

# Mapping the Outer Bulge with RR Lyrae stars in the VVV Survey

Felipe Gran M.

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Dante Minniti

# Mapping the Outer Bulge with RR Lyrae stars in the VVV Survey

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Online material available:  
Slides, plots, IPython notebook, and more!

[fegran.github.io](http://fegran.github.io)

# Outline

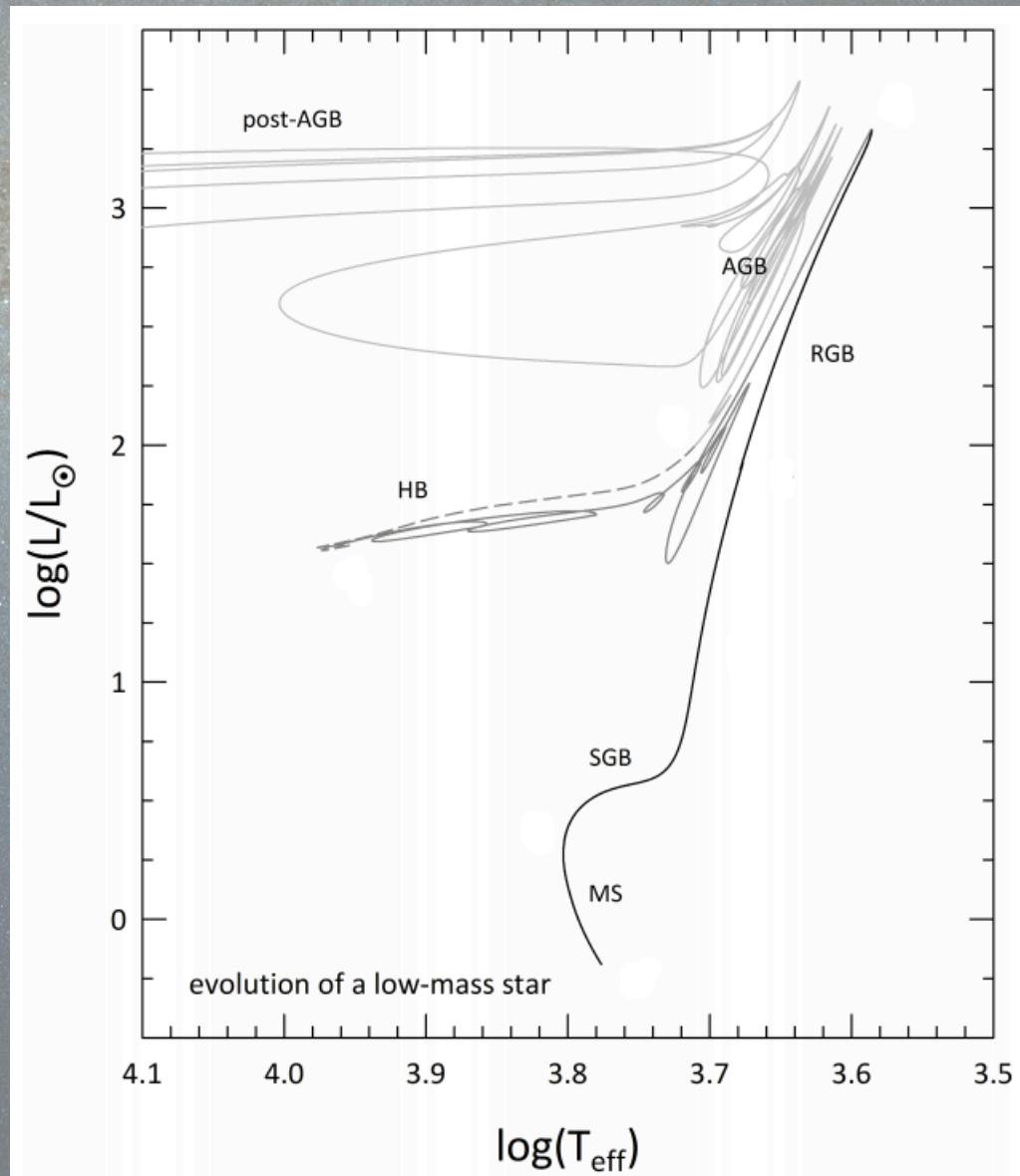
- ★ Introduction:
  - ★ Low mass stars
- ★ Motivation:
  - ★ VVV Survey
  - ★ “Outer bulge”
- ★ Analysis:
  - ★ Mining the catalog
- ★ Results:
  - ★ 3D Distribution of RR Lyrae stars
  - ★ Comparison with known structure (x-shape)
- ★ Summary

# Introduction

## ★ Stellar evolution of low mass stars

- $M \leq 2 M_{\odot}$
- H burning in the MS
- Degenerate He core after H depletion
- He flash
- HB stage

Evolution of a  $M \approx 0.8 M_{\odot}$  star in the Hertzsprung–Russell diagram  
(Catelan, M. 2008)

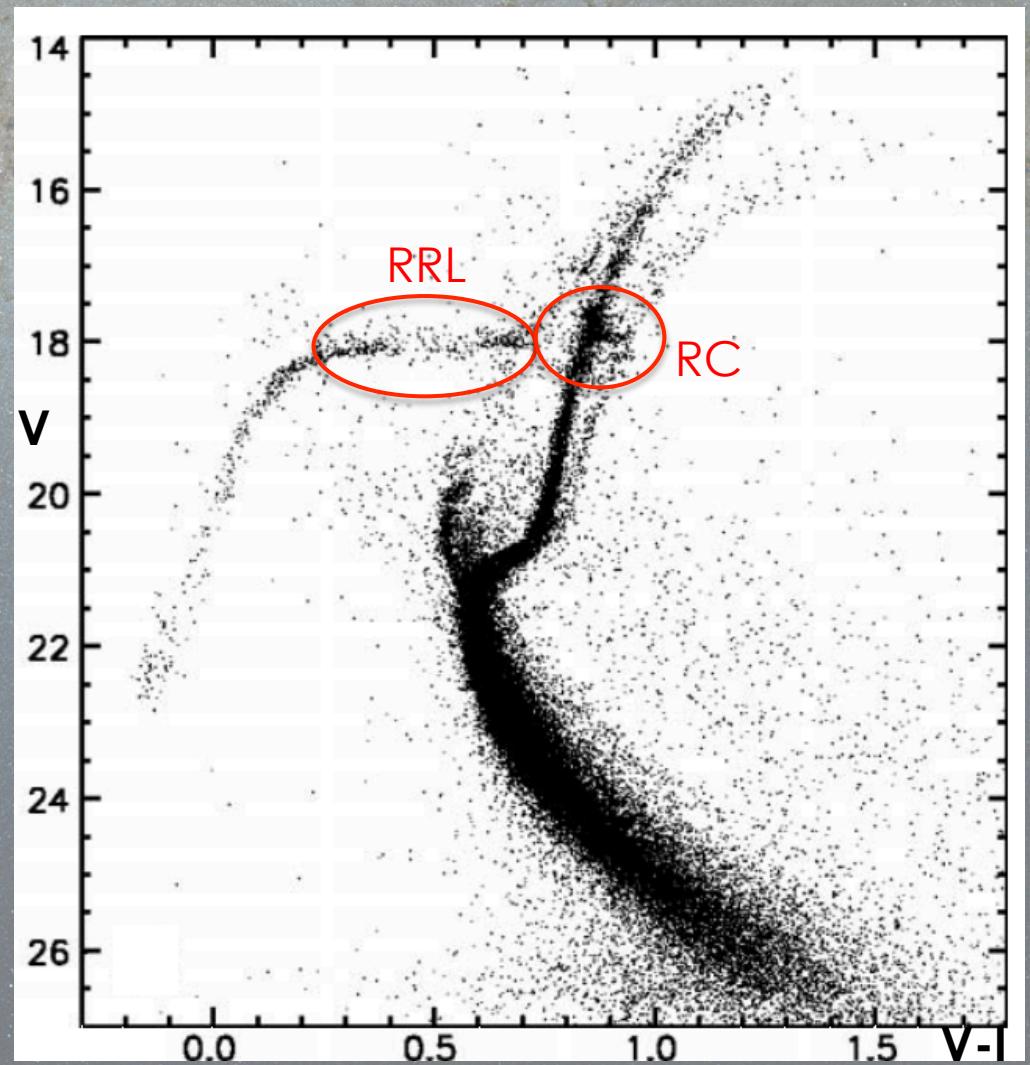


# Introduction

## ★ Stellar evolution of low mass stars

- $M \leq 2 M_{\odot}$
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HST color-magnitude diagram of M54  
(Siegel al. 2007)



# Introduction

## ★ Variable stars

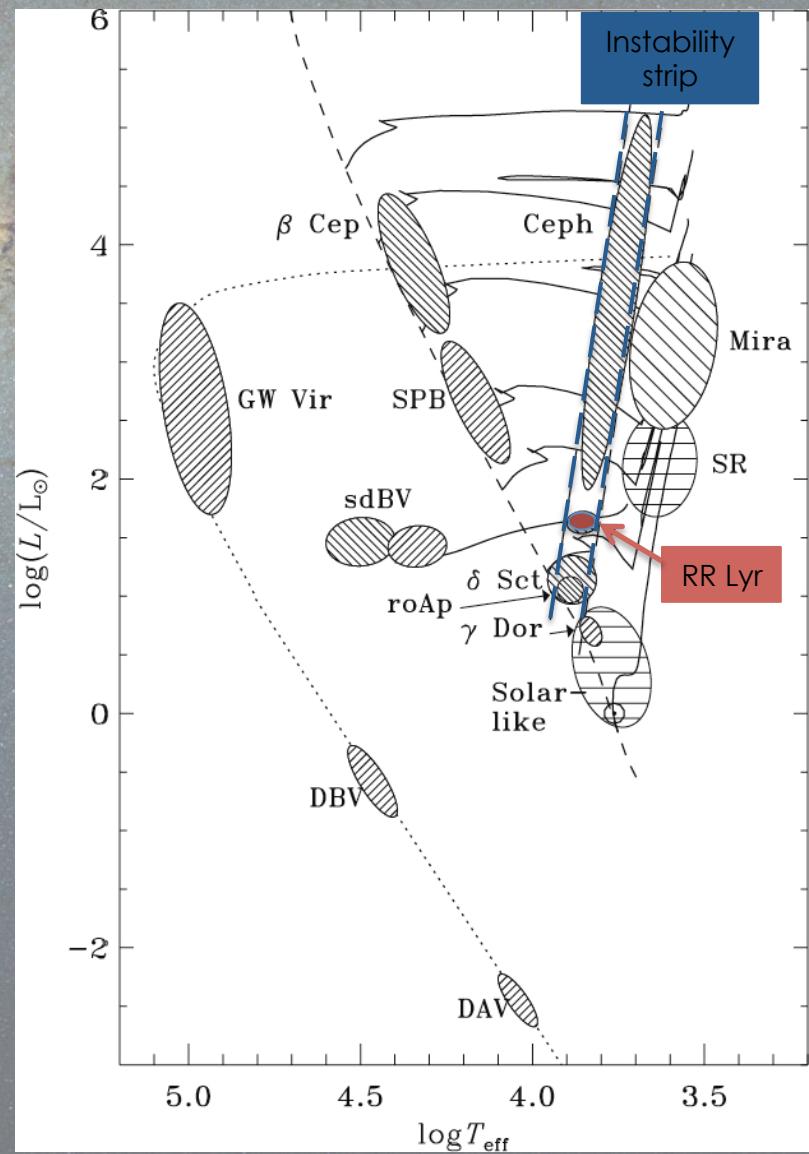
### Instability strip

- Narrow temperature region where stars are unstable against radial pulsation.

### RR Lyrae stars:

- $M \approx 0.7 M_{\odot}$
- $0.2 \leq P \text{ (days)} \leq 1.2$
- $0.3 \leq A_V \text{ (mag)} \leq 1.6$
- $0.2 \leq A_{Ks} \text{ (mag)} \leq 0.5$

Hertzsprung-Russell diagram showing different classes of pulsating stars.  
(Cunha et al. 2007)



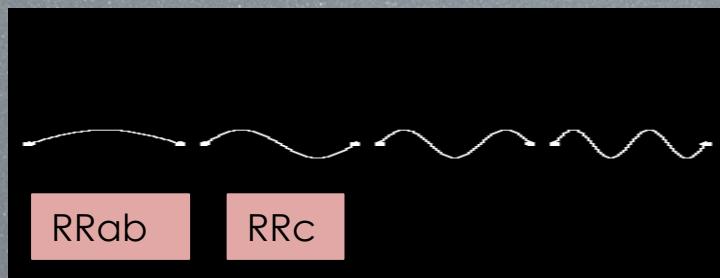
# Introduction

## ★ Variable stars

### Instability strip

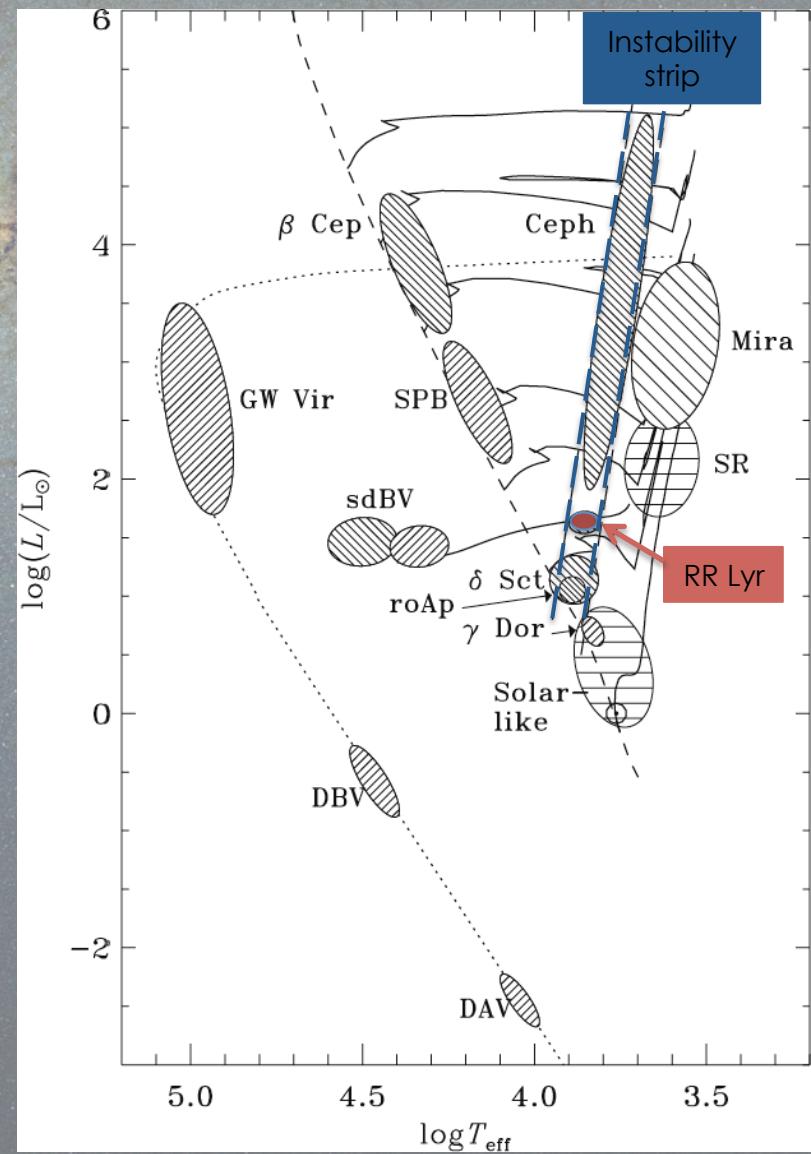
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RR Lyrae stars:



© R. Szabo

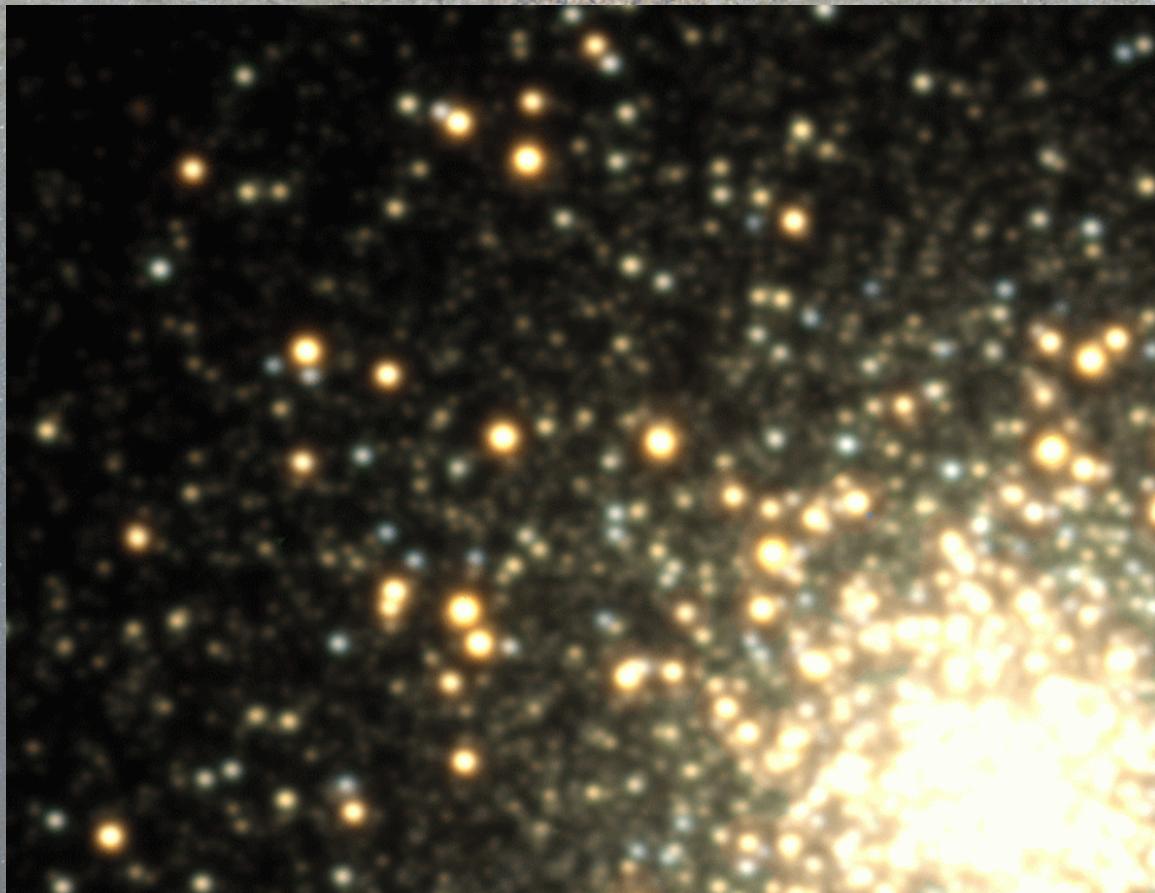
Hertzsprung-Russell diagram showing different classes of pulsating stars.  
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# Introduction

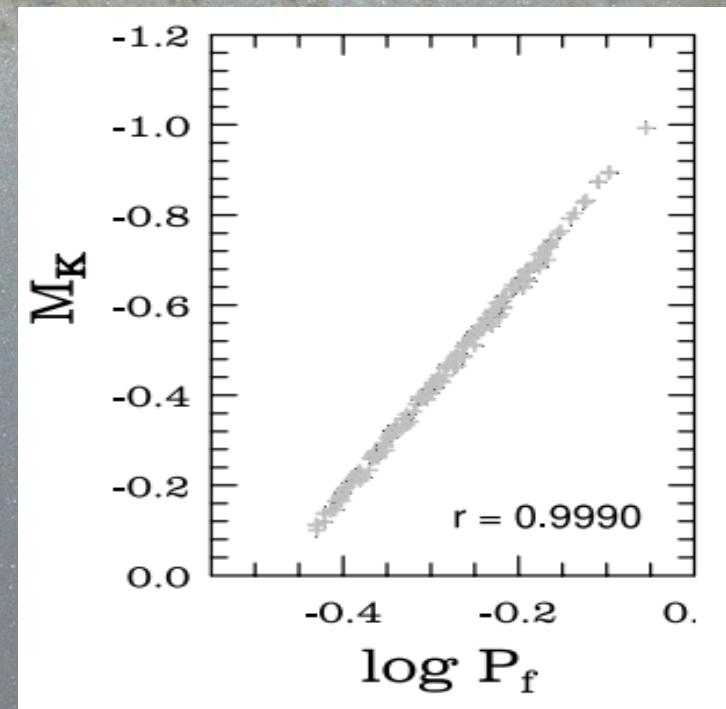
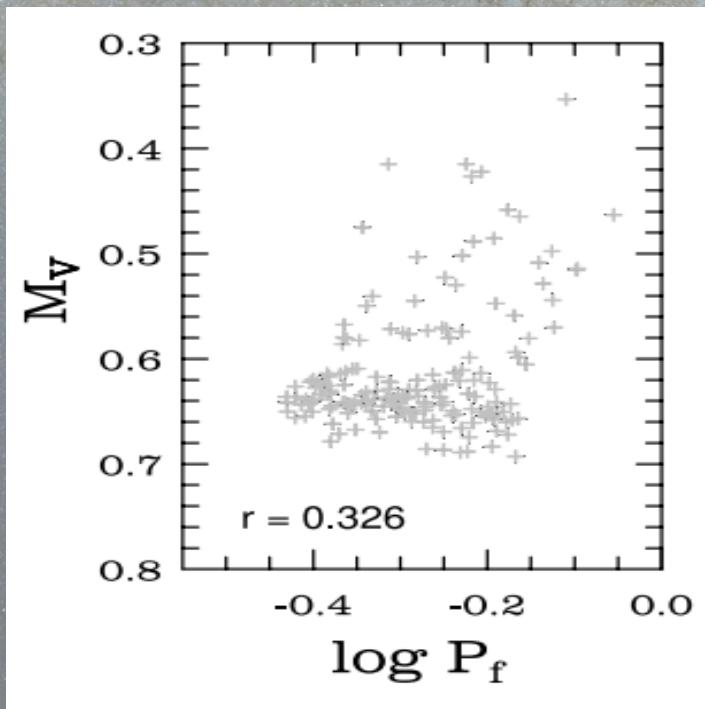
★ Variable stars

RR Lyrae stars:



# Introduction

**RR Lyr stars are excellent distant indicators !!  
(follow precise P-L Relation in the near-IR)**



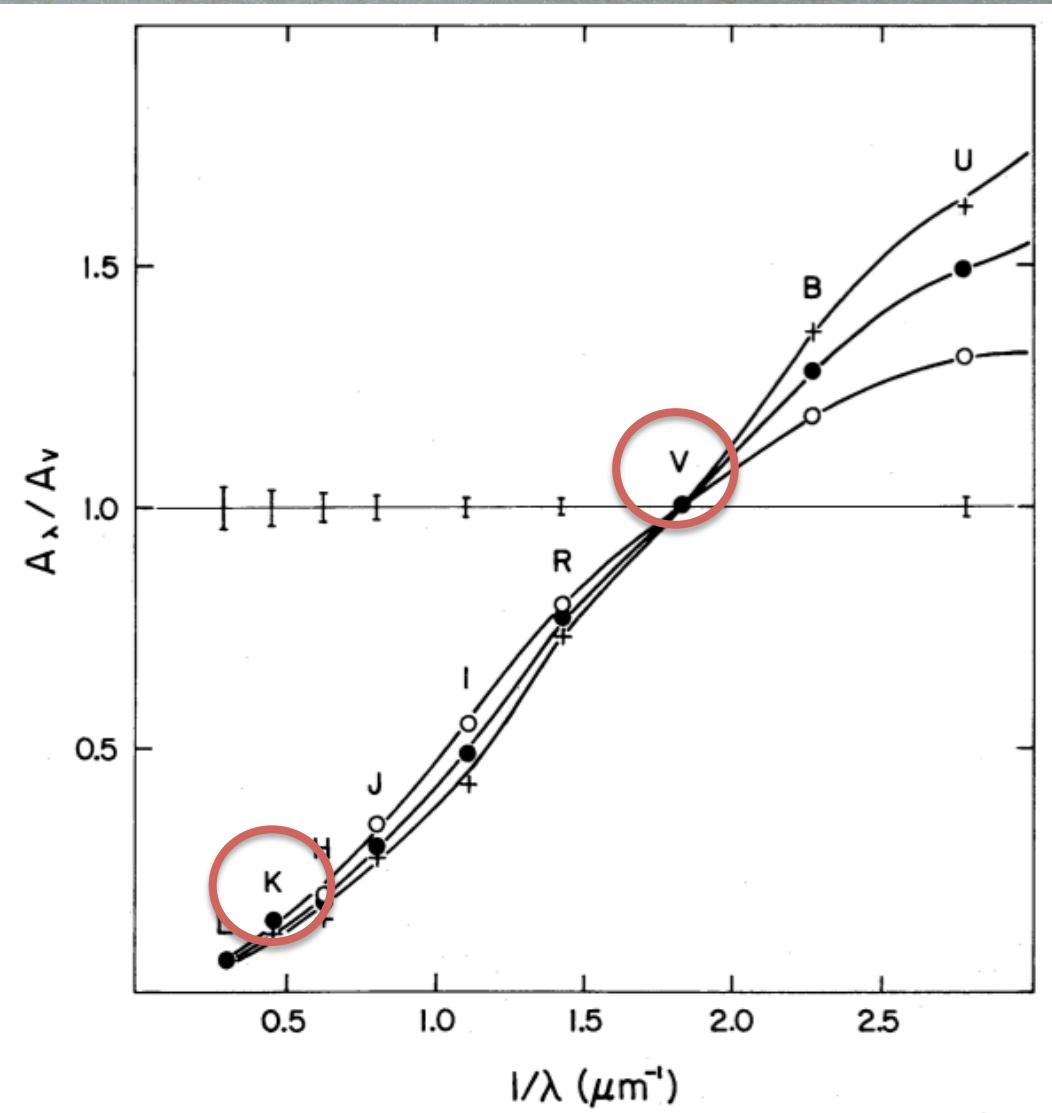
Optical (V) v/s near-IR (K)

# Introduction

- ★ Observing in near-IR bands It has many advantages:

*Lower interstellar extinction*

Comparison  
between the  
optical/near-IR  
extinction laws.  
(Cardelli et al. 1989)

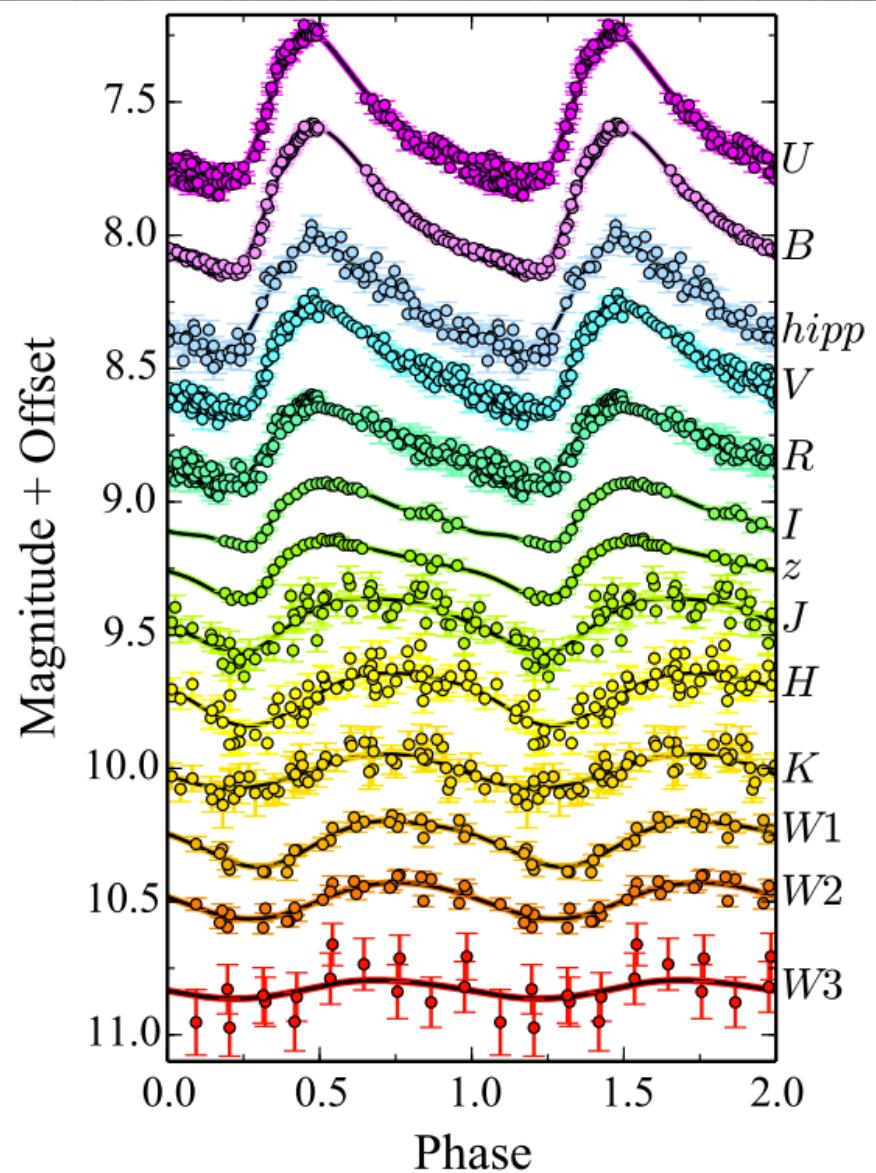


# Introduction

- ★ Observing in near-IR bands It has many advantages:

Better constrained magnitudes

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



# Introduction

Distribution of red clump stars in the Milky Way



Barred/x-shape

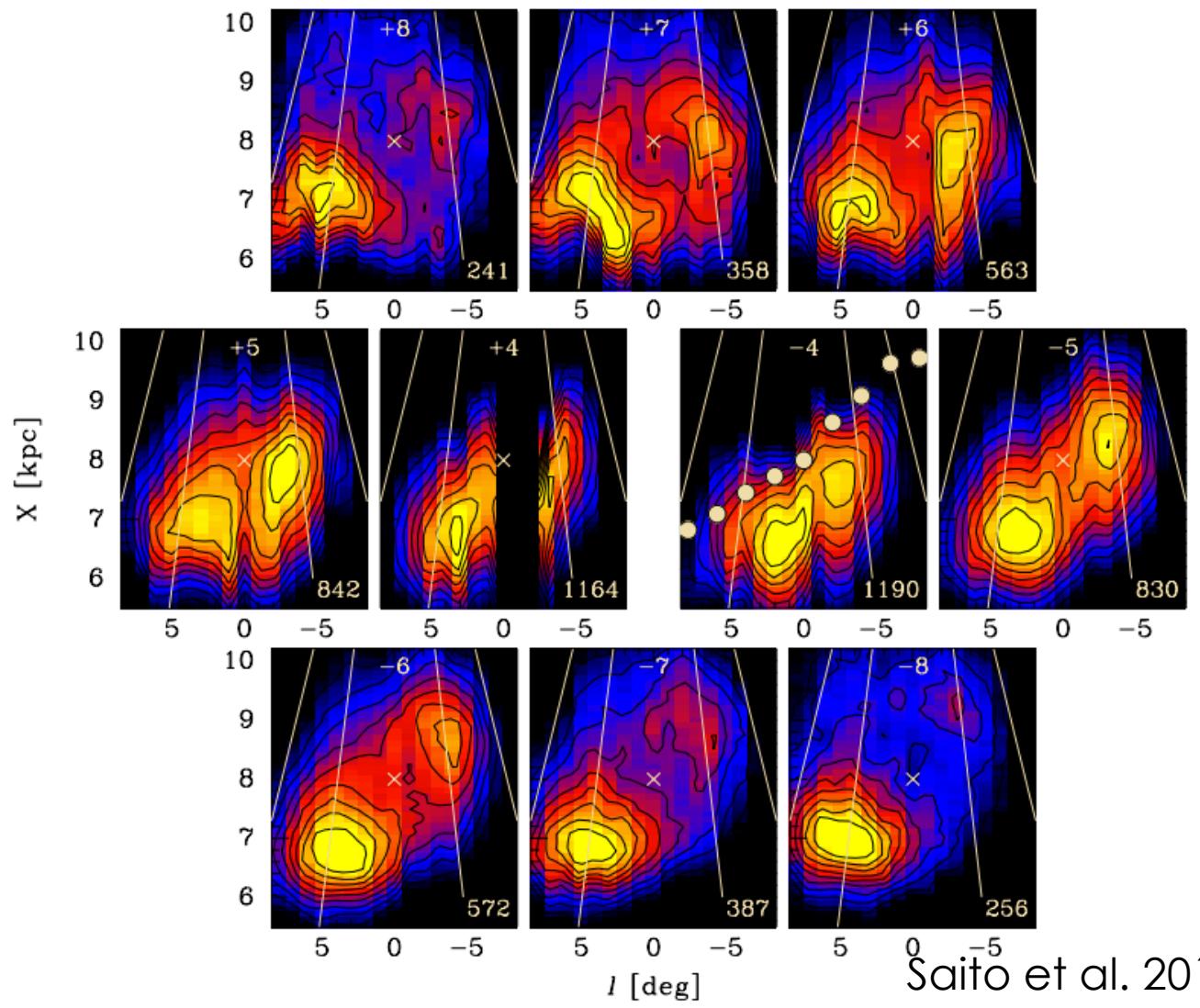
Rattenbury et al. 2007  
McWilliam

& Zoccali 2010

Nataf et al. 2010

Saito et al. 2011

Gonzalez et al. 2012



# Introduction

Known distribution of red  
clump stars in the Milky Way → Barred/x-shape



← Full moon size

# Motivation

- ★ Vista Variables in the Vía Láctea (VVV) is a currently ongoing ESO Public Survey (Minniti et al. 2010)

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- ★ VVV uses **near-IR filters** (ZYJHK<sub>s</sub>) to observe ~300 deg<sup>2</sup> in the Galactic bulge
  - ★ ZYJH one epoch at the first year of operation
  - ★ K<sub>s</sub>-band variability survey: ~100 epochs

# Motivation

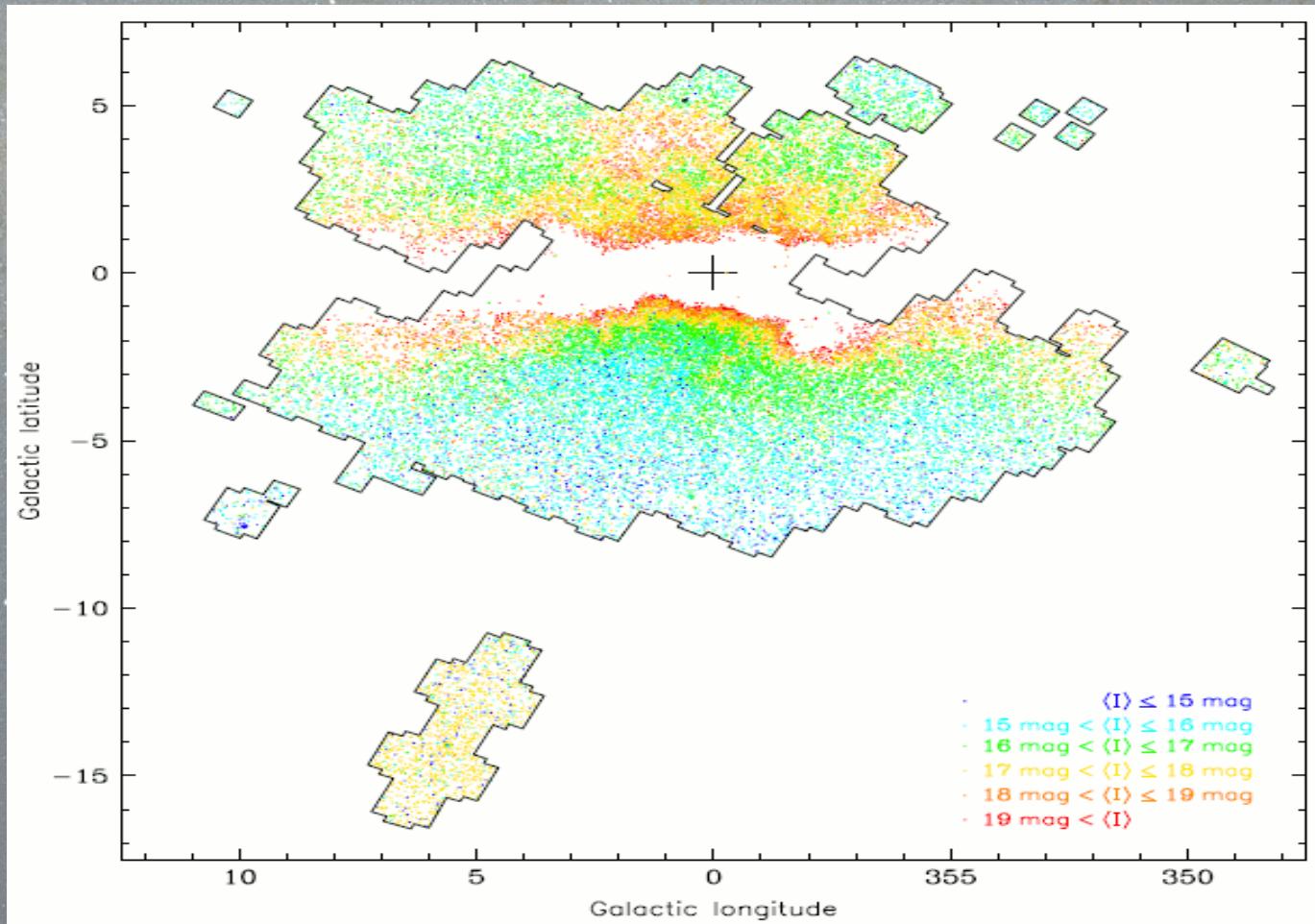
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  - ★ ZYJH one epoch at the first year of operation
  - ★ K<sub>s</sub>-band variability survey: ~100 epochs
- ★ “Outer bulge” avoided by other variability surveys:
  - ★ OGLE, MACHO, EROS



$$l \leq -8 \text{ deg}$$

# Motivation

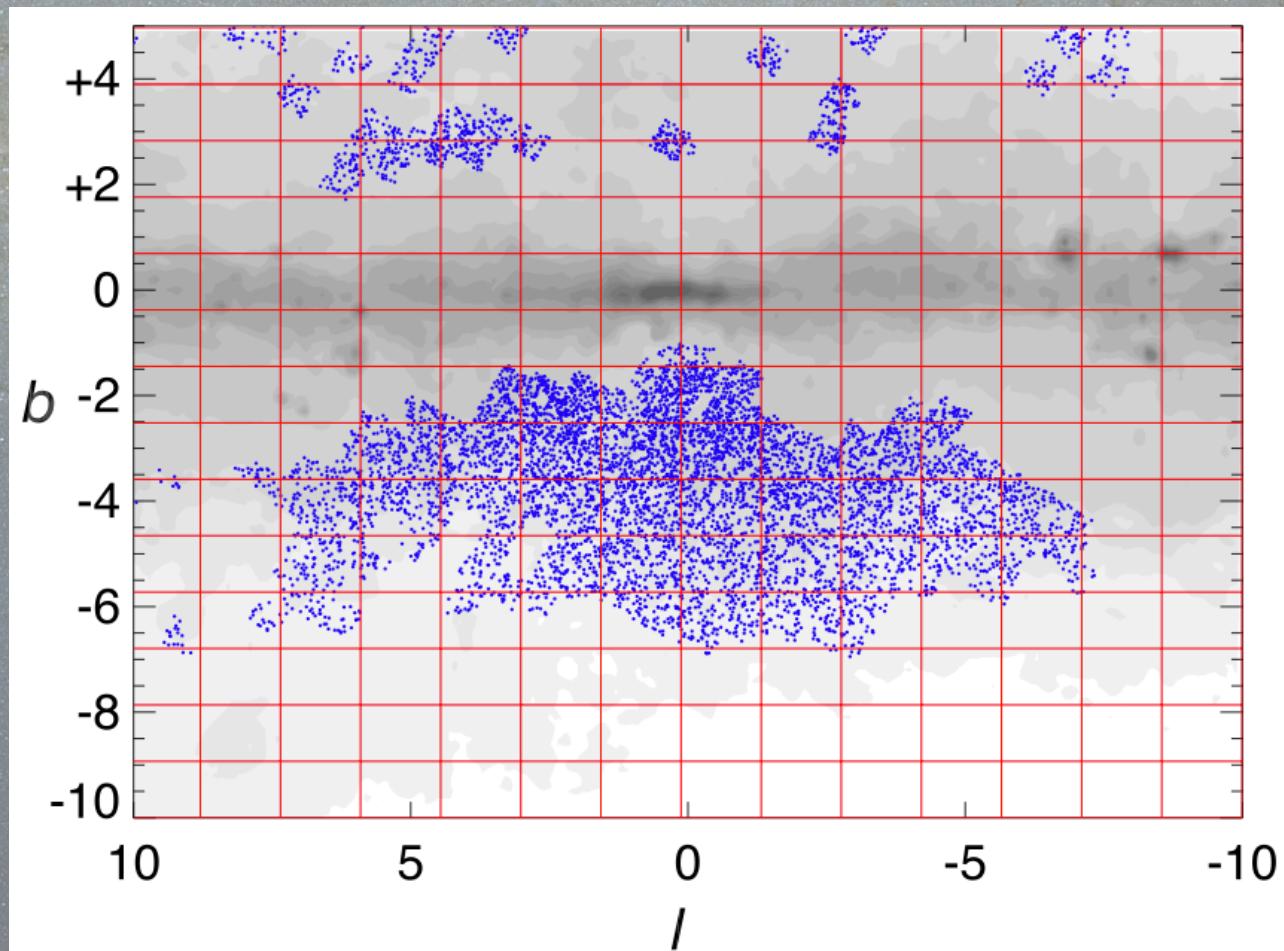
OGLE IV – 36257 bulge + 2000 Sgr dSph RR Lyr stars



Soszyński et al. 2014 + Pietrukowicz et al. 2014

# Motivation

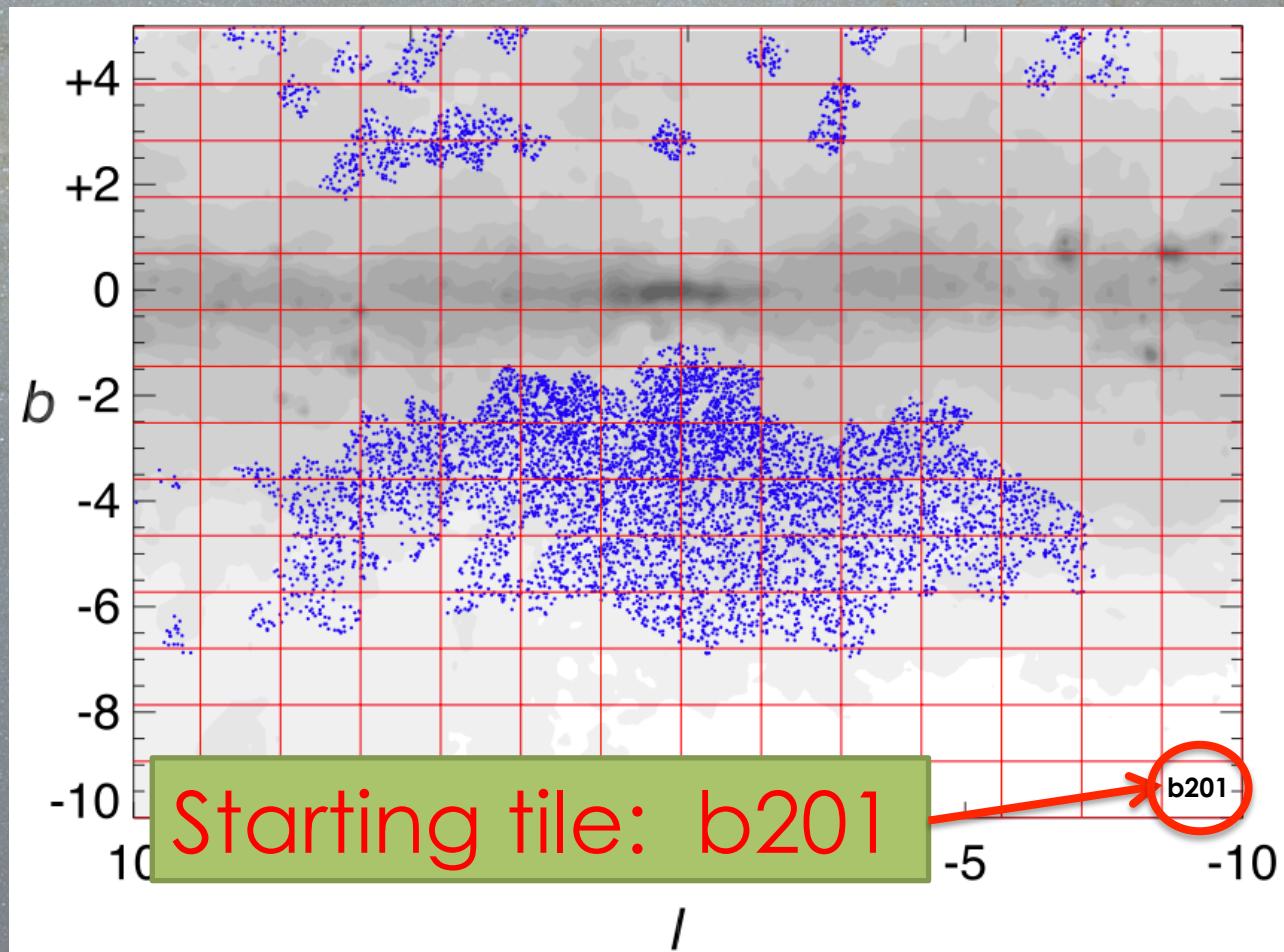
VVV – 7663 bulge RR Lyr stars



Dékány et al. 2013

# Motivation

VVV – 7663 bulge RR Lyr stars



Dékány et al. 2013

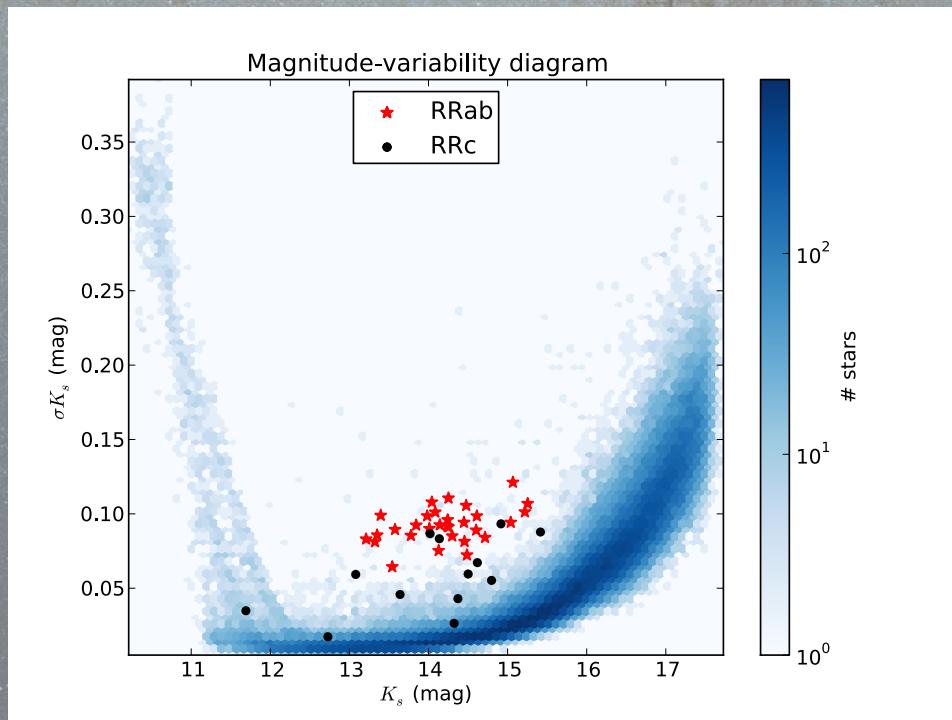
# Analysis

★ Variable discrimination:

★ RMS –  $\chi^2$  value

★ Periodic search:

★ Analysis of variance (AoV; Schwarzenberg-Czerny 1989)



Magnitude-variability diagram (rms – magnitude) for the tile b201 (Gran et al. 2015)

# “Bulge RR Lyrae stars in the VVV tile b201”

## Bulge RR Lyrae stars in the VVV tile b201<sup>★</sup>

F. Gran<sup>1,2</sup>, D. Minniti<sup>3,4</sup>, R. K. Saito<sup>5</sup>, C. Navarrete<sup>1,2</sup> I. Dékány<sup>2,1</sup>, I. McDonald<sup>6</sup>, R. Contreras Ramos<sup>1,2</sup>, M. Catelan<sup>1,2</sup>

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<sup>5</sup> Universidade Federal de Sergipe, Departamento de Física, Av. Marechal Rondon s/n, 49100-000, São Cristóvão, SE, Brazil

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### ABSTRACT

**Context.** The VISTA Variables in the Vía Láctea (VVV) Survey is one of the six ESO public surveys currently ongoing at the VISTA telescope on Cerro Paranal, Chile. VVV uses near-IR ( $ZYJHK_s$ ) filters that at present provide photometry to a depth of  $K_s \sim 17.0$  mag in up to 36 epochs spanning over four years, and aim at discovering more than  $10^6$  variable sources as well as trace the structure of the Galactic bulge and part of the southern disk.

**Aims.** A variability search was performed to find RR Lyrae variable stars. The low stellar density of the VVV tile *b201*, which is centered at  $(\ell, b) \sim (-9^\circ, -9^\circ)$ , makes it suitable to search for variable stars. Previous studies have identified some RR Lyrae stars using optical bands that served to test our search procedure. The main goal is to measure the reddening, interstellar extinction, and distances of the RR Lyrae stars and to study their distribution on the Milky Way bulge.

**Methods.** For each star in the tile with more than 25 epoch (~90% of the objects down to  $K_s \sim 17.0$  mag), the standard deviation and  $\chi^2$  test were calculated to identify variable candidates. Periods were determined using the analysis of variance. Objects with periods in the RR Lyrae range of  $0.2 \leq P \leq 1.2$  days were selected as candidate RR Lyrae. They were individually examined to exclude false positives.

**Results.** A total of 1.5 sq deg were analyzed, and we found 39 RR Lyr stars, 27 of which belong to the ab-type and 12

analysis recovers all the previously identified RR Lyrae variables in the field and discovers 29 new RR Lyrae stars. The extinction toward all the RRab stars in this tile were derived, and distance estimations were made using the  $M_K - K_s$  relation. Despite the limited amount of RR Lyrae stars studied, our results are in agreement with previous studies, with distances around  $\sim 8.1$  and  $\sim 8.5$  kpc. for either the Cardelli or Nishiyama extinction law.

Nevertheless, a larger area must be analyzed to definitively answer this question.

**Key words.** Galaxy: bulge – Galaxy:

Published !!  
Gran et al. 2015, A&A, 575, 114

★ Completed:

b201

★ To analyze:

195 bulge tiles (b202 – b396)

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★ But our goal is the  
**outer bulge!**



b228 ✓	b227 ✓	b226 ✓	b225 ✓	b224 ✓	b223 ✓	b222 ✓	b221 ✓	b220 ✓	b219 ✓	b218 ✓	b217 ✓	b216 ✓	b215 ✓
b214 ✓	b213 ✓	b212 ✓	b211 ✓	b210 ✓	b209 ✓	b208 ✓	b207 ✓	b206 ✓	b205 ✓	b204 ✓	b203 ✓	b202 ✓	b201 ✓

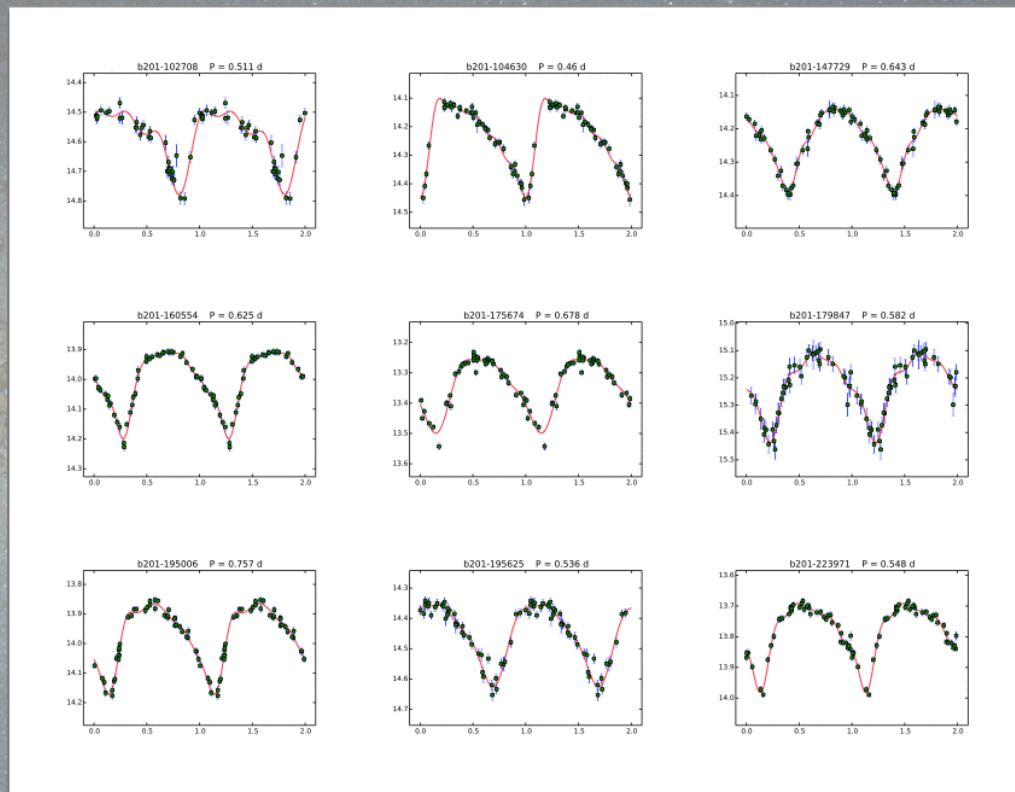
★ Completed:

b201

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b228 ✓	b227 ✓	b226 ✓	b225 ✓	b224 ✓	b223 ✓	b222 ✓	b221 ✓	b220 ✓	b219 ✓	b218 ✓	b217 ✓	b216 ✓	b215 ✓
b214 ✓	b213 ✓	b212 ✓	b211 ✓	b210 ✓	b209 ✓	b208 ✓	b207 ✓	b206 ✓	b205 ✓	b204 ✓	b203 ✓	b202 ✓	b201 ✓

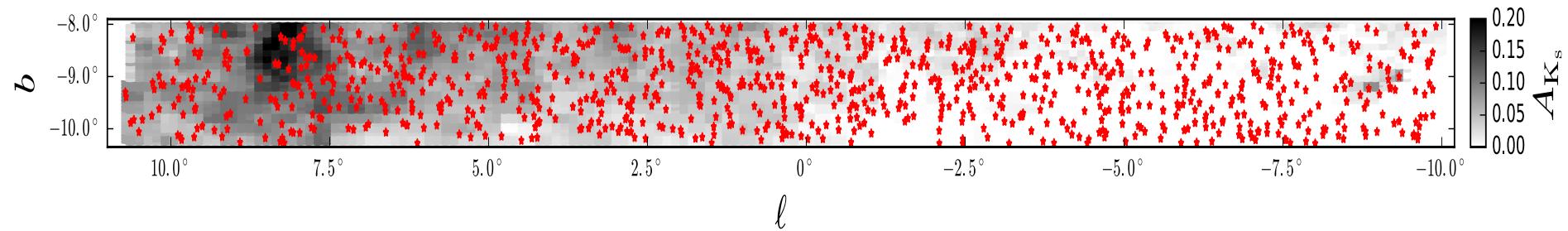
★ Completed:

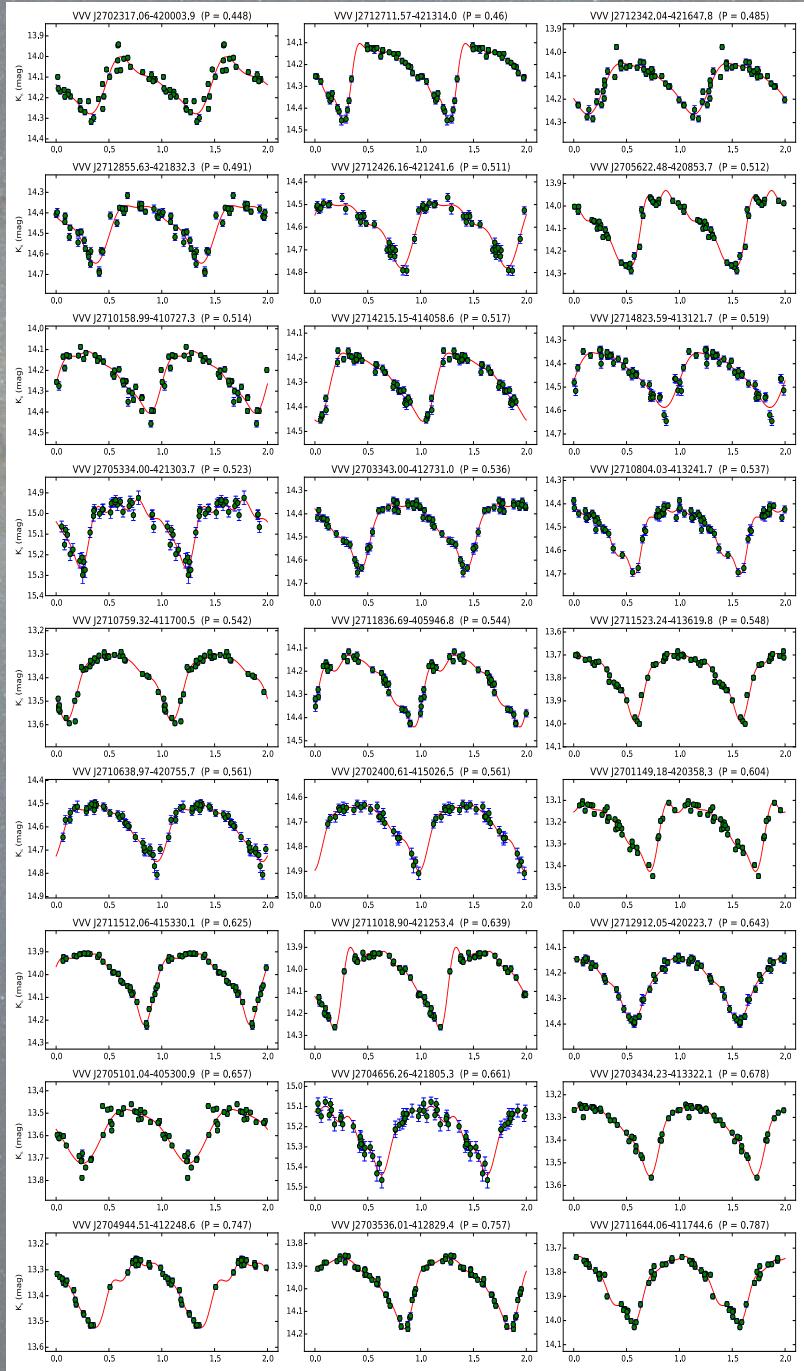
b201

★ To do:

A total of **1019 RRab** stars were discovered  
in  $\sim 47$  sq deg (28 VVV tiles)

★ But our goal is the  
**outer bulge!**



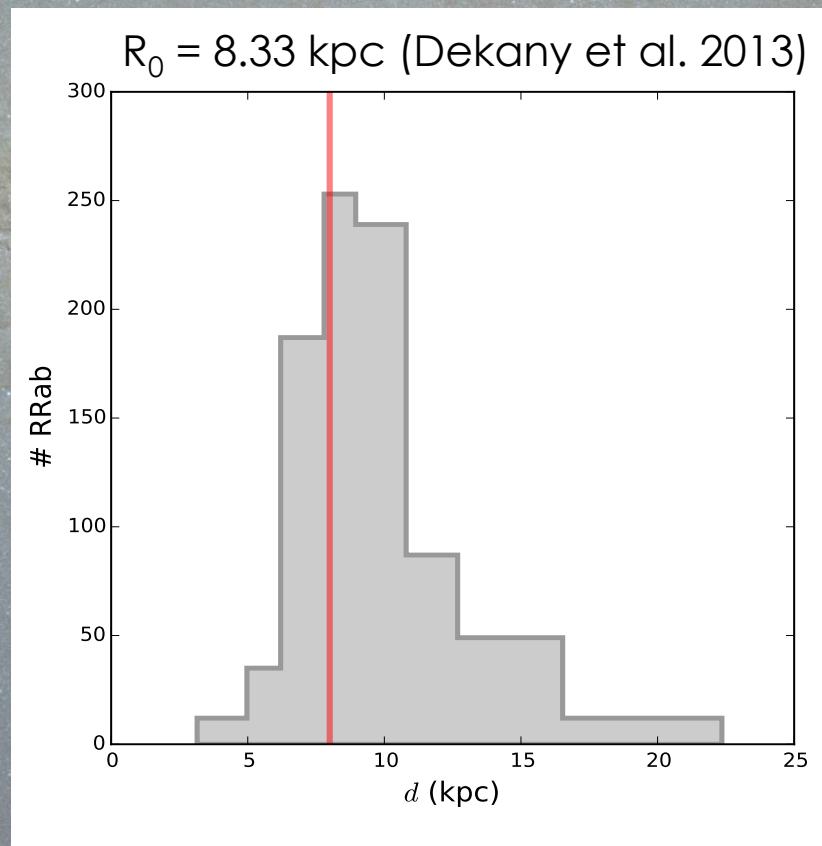


$$\begin{aligned}
 & + E(J-K_s) \longleftrightarrow (J-K_s) - (J-K_s)_0 \\
 & + [Fe/H] \longleftrightarrow OGLE [Fe/H] \sim -1 \\
 & + A_{K_s} \longleftrightarrow 0.698 E(J-K_s) \\
 & + P-L \text{ Relation} \longleftrightarrow \text{Catelan et al. (2004)} \\
 & \quad \quad \quad \quad Alonso-García et al. (2015)
 \end{aligned}$$

DISTANCES

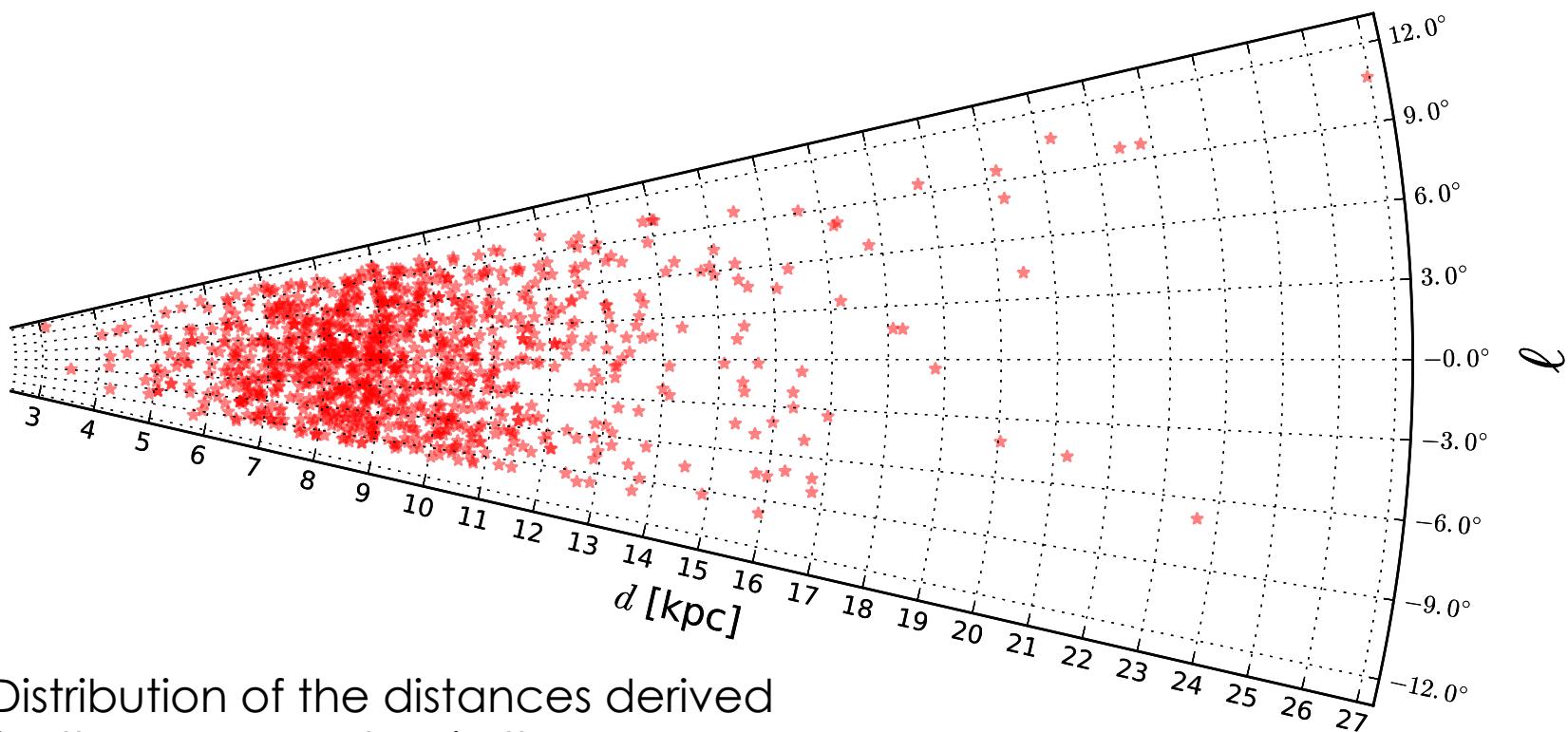
$$\log d = 1 + 0.2(K_{s,0} - M_{K_s})$$

# Results



Distribution of the distances derived  
for the RR Lyrae stars in the  
complete outer bulge.

# Results

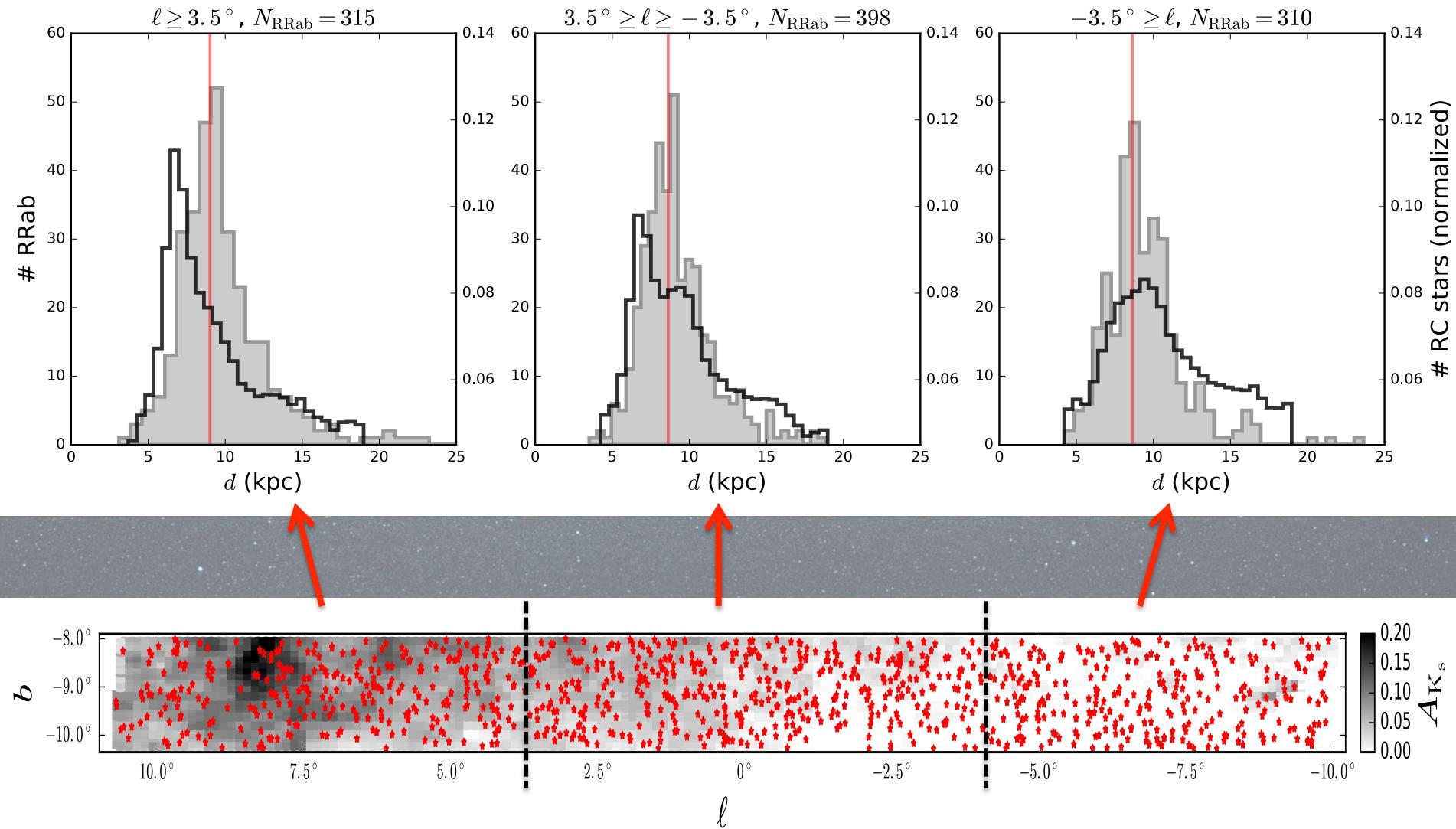


Distribution of the distances derived  
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# Results

RR Lyrae stars

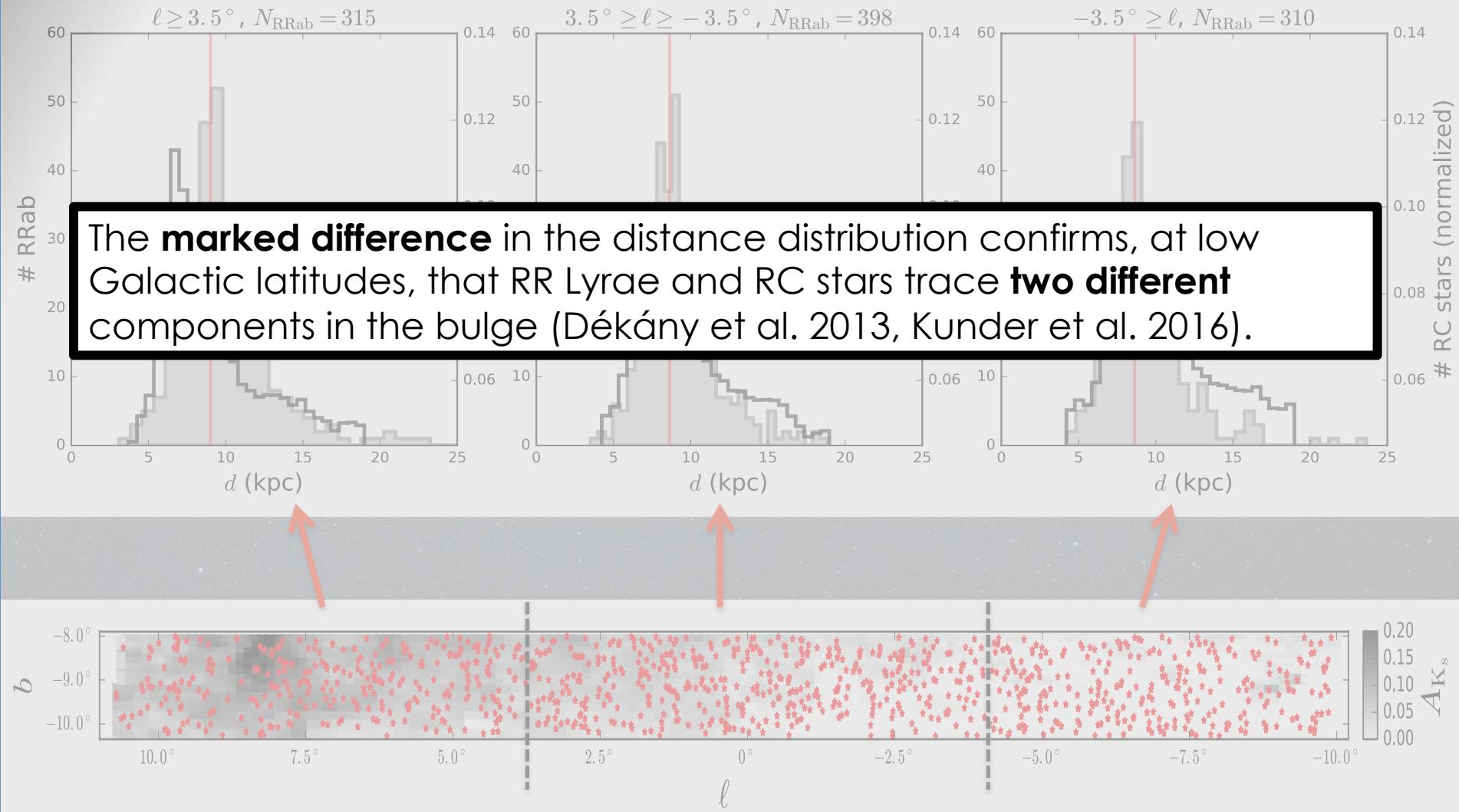
Red clump stars



# Results

RR Lyrae stars

Red clump stars



# Mapping the outer bulge with RRab stars from the VVV Survey

F. Gran<sup>1,2</sup>, D. Minniti<sup>3,2,4</sup>, R. K. Saito<sup>5</sup>, M. Zoccali<sup>1,2</sup>, O. A. Gonzalez<sup>6,7</sup>, C. Navarrete<sup>1,2</sup>, M. Catelan<sup>1,2</sup>, R. Contreras Ramos<sup>2,1</sup>, F. Elorrieta<sup>8,2</sup>, S. Eyheramendy<sup>8,2</sup>, A. Jordán<sup>1,2</sup>

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## ABSTRACT

**Context.** The VISTA Variables in the Vía Láctea (VVV) is a near-IR time-domain survey of the Galactic bulge. One of the main goals of this survey is to reveal the 3D structure of the Milky Way through the study of RR Lyrae stars. These stars have been massively discovered in the inner regions of the bulge ( $-8^\circ \leq \delta \leq +8^\circ$ ) and in the fields around the Galactic center as OGLE and MACHO but leaving an unexplored window of more than  $\sim 47$  sq deg ( $\sim 0^\circ \leq \ell \leq 180^\circ$  and  $\delta \lesssim -8.0^\circ$ ) observed by the VVV Survey.



# Summary

- ★ VVV is mapping the 3D structure of the Galaxy through RR Lyrae stars.
- ★ A total of 1019 RRab stars have been detected in 28 tiles of the outer bulge.
- ★ RR Lyrae stars trace a centrally concentrated distribution, different to the one traced by red clump stars known to follow a bar (x-shape)

{ Periods  
Amplitudes  
Fourier Coeff.  
Mean mags.  
Distances }

*Thanks for your  
attention !!*