

# Unveiling the Milky Way bulge structure

Felipe Gran M.

# Outline

- ★ Motivation:

- ★ Why study the Milky Way bulge?

- ★ Key surveys:

- ★ 2MASS, BRAVA, COBE, OGLE, VVV, WISE

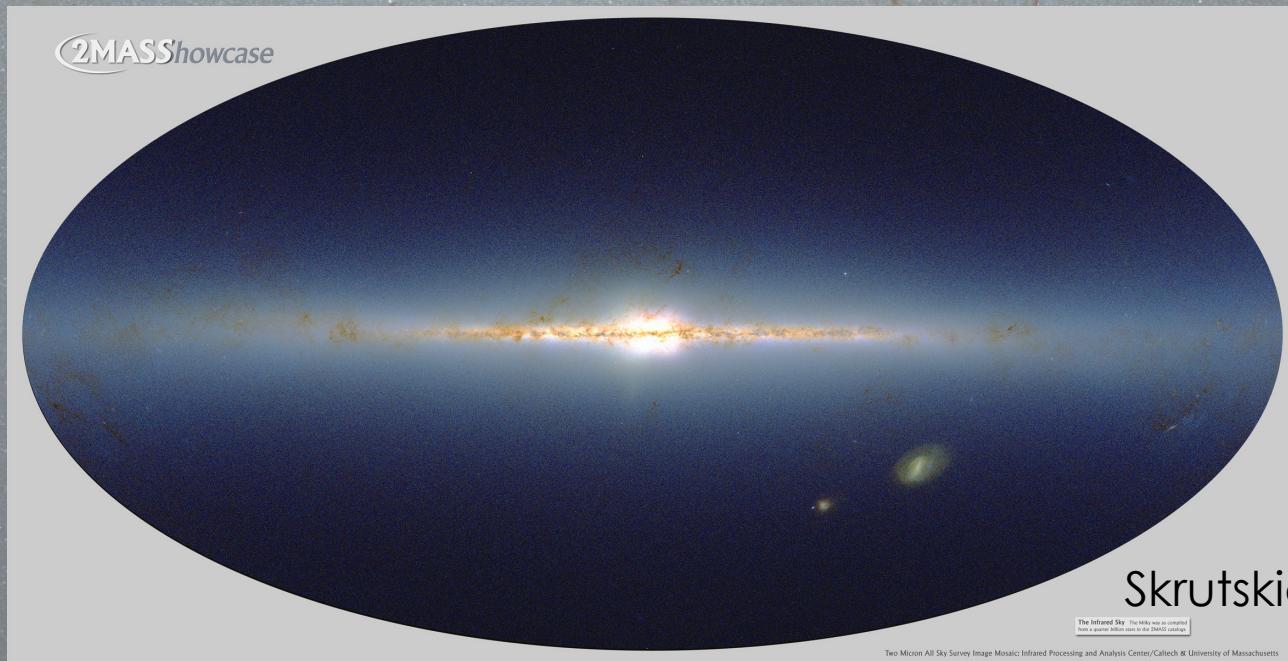
- ★ Results:

- ★ Different structure within the Galactic bulge: RC and RRL

- ★ Summary

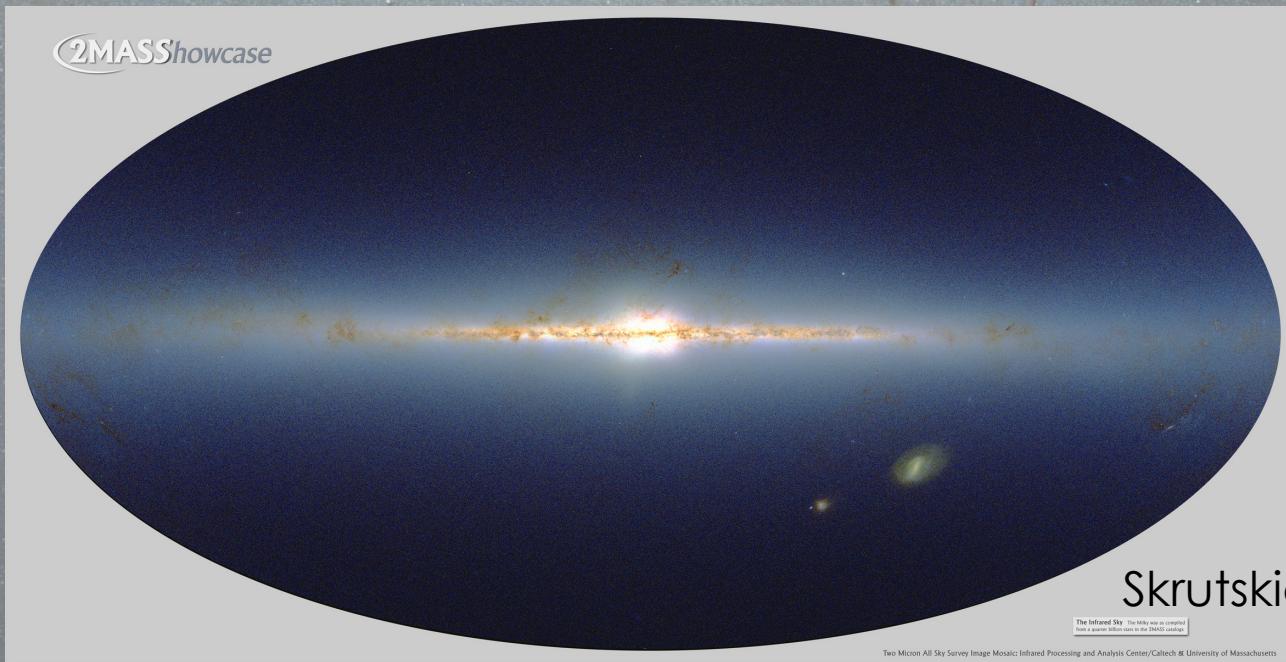
# Motivation

- ★ What type of events took place during the formation and evolution of the Galaxy?



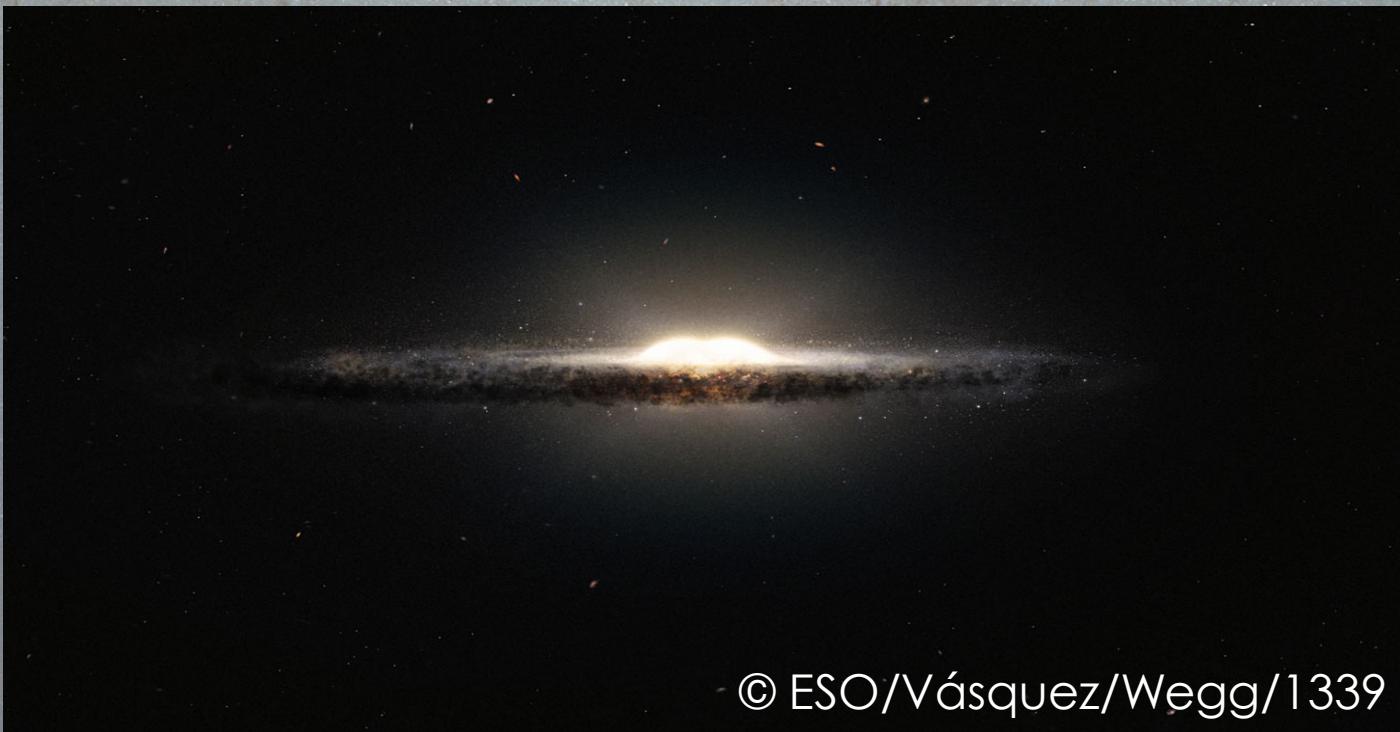
# Motivation

- ★ Is the bulge a different Galactic component?
- ★ What are the origin of the bulge of the Milky Way?



# Motivation

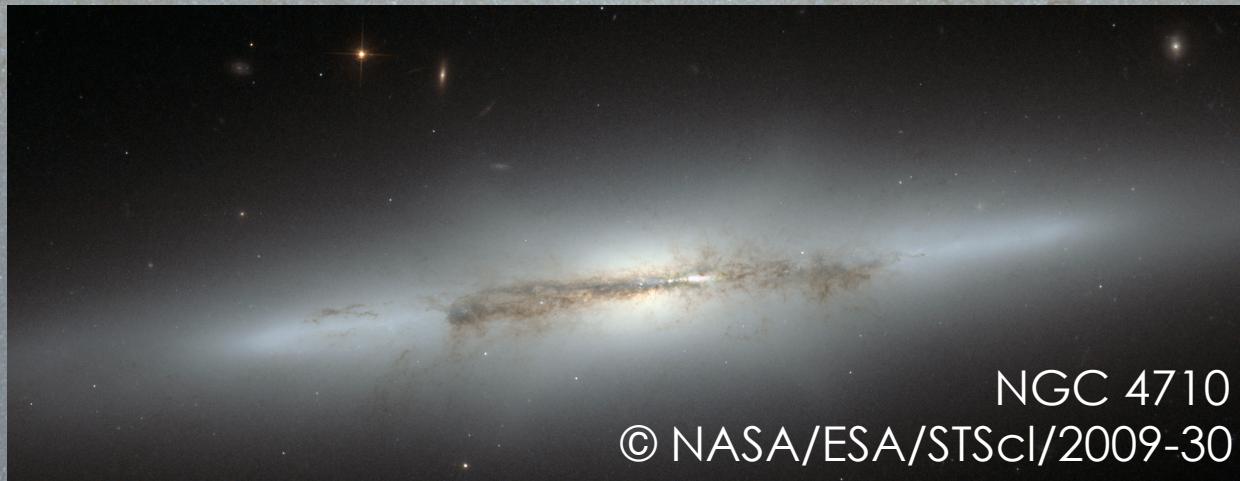
- ★ What is exactly a galaxy bulge?
- ★ It is an over-density that rise from the plane of the disk



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# Motivation

- ★ In a global view the Milky Way bulge can be compared with the bulges of other galaxies
  - ★ “Template” for detailed comparisons with other bulges



- ★ Connecting Galactic + Extragalactic research

# The Galactic bulge

## ★ Advantages:

- ★ Study a fully resolved stellar population
- ★ High resolution spectroscopic and photometric surveys

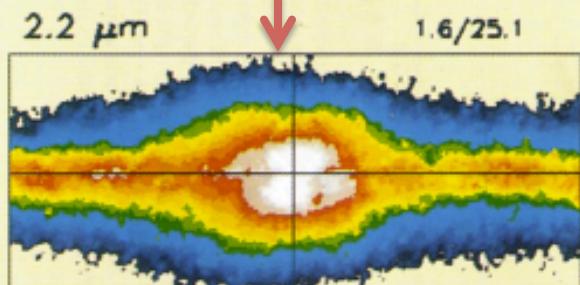
## ★ Disadvantages:

- ★ High extinction at low latitudes ( $A_V \sim 1/6 A_H \sim 1/10 A_K$ )
- ★ Lack of homogeneous and deep observations
- ★ Different methodologies result in different conclusions

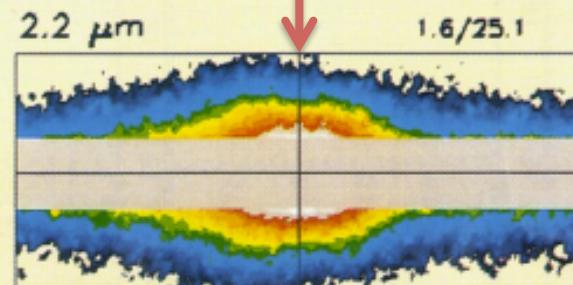
# The structure of the Milky Way bulge

- ★ The advent of near-IR detectors to overcome the dust obscuration towards the inner Galaxy allows COBE to survey the complete bulge

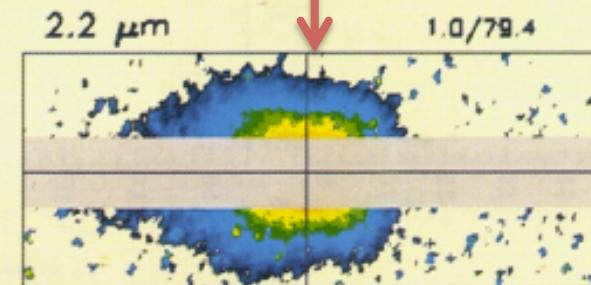
Observations



Interstellar extinction corrected



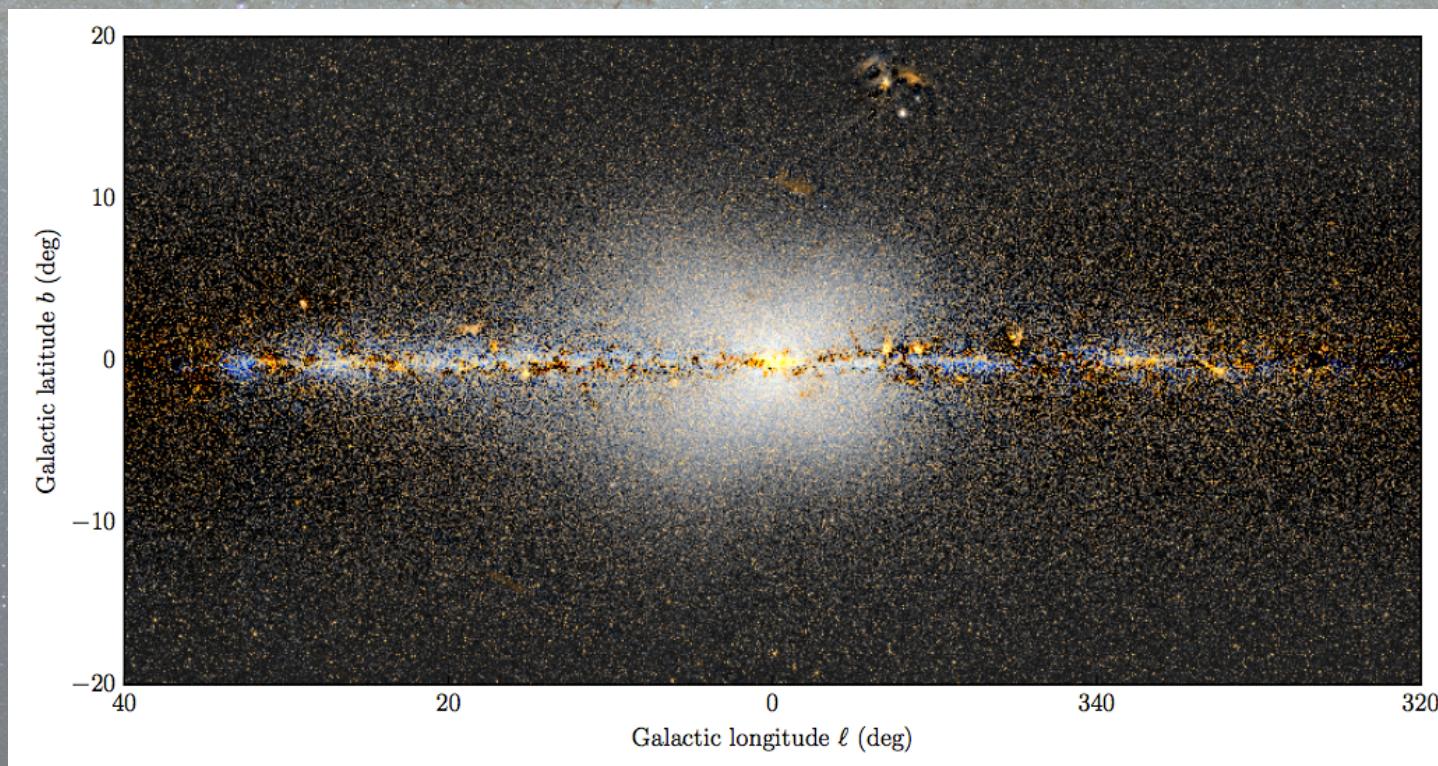
Disk model residuals



Weiland et al. 1994  
Dwek et al. 1995

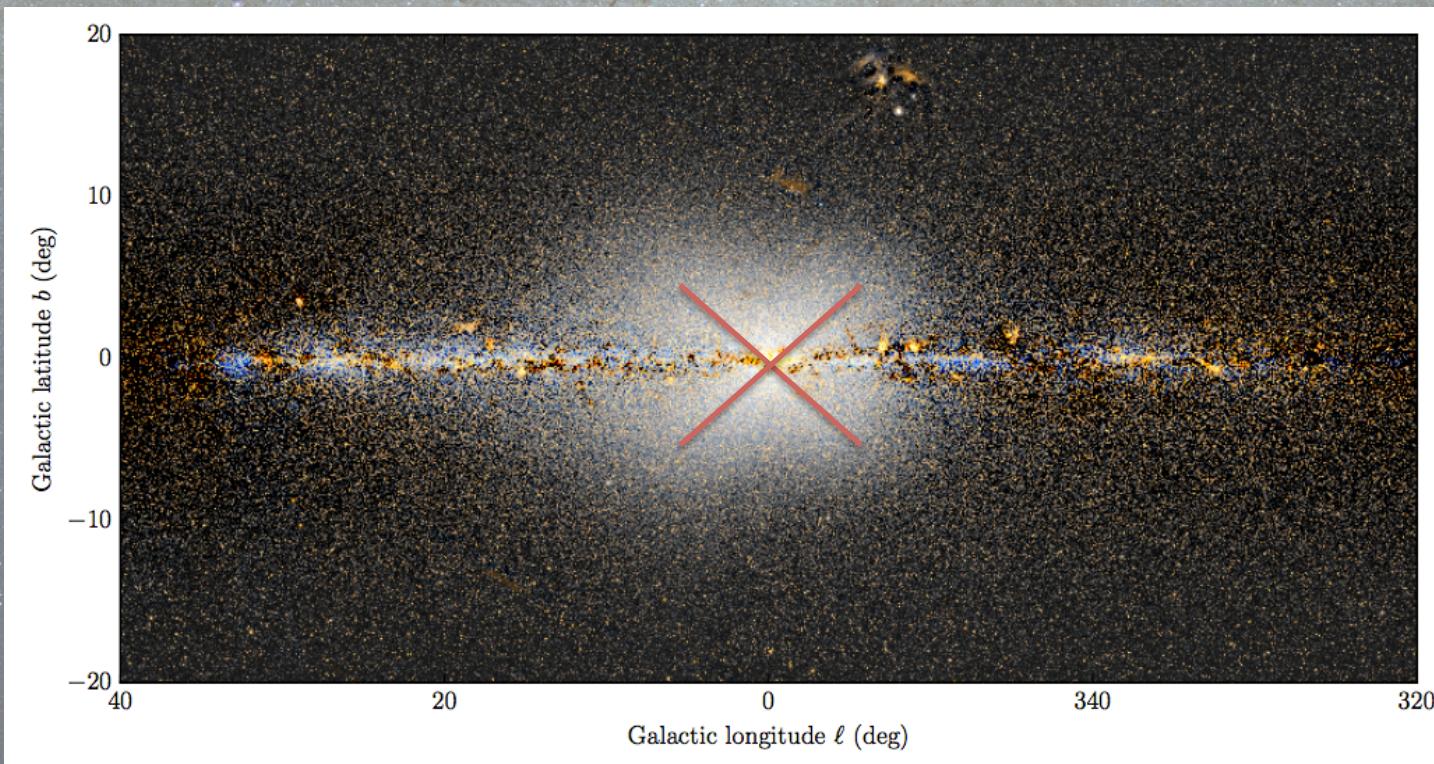
# The structure of the Milky Way bulge

- ★ Recently has been shown that the Milky Way has a boxy/peanut shape structure through WISE images.



# The structure of the Milky Way bulge

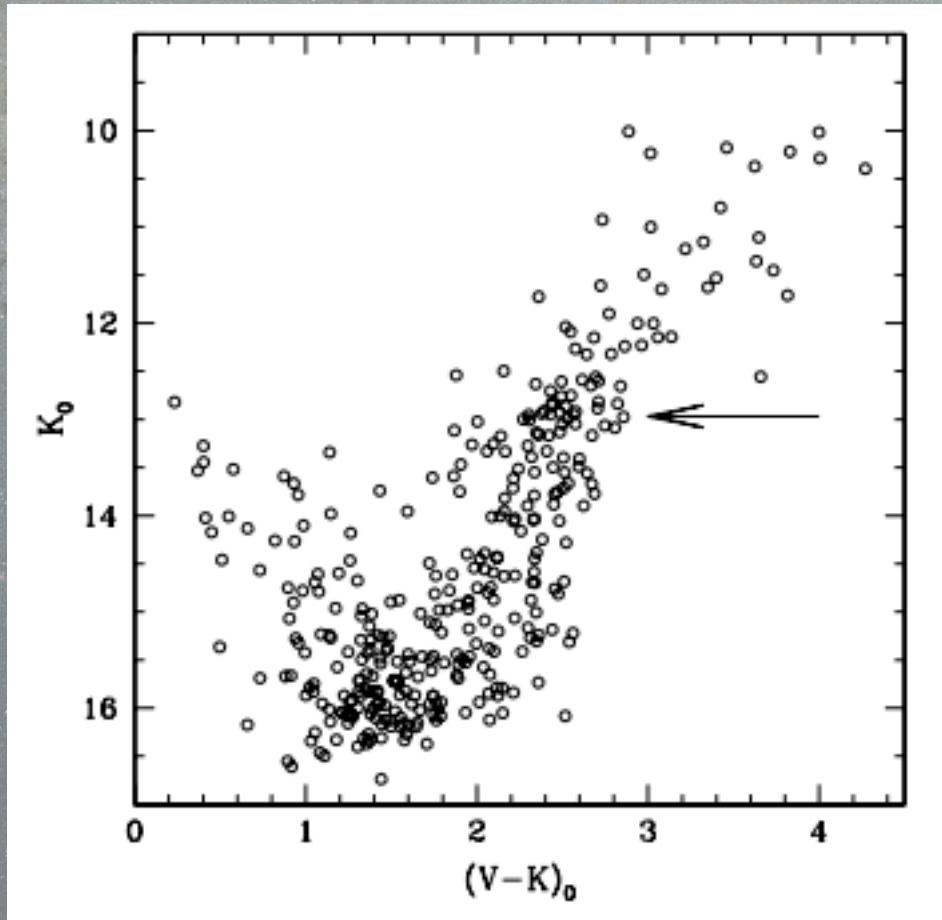
- ★ Recently has been shown that the Milky Way has a boxy/peanut shape structure through WISE images.



# Stellar distance indicators: RC stars

- ★ Many previous studies have been based on stellar counts of red-clump stars.
- ★ Red-clump stars:
  - ★ Metal-rich counterpart of the horizontal branch
  - ★ Intermediate to old population (1-10 Gyr; Alves 2000)
  - ★ Absolute magnitudes have little dependence on age and metallicity → **excellent distance indicators**  
(Castellani et al. 1992)

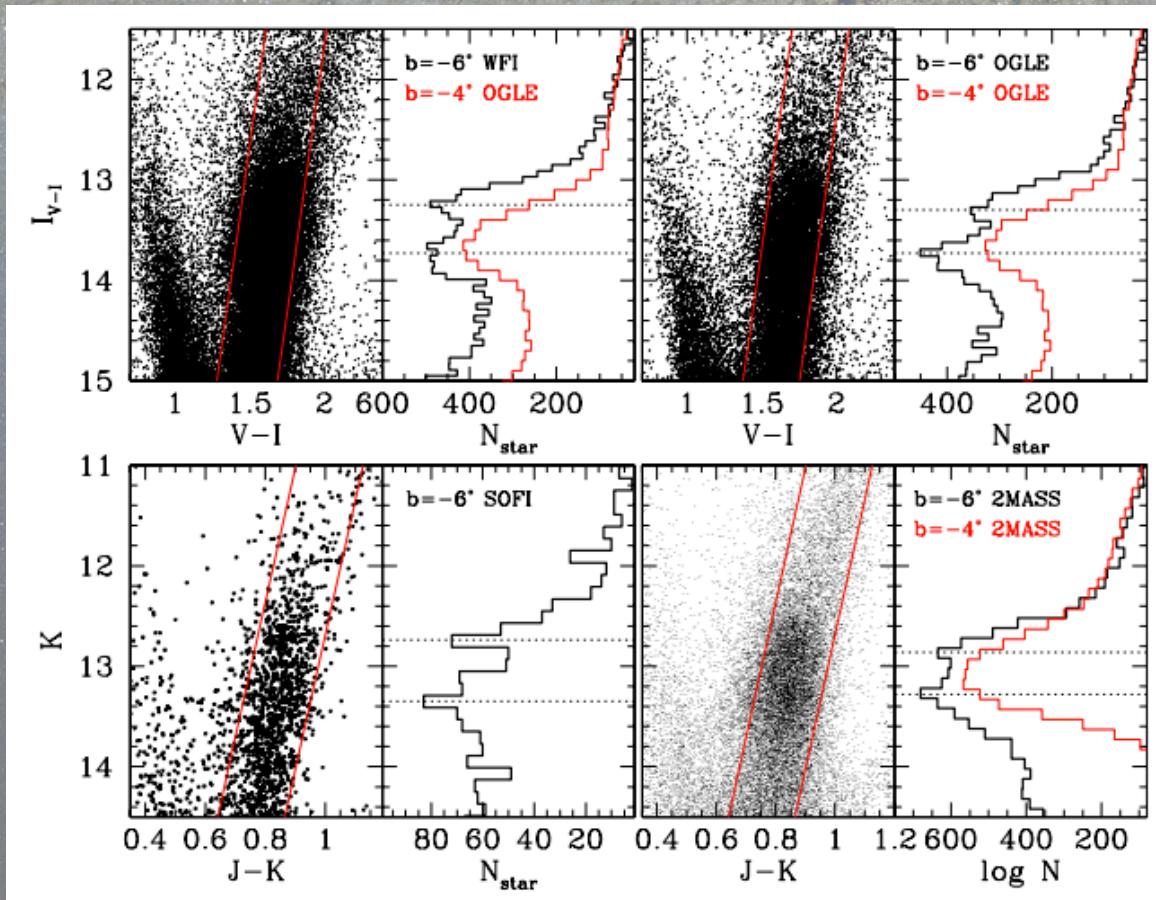
# Stellar distance indicators: RC stars



Color-magnitude diagram  
for Baade's window. The  
red-clump deature are  
marked with an arrow.  
Alves 2000

# RC stars and the X-shape

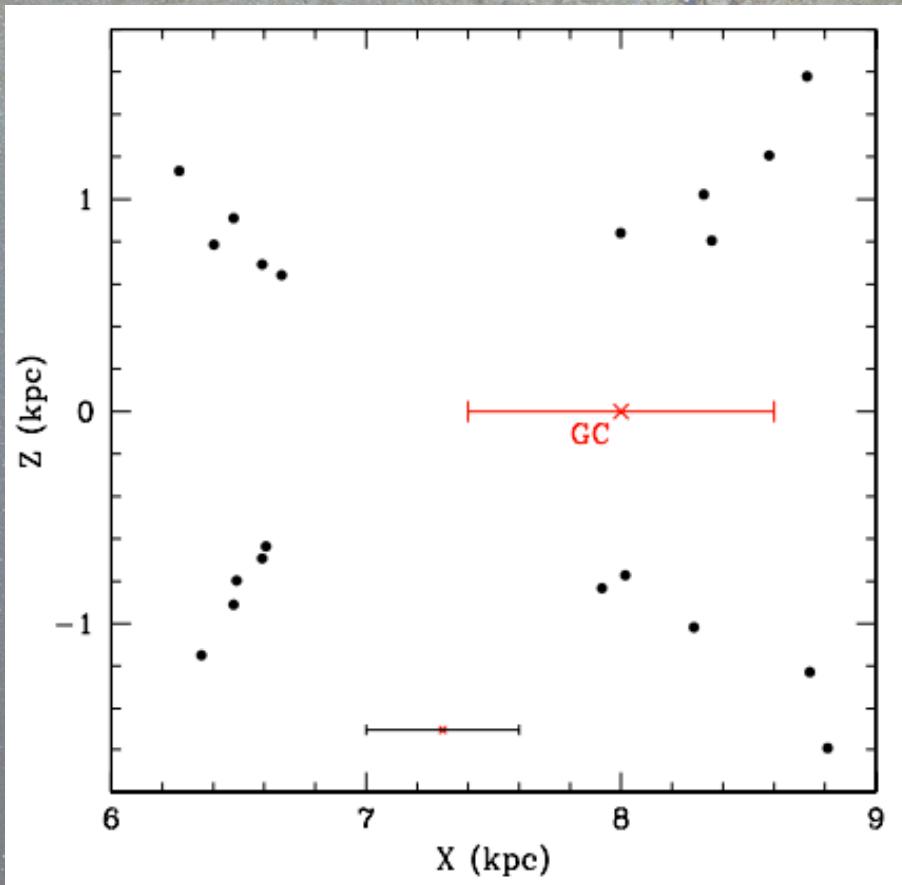
- ★ Detailed analysis of bulge photometric catalogs leads to the discover of the Milky Way X-shape.



Color-magnitude  
diagrams and luminosity  
functions for the red-  
clump stars ate the  
indicated fields.  
McWilliam & Zoccali 2010

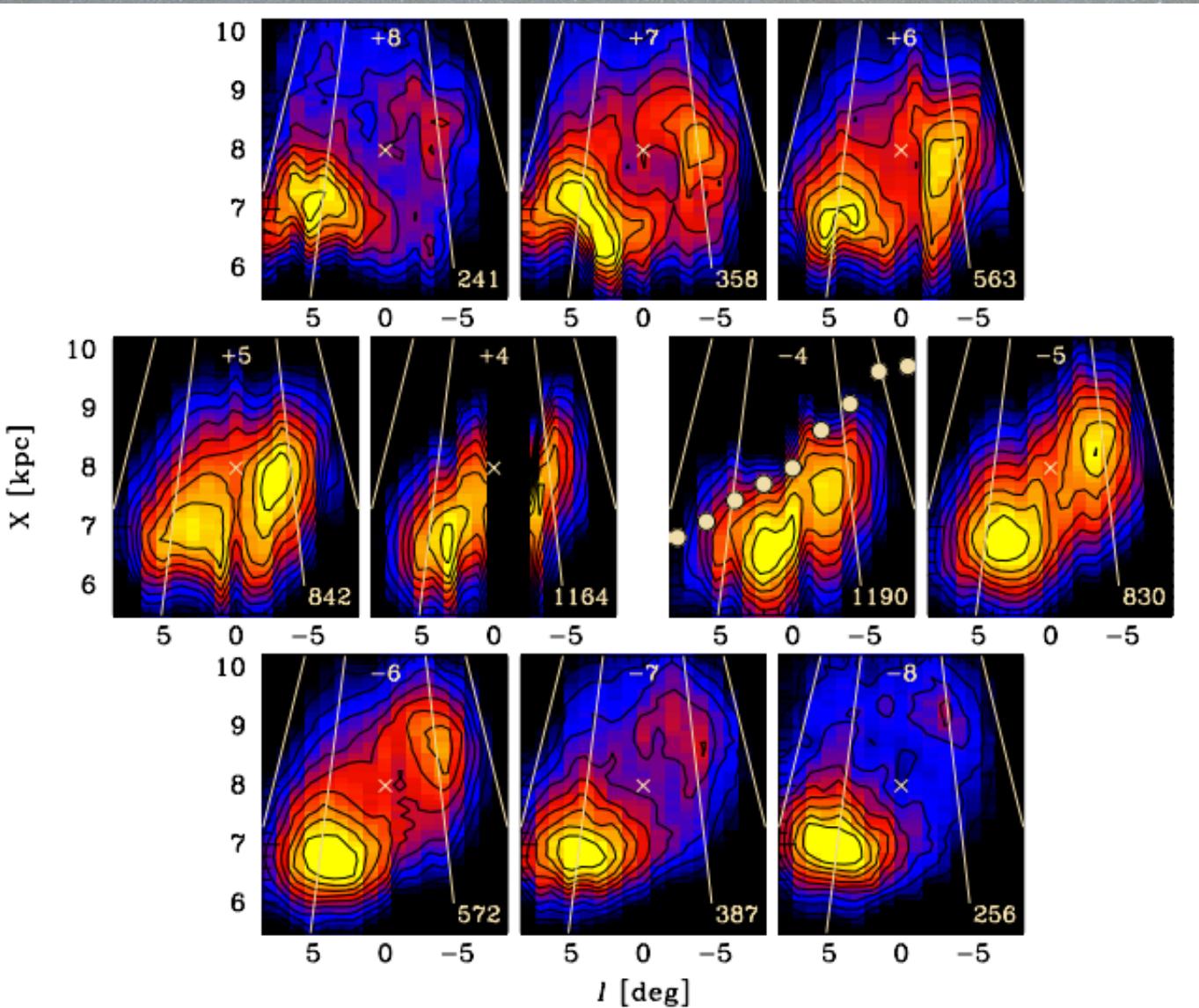
# RC stars and the X-shape

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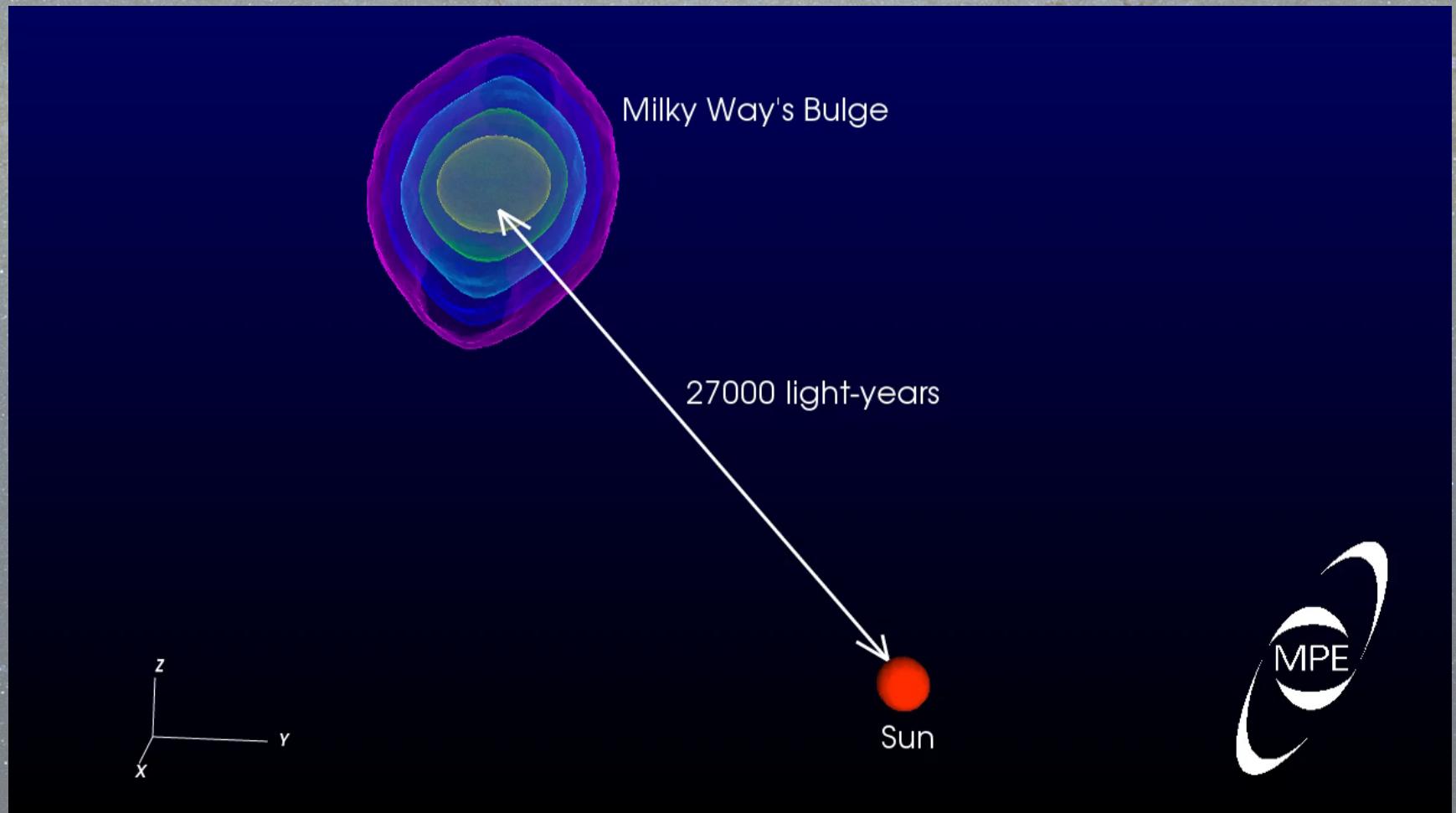
Distances of the two red-clumps as a function of latitude.  
McWilliam & Zoccali 2010

# RC stars and the X-shape

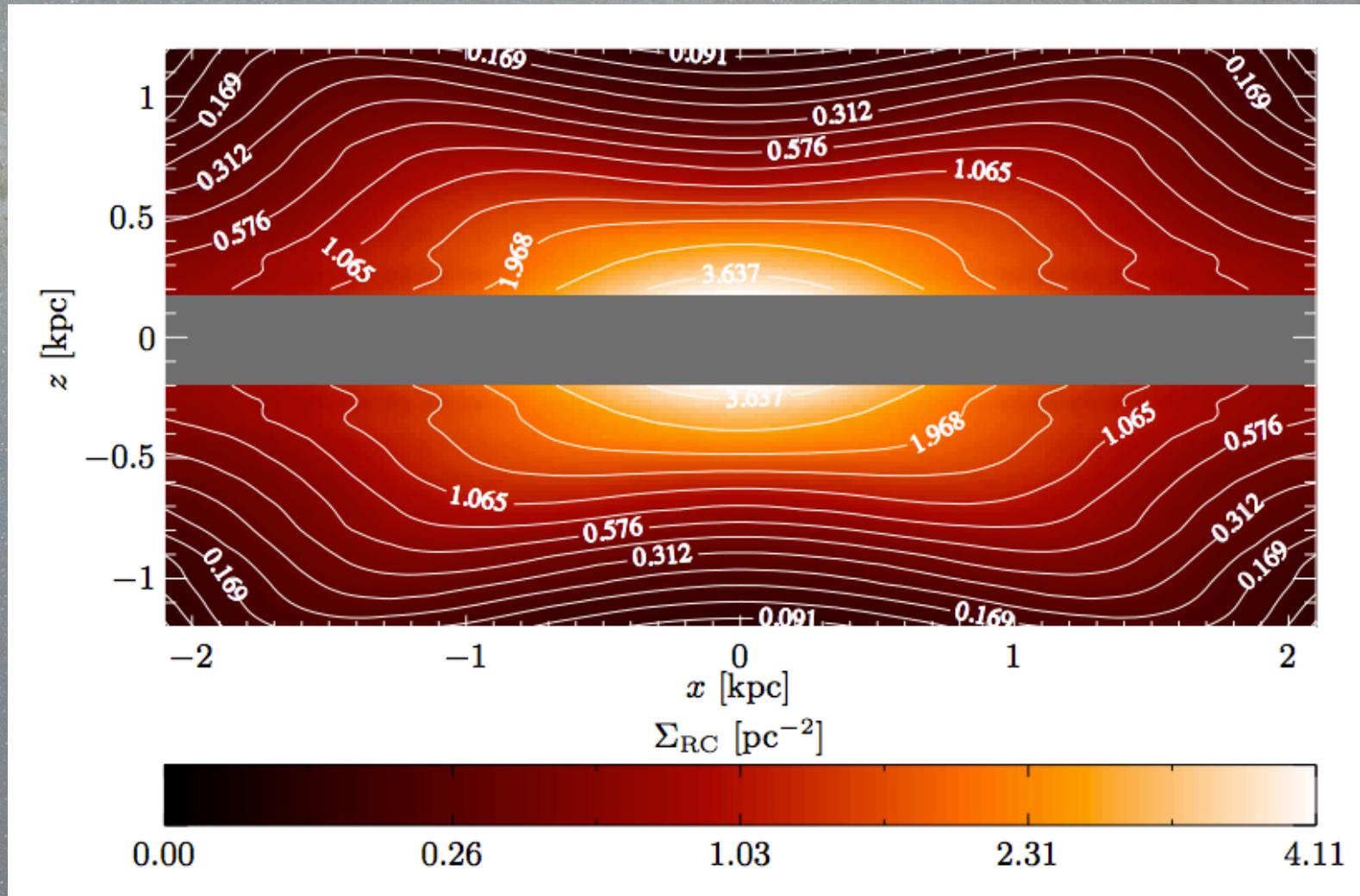


Density maps for  
red-clump stars in  
the 2MASS  
catalog as seen  
from above.  
Saito et al. 2011

# RC and the X-shape

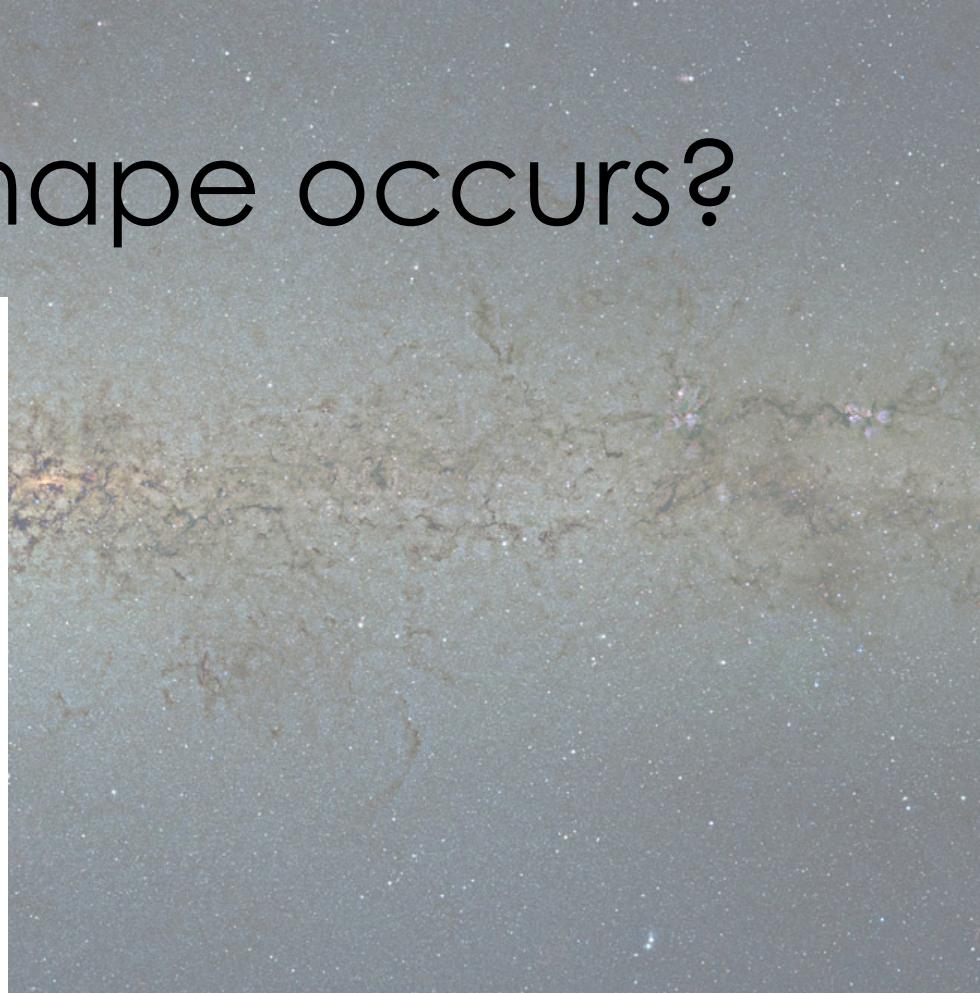
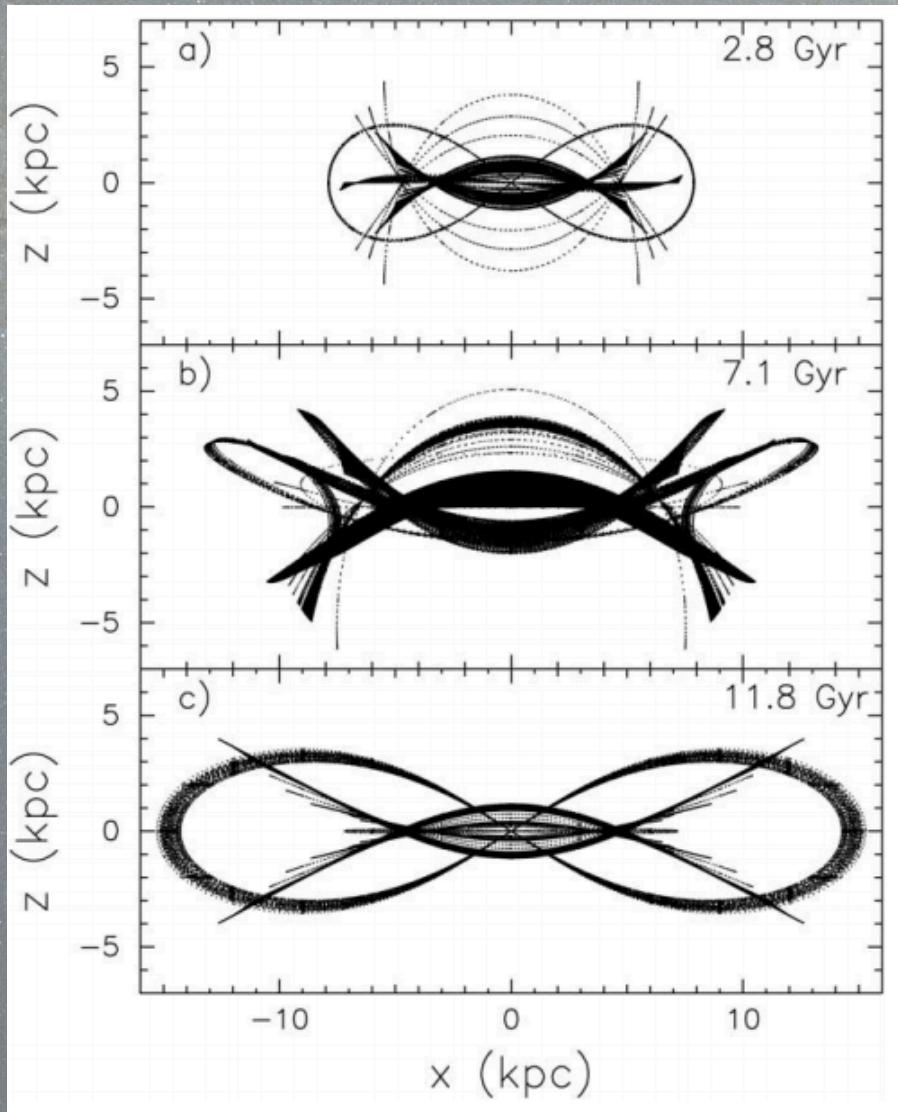


# RC stars and the X-shape



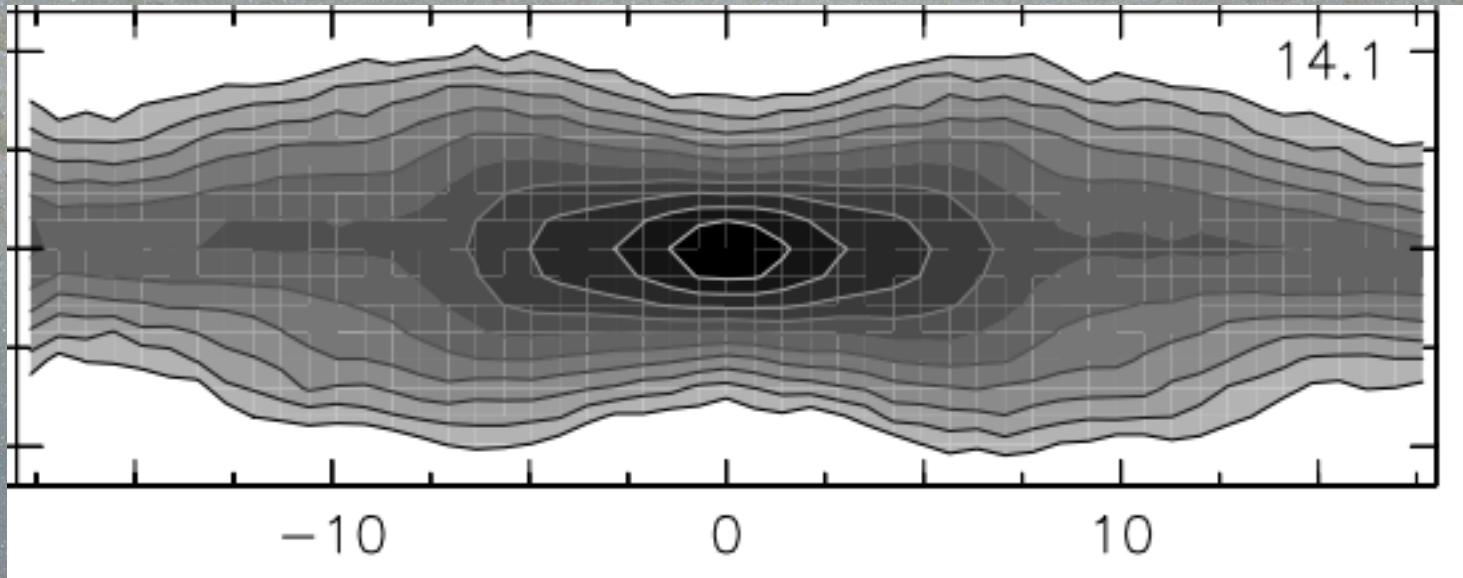
Wegg & Gerhard 2012

# Why the X-shape occurs?



Stable orbits of stars in a N-body simulation. Dynamical instabilities in the vertical direction develop peanut-shape when observed edge-on.  
Martinez-Valpuesta et al. 2006

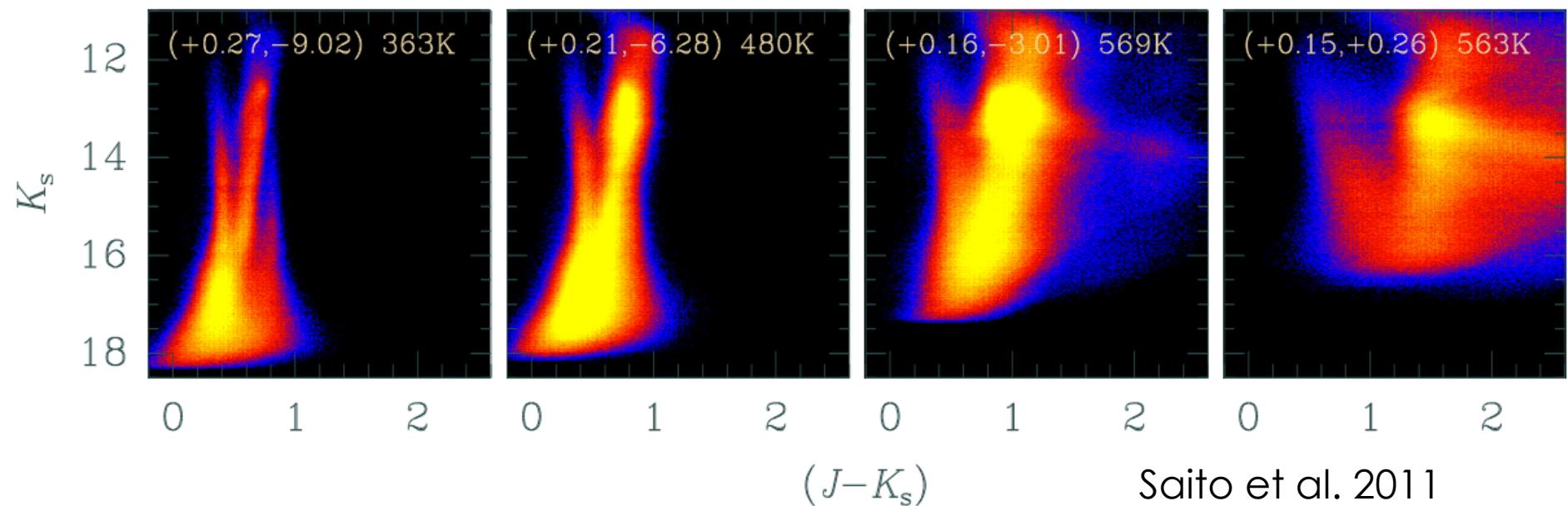
# Why the X-shape occurs?



Distribution of the vertical structure  
Martinez-Valpuesta et al. 2006

# RC stars: disadvantages

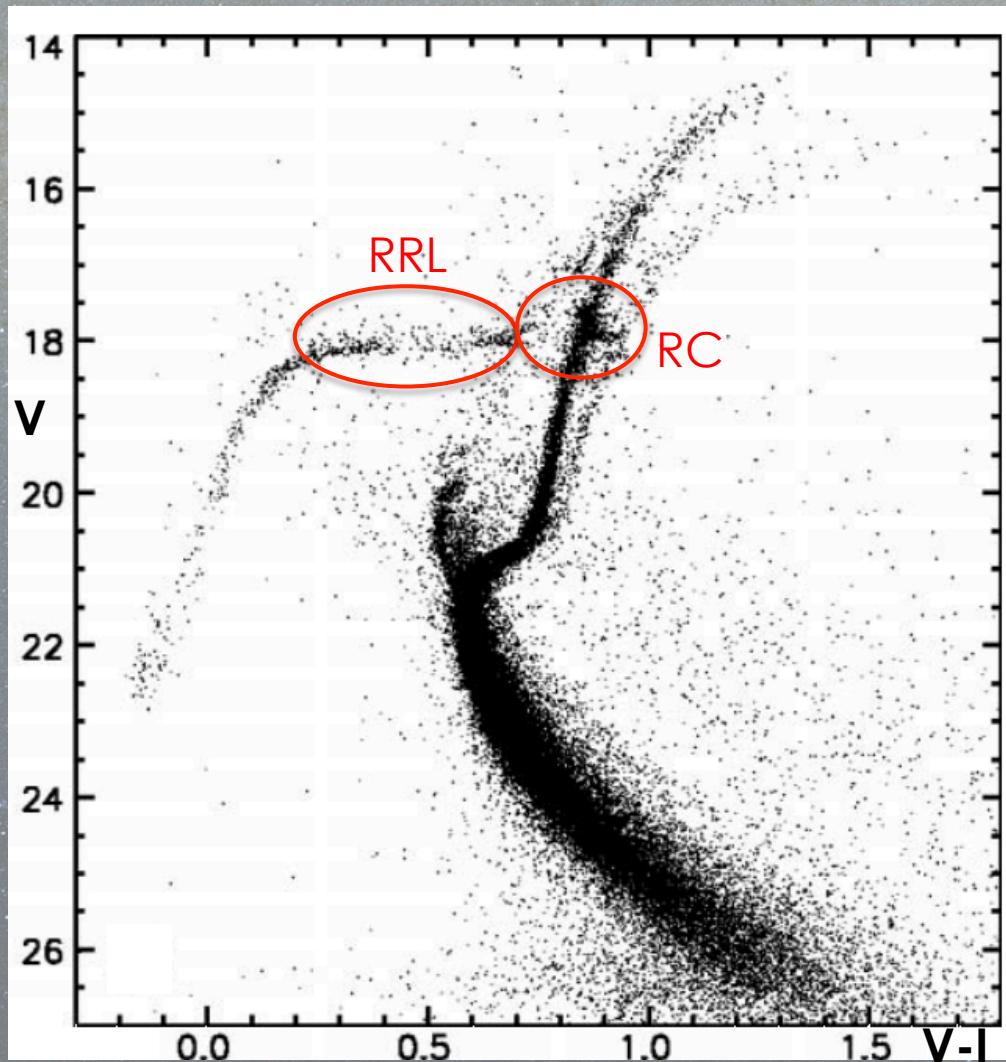
- ★ Although red-clump stars are excellent distance indicators, also suffers from complications when looking towards the inner bulge:
  - ★ Disk contamination
  - ★ Extinction



# RC stars: disadvantages

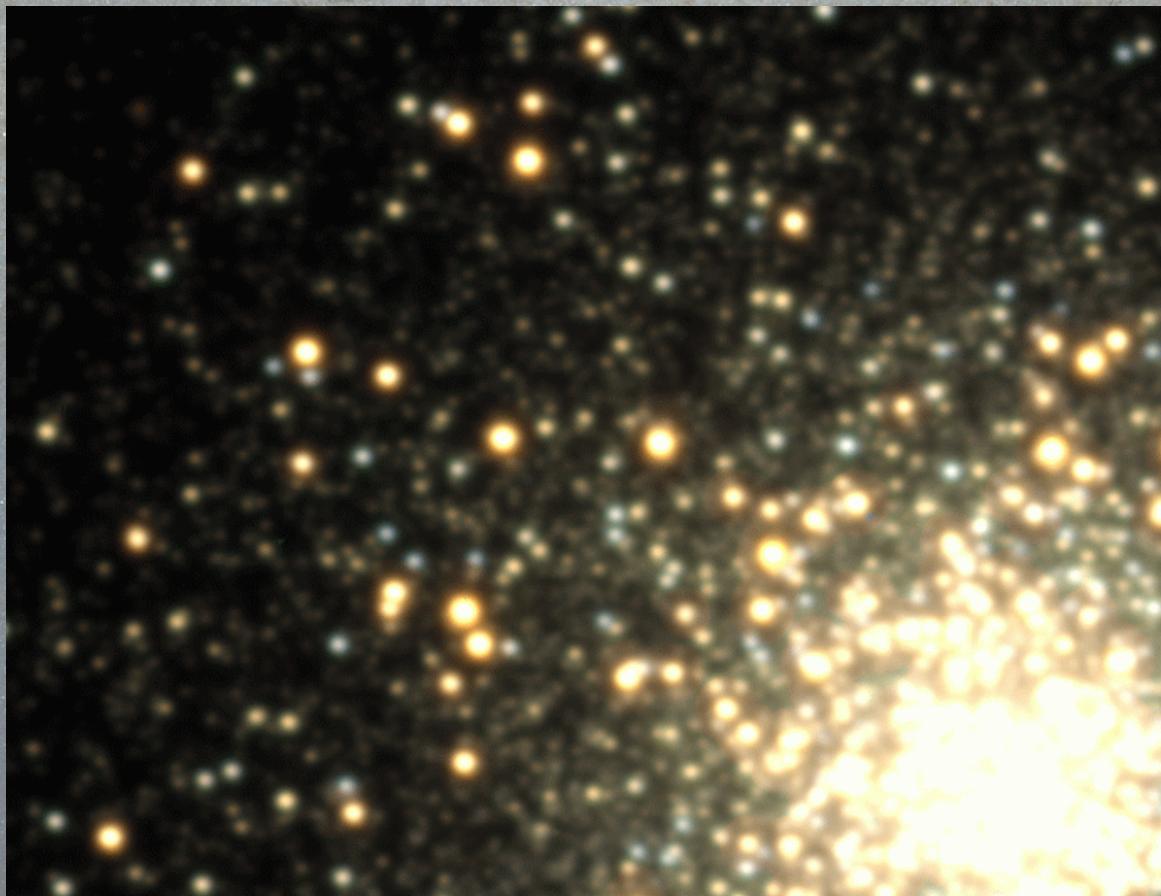
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  - ★ Disk contamination
  - ★ Extinction
- ★ Variable stars, specifically **RR Lyrae**, have provided a new perspective for the bulge structural properties.

# RR Lyrae stars: old tracers of the bulge



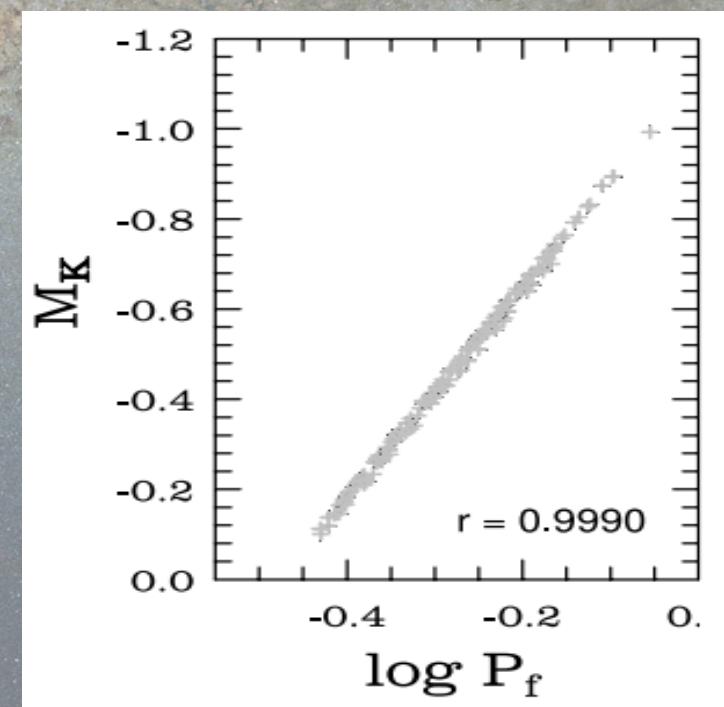
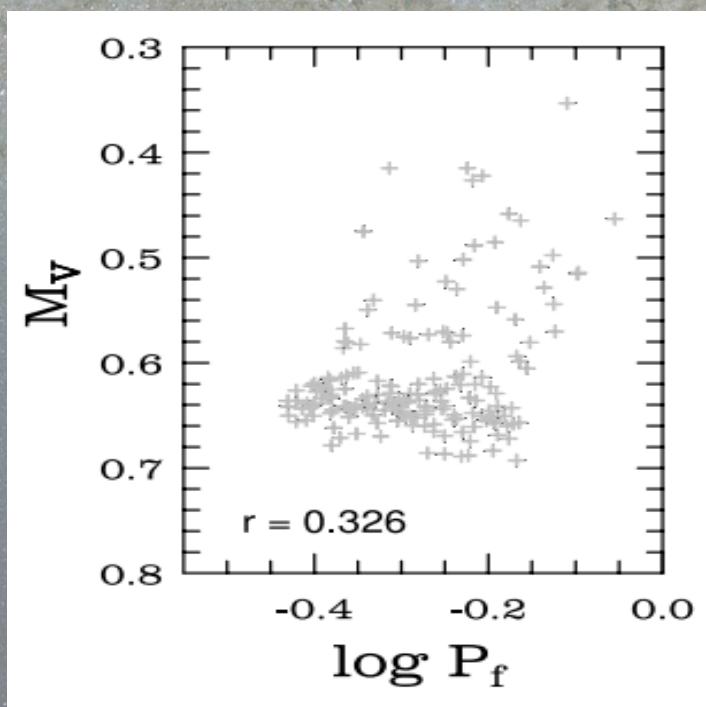
HST color-magnitude  
diagram of M54  
(Siegel al. 2007)

# RR Lyrae stars: old tracers of the bulge



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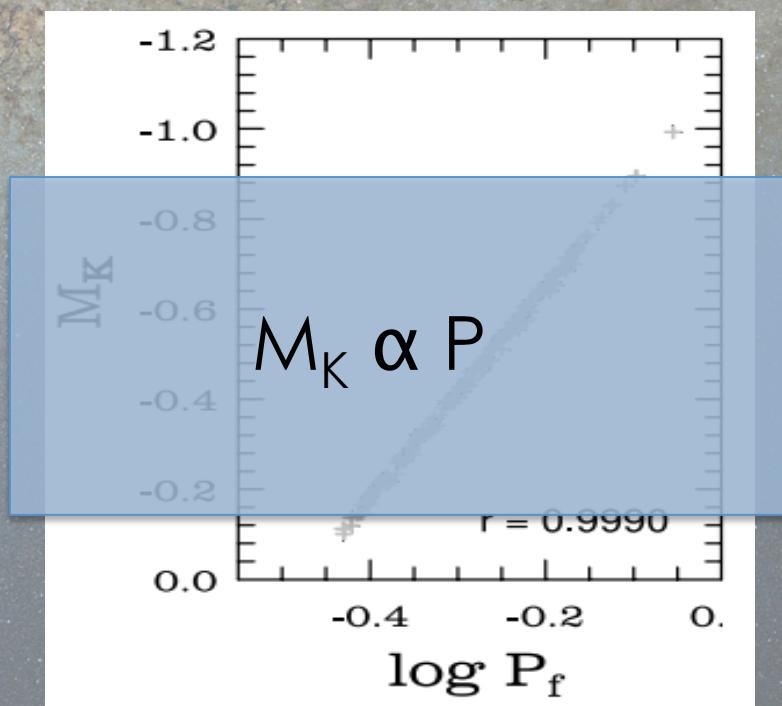
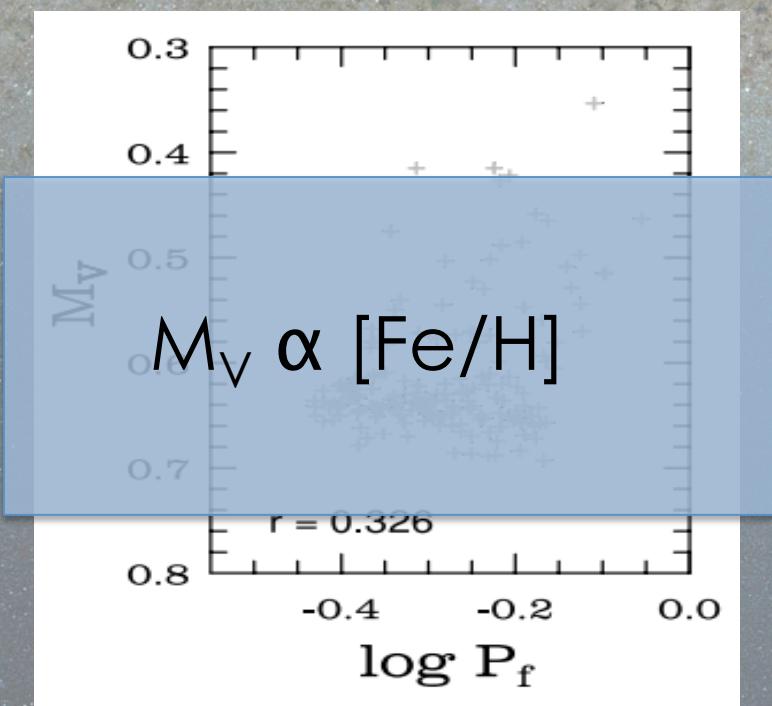
# RR Lyrae: Period-Luminosity Relation



Optical (V) v/s near-IR (K)

Catelan et al. 2004

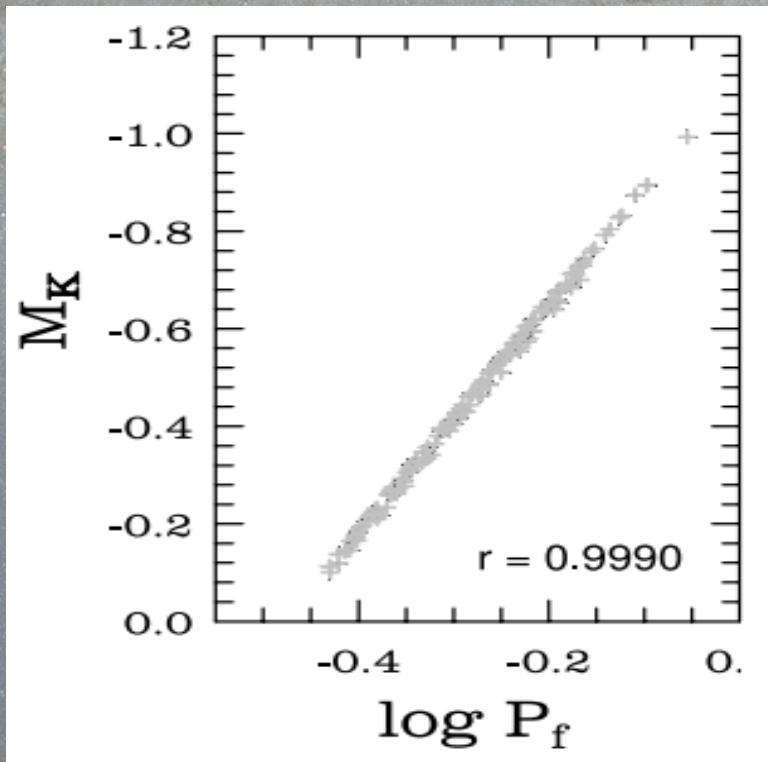
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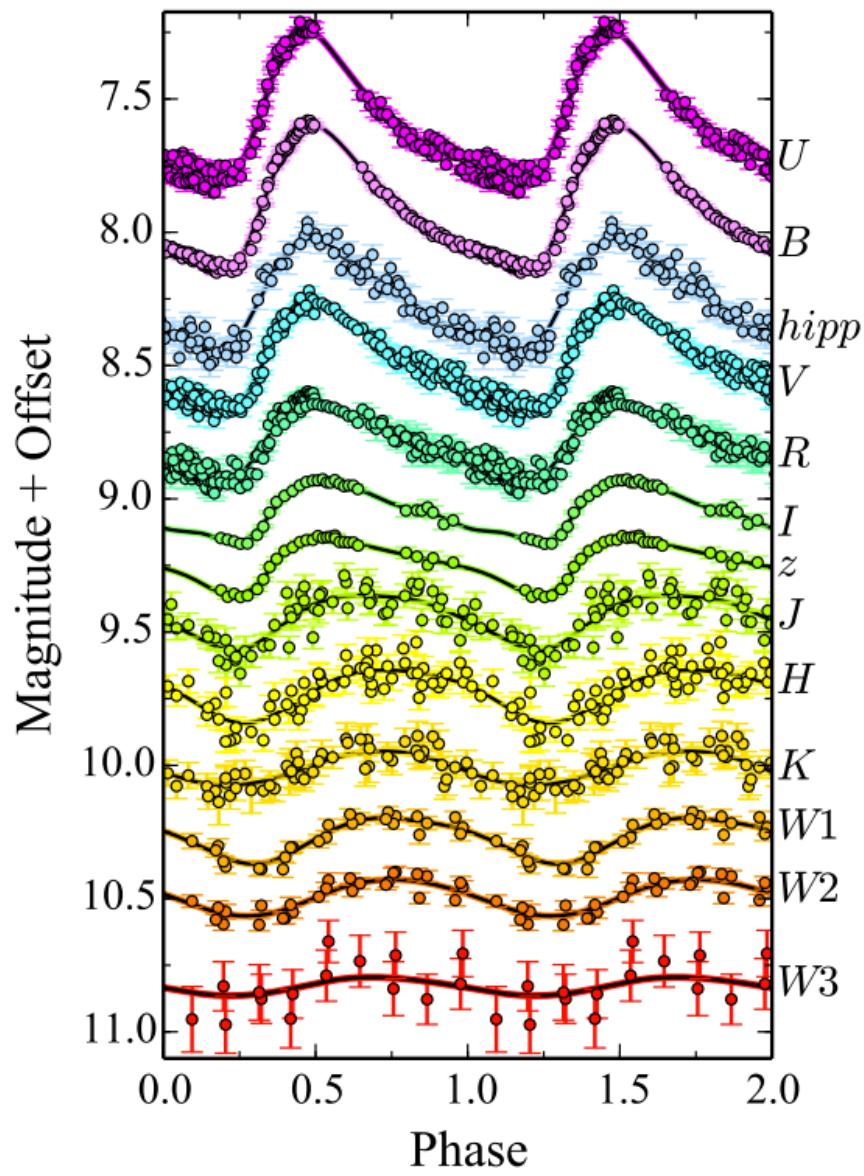
# RR Lyrae: PL Relation in the near-IR



Catelan et al. 2004

The fact that the **bolometric corrections** in the infrared bands steadily decreases when moving from the hot to the cool edge of the RRL IS (Smith 1995; Catelan et al. 2004; Bono et al. 2011), producing that the redder stars become brighter than the bluer.

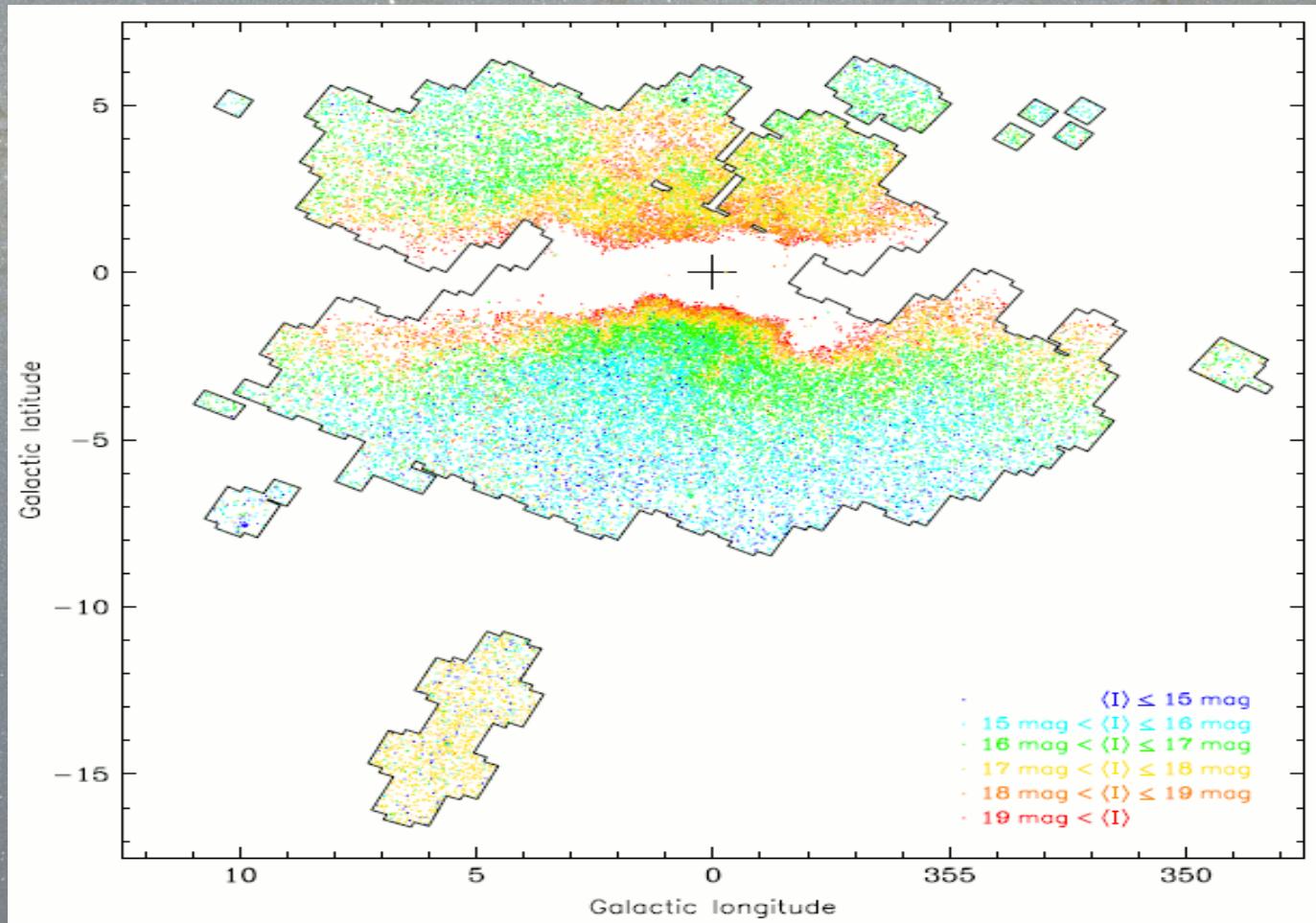
# Observations of RR Lyrae



Comparison of the UV/optical/near-IR light curve of the RR Lyrae AB UMa ( $P \approx 0.6$  days; Klein et al. 2014)

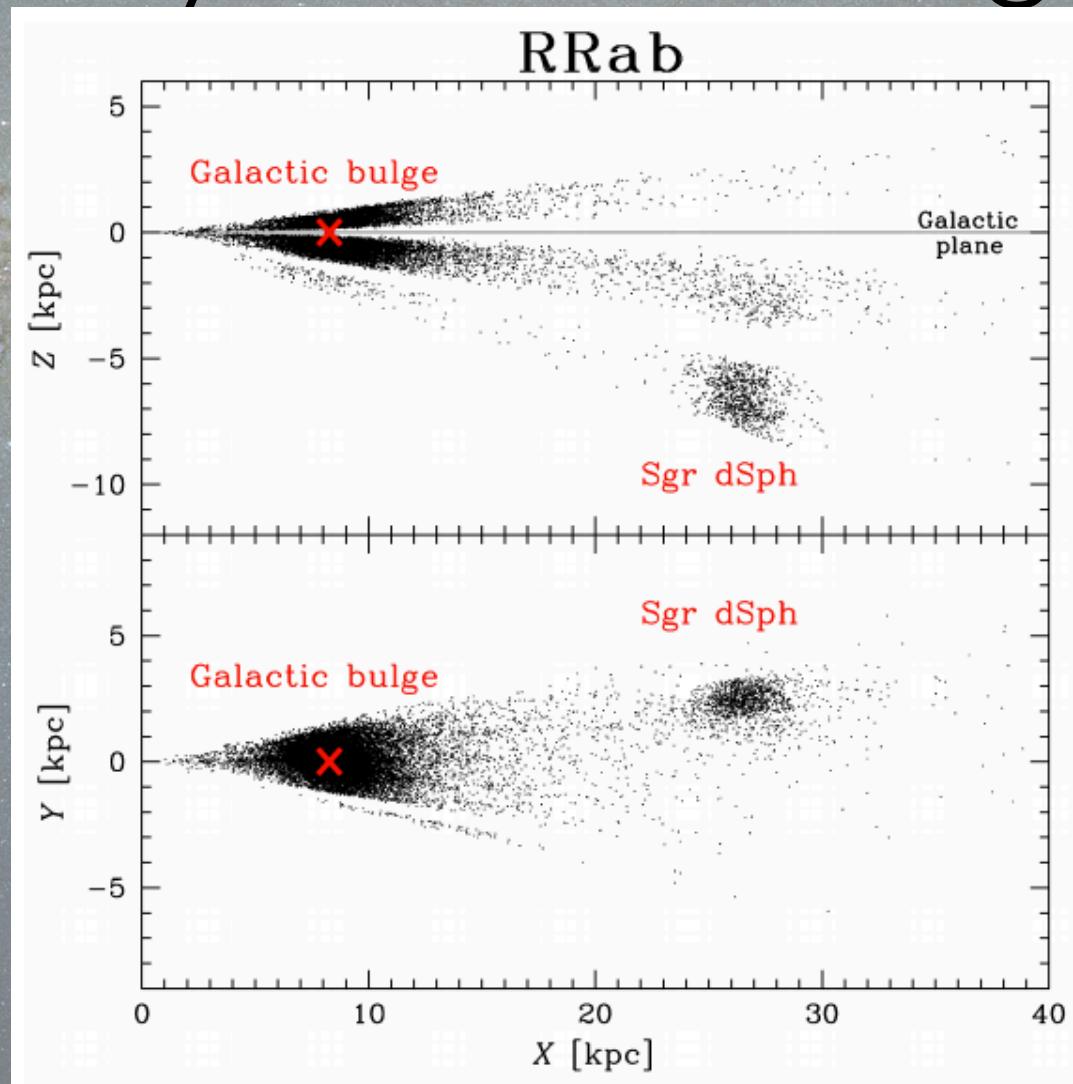
# RR Lyrae in the bulge

OGLE IV – 36257 bulge + 2000 Sgr dSph RR Lyr stars



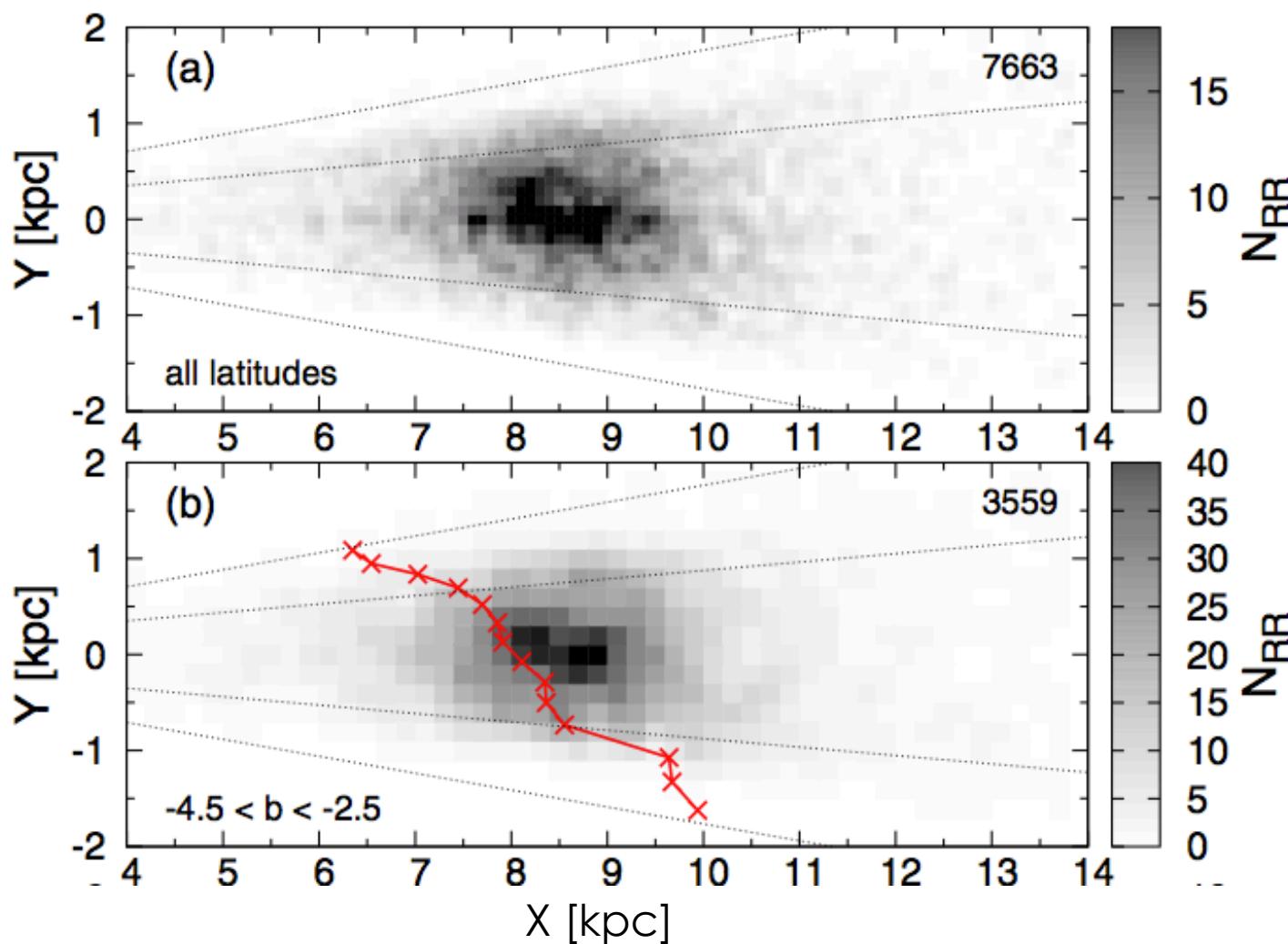
Soszyński et al. 2014 + Pietrukowicz et al. 2014

# RR Lyrae in the bulge



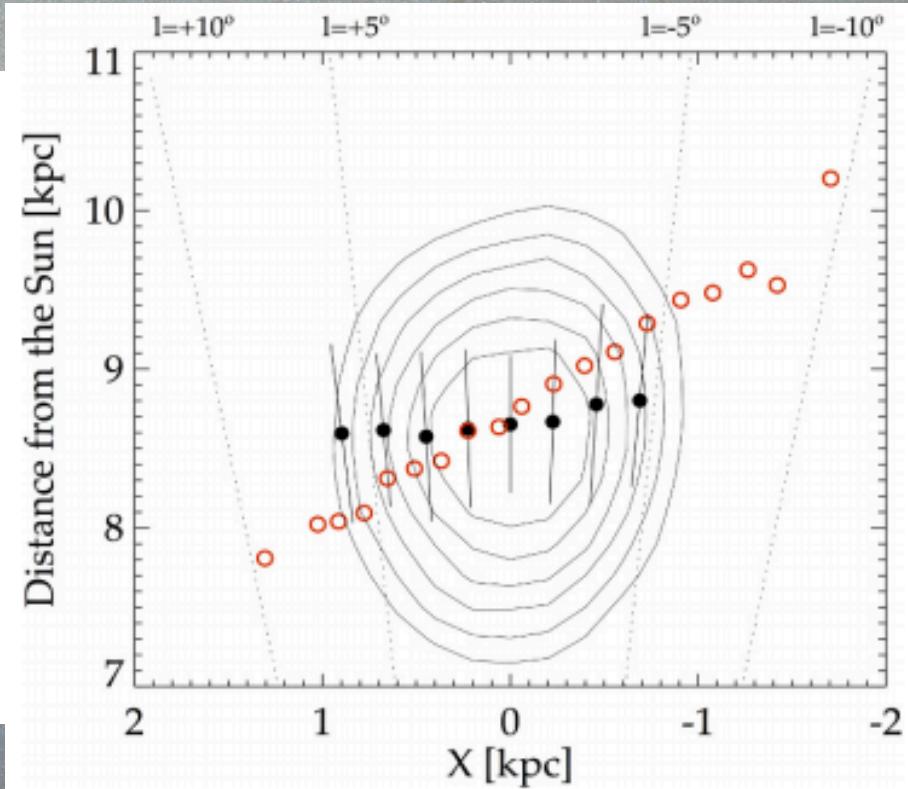
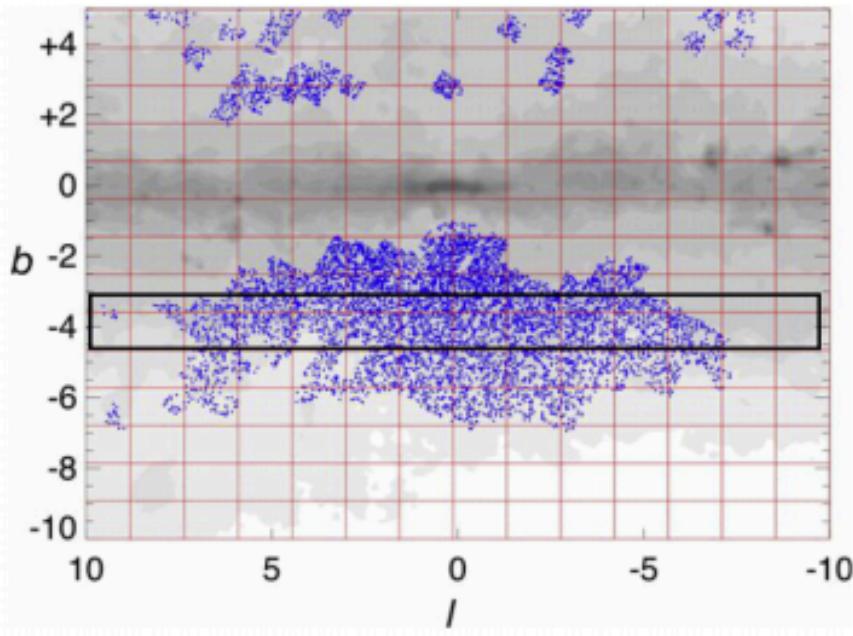
Pietrukowicz et al. 2015

# RR Lyrae in the bulge



Gonzalez et al. 2012, Dékány et al. 2013

# RRL v/s RC



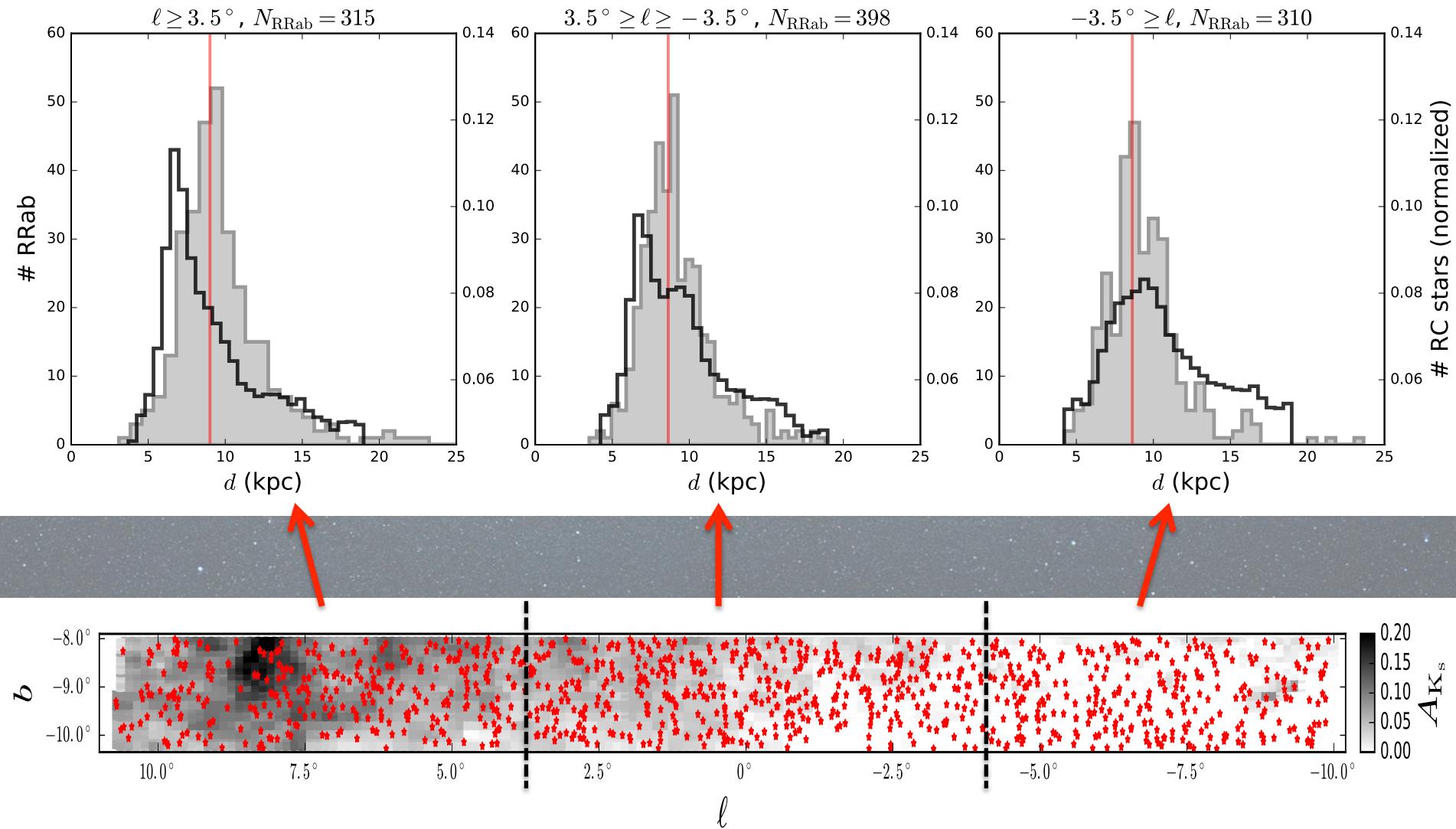
Unlike red-clump stars, the RR Lyrae stars shows a more spheroidal, centrally concentrated distribution  
(Gonzalez & Gadotti 2015)

# RRL v/s RC

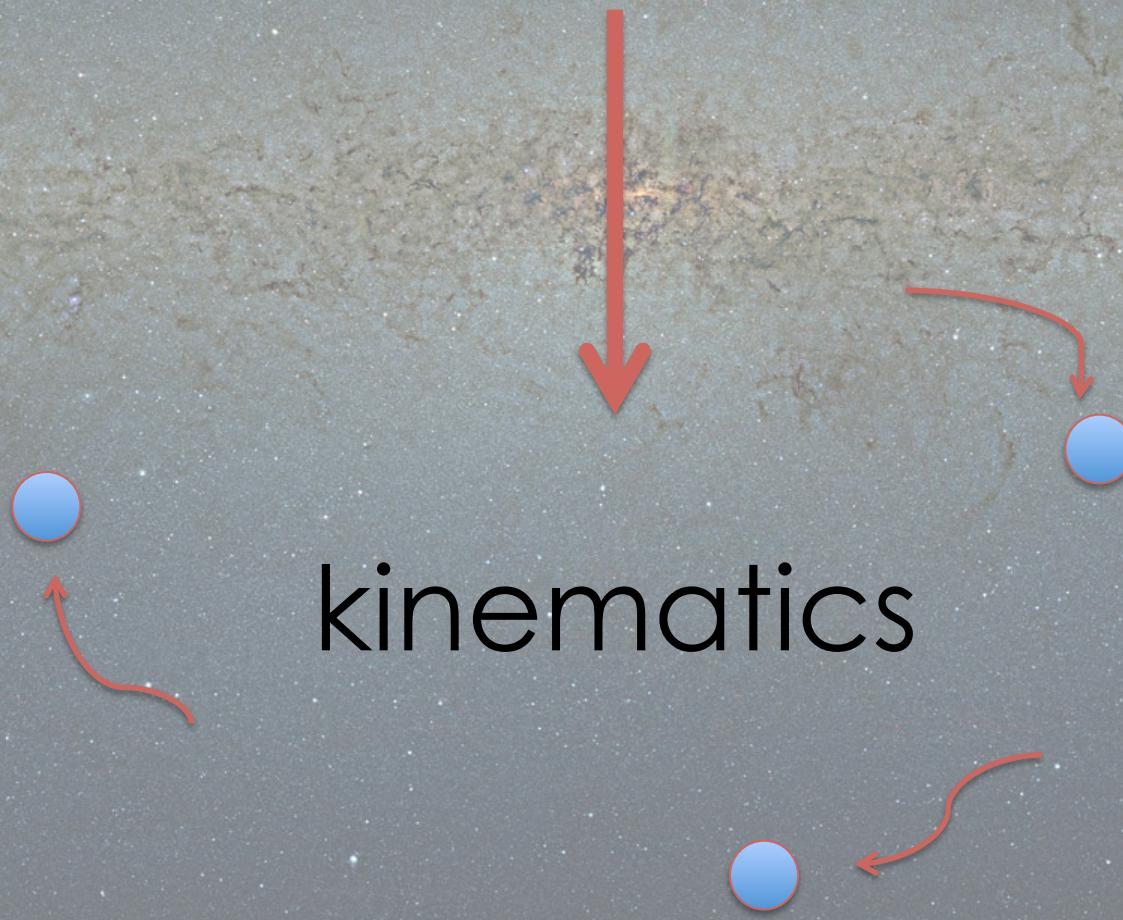
RR Lyrae stars

Red clump stars

Gran et al. 2016

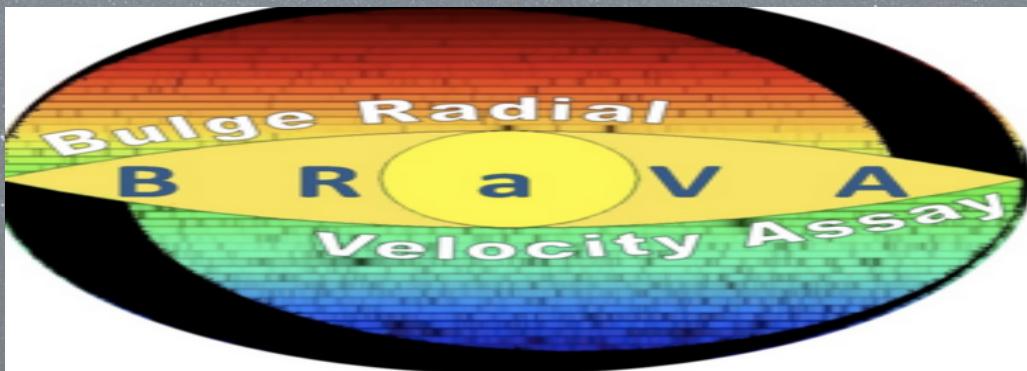


# Linking the two structures



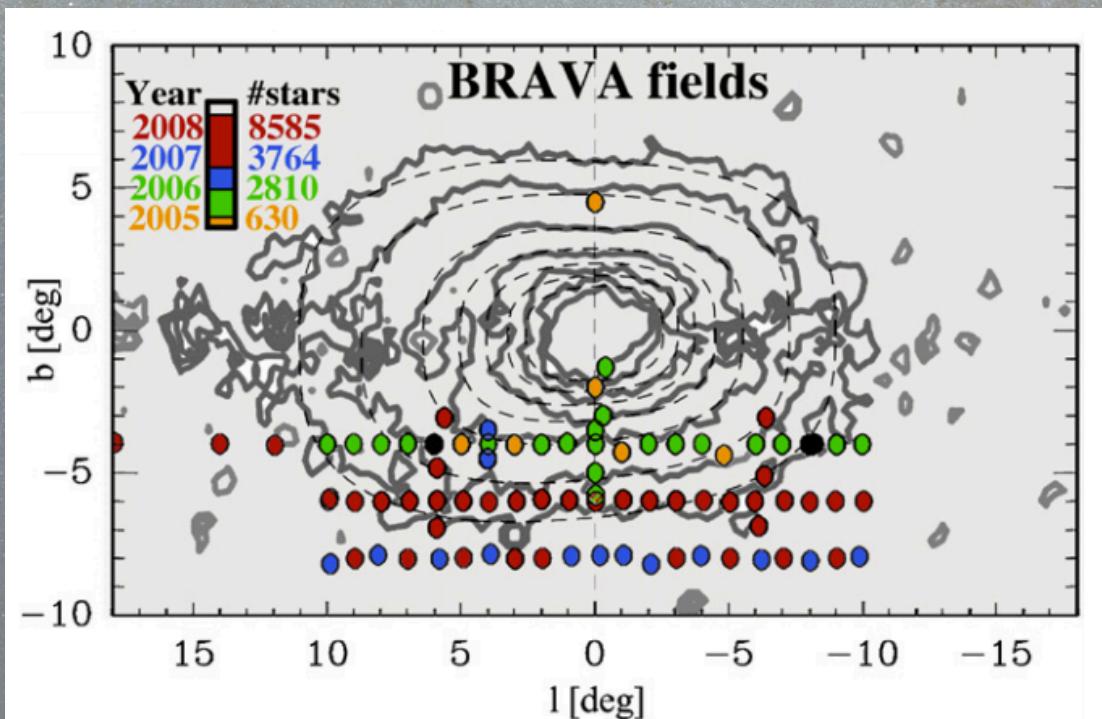
# Linking the two structures

- ★ The **B**ulge **R**adial **V**elocity **A**ssay (BRAVA) observed up to date  $\sim$ 10000 bulge giants and  $\sim$ 1000 RR Lyrae stars, deriving line-of-sight radial velocities
- ★ Objectives:
  - ★ Measure the rotation curve and velocity dispersion profile of the inner Milky Way  
(R. Michael Rich et al. 2007, Kunder et al. 2012, 2016)



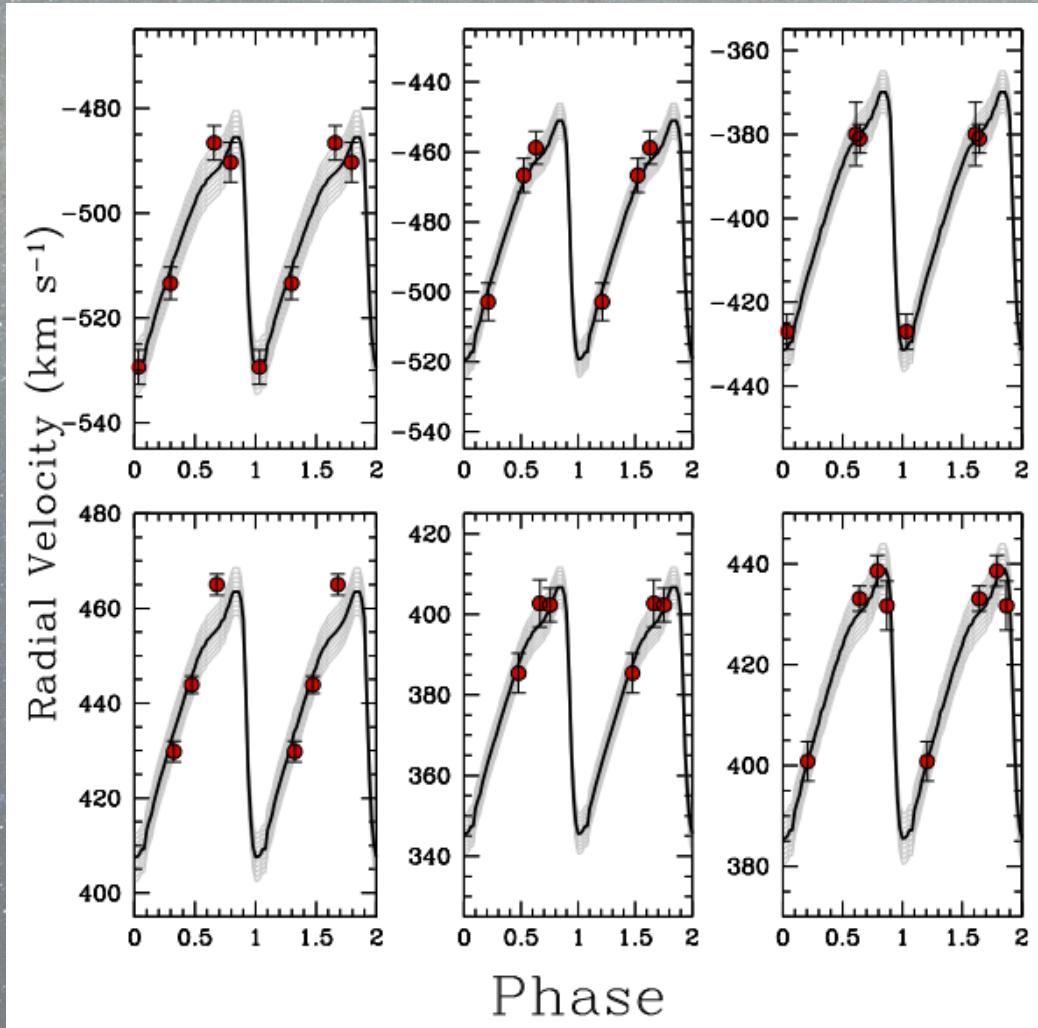
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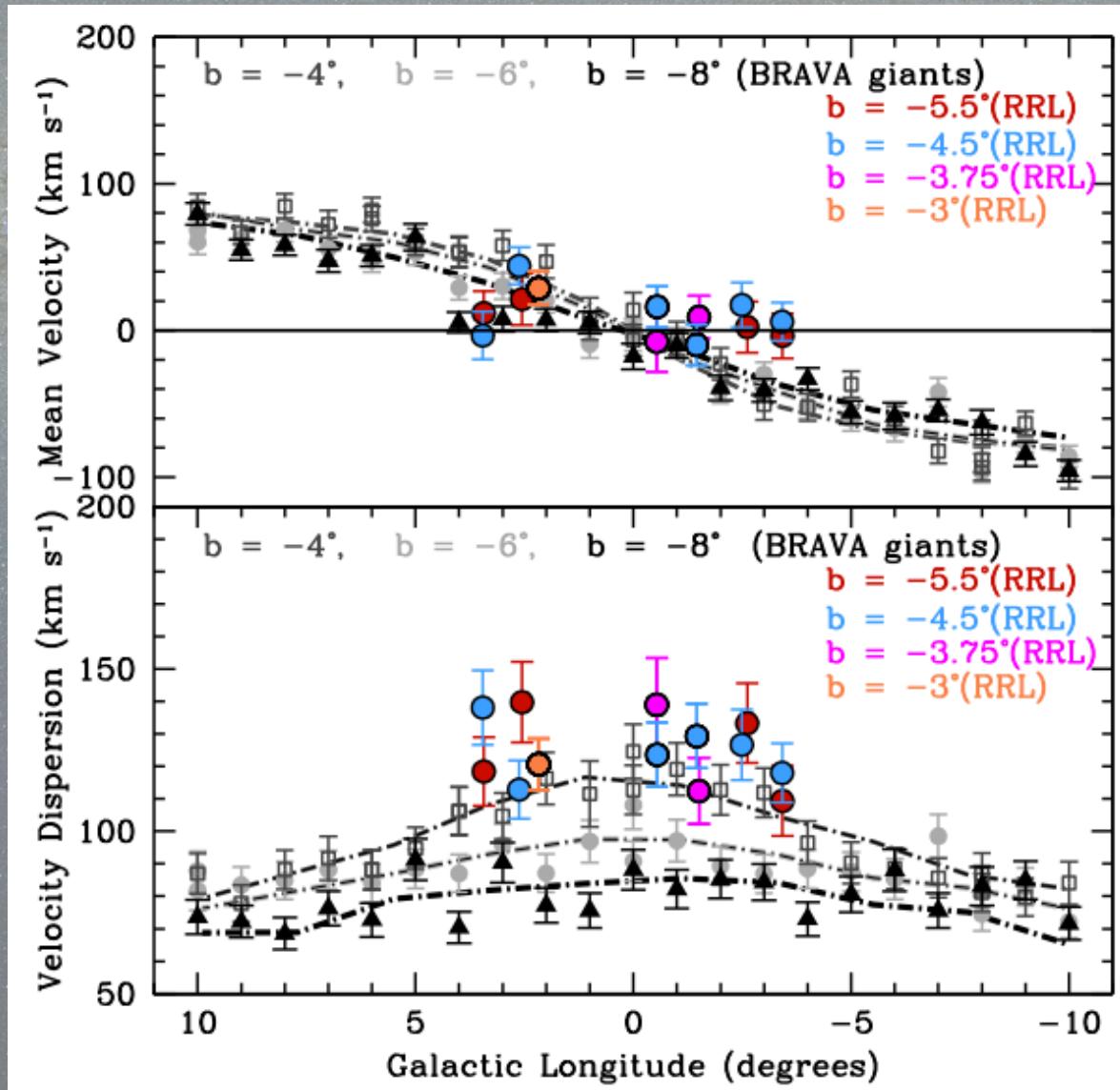
BRAVA fields in the  
Galactic bulge  
(Kunder et al. 2012)

# Linking the two structures



The **B**ulge **R**R **L**yrae **R**adial **V**elocity **A**ssay (BRAVA-RR) observes  $\sim$ 1000 bulge RR Lyrae from the OGLE catalog, deriving line-of-sight radial velocities (Kunder et al. 2016)

# Linking the two structures



Rotation curve and  
velocity dispersion  
for giants and RR  
Lyrae stars in the  
BRAVA survey  
(Kunder et al. 2016)

# Summary

- ★ **Key questions** to understand the Galactic bulge that we can resolve allow us to constraint other **bulge-like galaxies** in the Universe.
- ★ **RR Lyrae** stars trace a centrally concentrated distribution, different to the one traced by **red clump** stars known to follow a bar (x-shape)
- ★ The complex scenario of the Galactic bulge is far from resolved, and future surveys (APOGEE-S, 4MOST, MOONS) will help us to **solve** this questions

*Thanks for your  
attention !!*