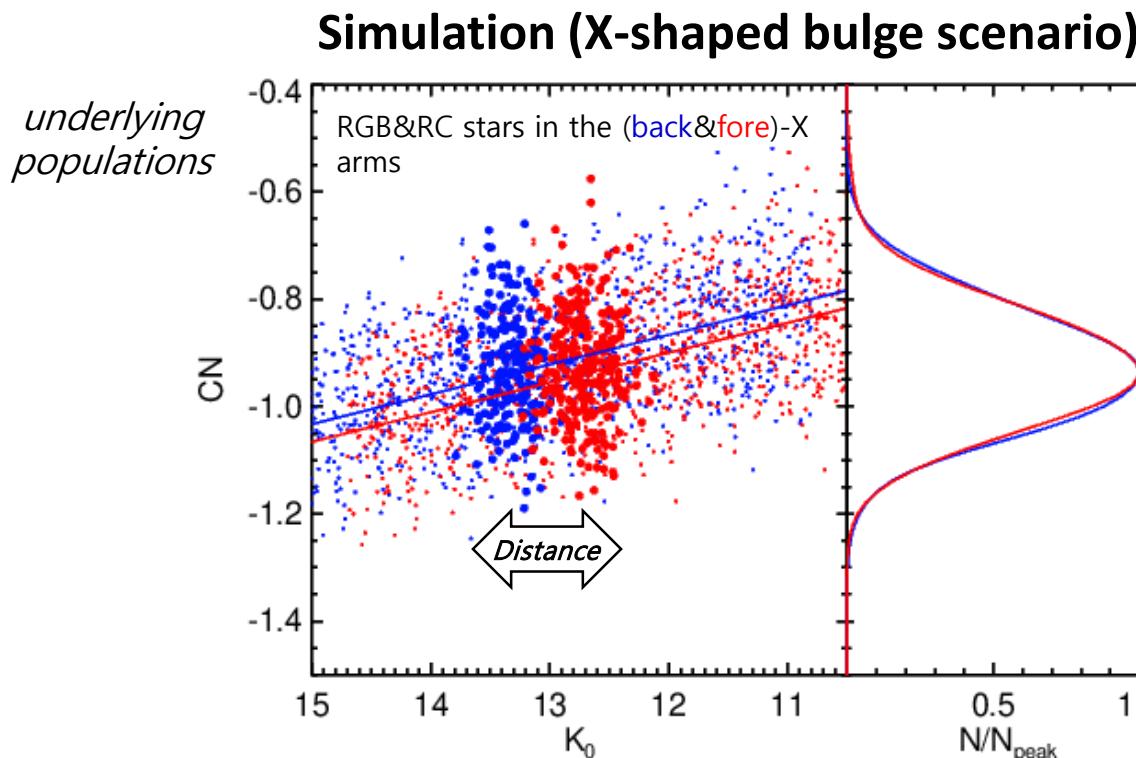


- 1. Bright RC stars are enhanced in CN !**
- 2. $\Delta CN(bRC - fRC)$ varies with latitude !**



In the X-shaped bulge scenario,

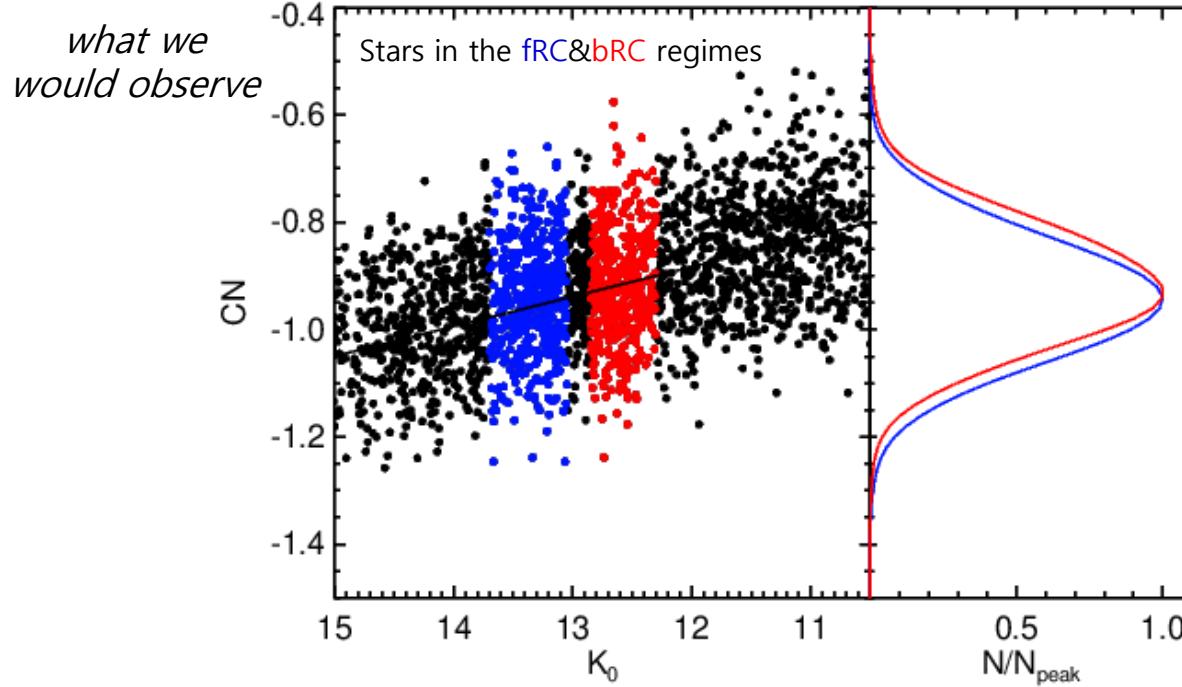
(1) No $\Delta CN(bRC - fRC)$, (2) No l & b dependence of $\Delta CN(bRC - fRC)$ is expected!



In the X-shaped bulge scenario,

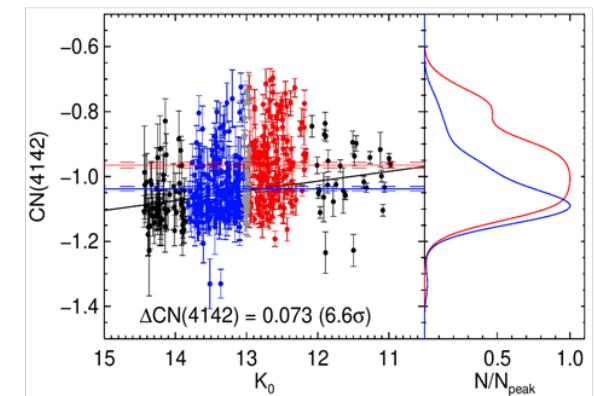
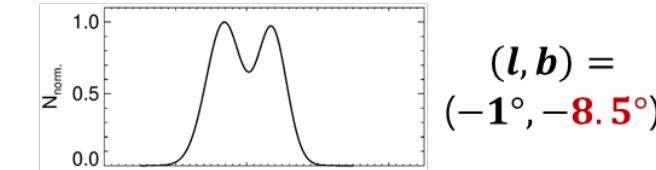
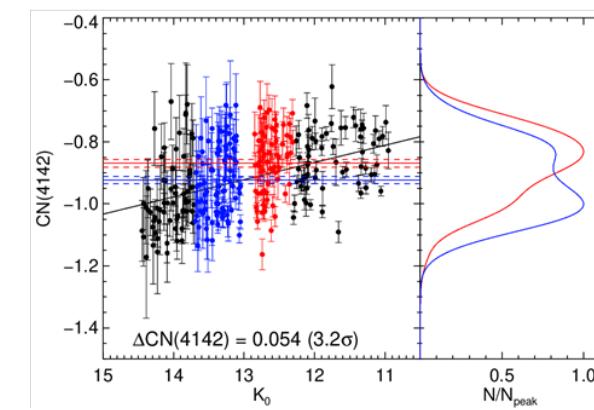
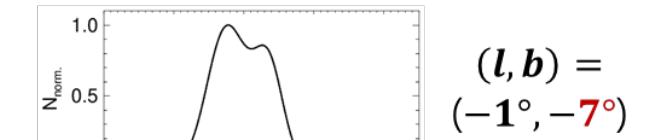
(1) No $\Delta CN(bRC - fRC)$, (2) No l & b dependence of $\Delta CN(bRC - fRC)$ is expected!

Simulation (X-shaped bulge scenario)



Expected to have same peak positions of CN distributions, regardless of l & b

Observation



Summary

1. *Bright RC stars are enhanced in CN (which trace N & He) !*

→ Direct evidence that double RC in MW bulge is another manifestation of Helium-enhanced *multiple population phenomenon*, and has little to do with an X-shaped structure.

2. *A significant population of stars in the MW bulge were provided by disrupted proto-GCs.*

→ “*GC-origin bulge*”

3. *$\Delta CN(bRC - fRC)$ varies with galactic latitude (b) !*

→ Composite bulge model (*tilted bar embedded in the “GC-origin bulge”*) can naturally explain l & b dependence of RC luminosity function and $\Delta CN(bRC-fRC)$, simultaneously.