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

Felipe Eduardo Gran Merino

Master thesis defense

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Dante Minniti

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Márcio Catelan

A. Katherina Vivas

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

fegran.github.io

Outline

- ★ Introduction:
  - ★ Low mass stars
  - ★ Variable stars: RR Lyrae
- ★ Motivation:
  - ★ VVV Survey
  - ★ "Outer bulge"
- ★ Analysis:
  - ★ Mining the catalog
- ★ Results:
  - ★ 3D Distribution of RR Lyrae stars
  - ★ Comparison with known structures (x-shape)
- ★ Summary & Future work

Outline

for my dad

- ★ Introduction:
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- ★ Conclusions & Future work

Fundamental things about stars

Why you studied this topic?

How did you do all the work?

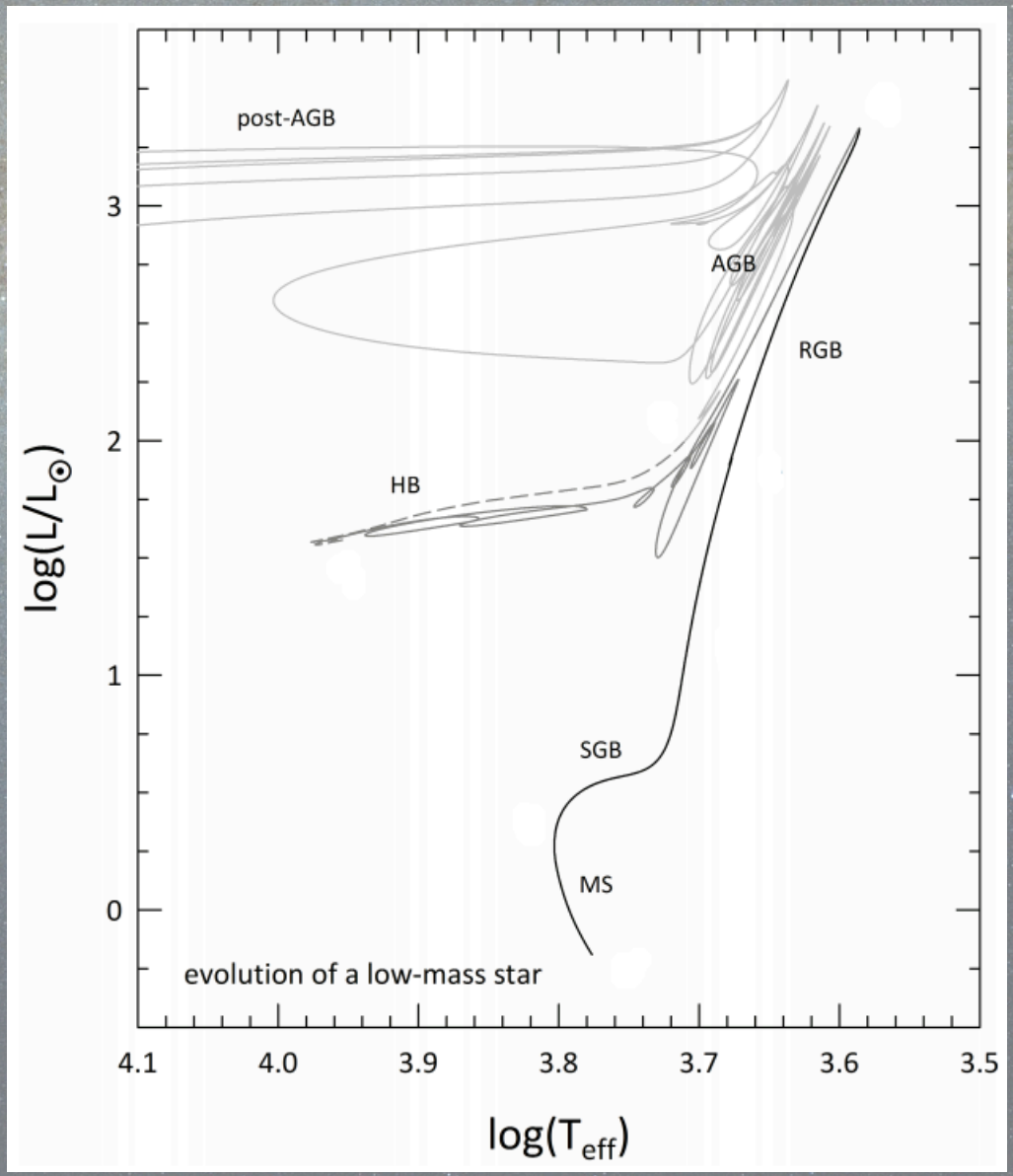
Boxed and colorful plots

What is the next step?

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

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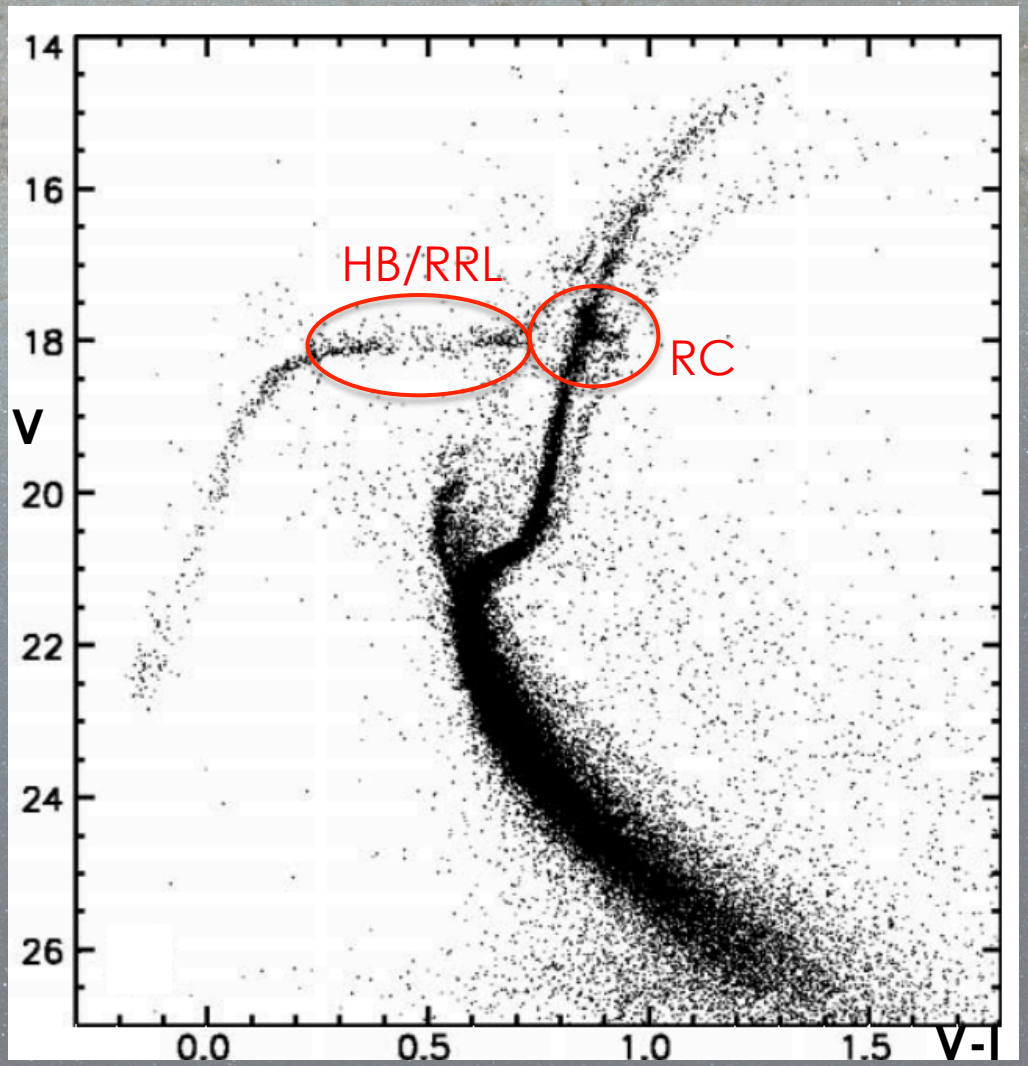


HST color-magnitude diagram of M54 (Siegel al. 2007)

Introduction

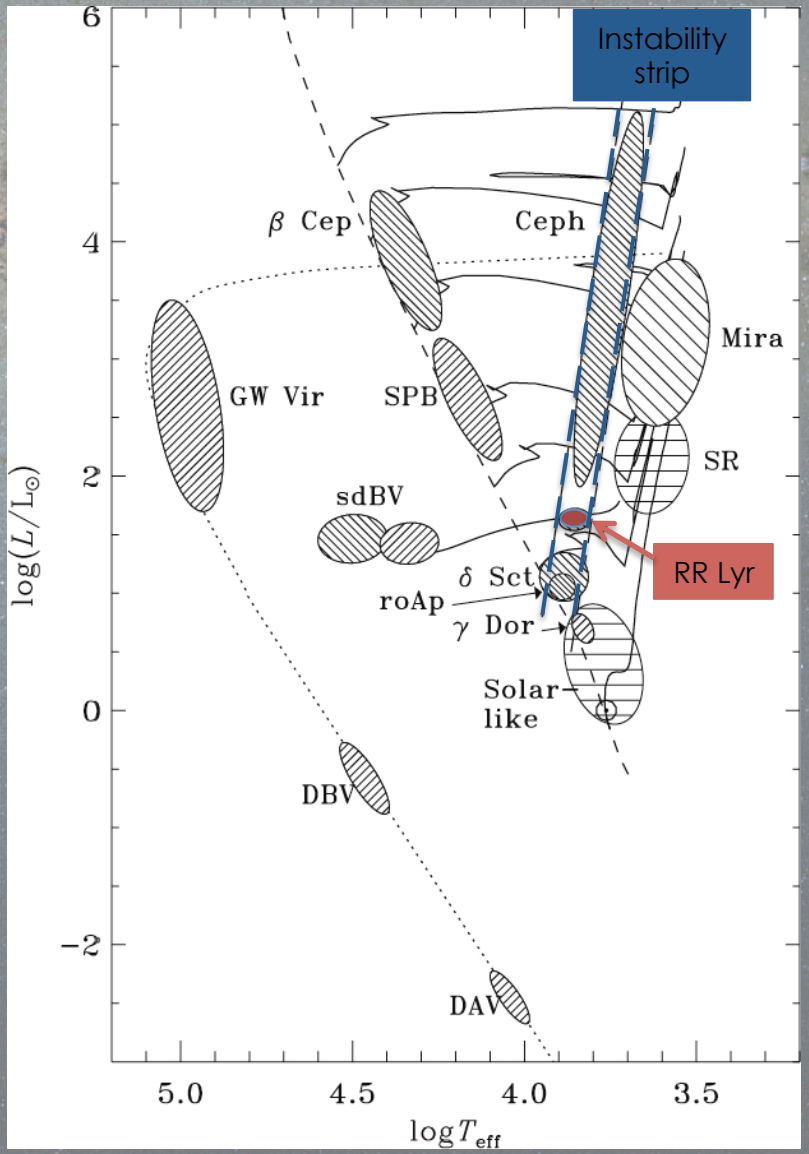
★ Variable stars

Instability strip

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

RR Lyrae stars:

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



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

Introduction

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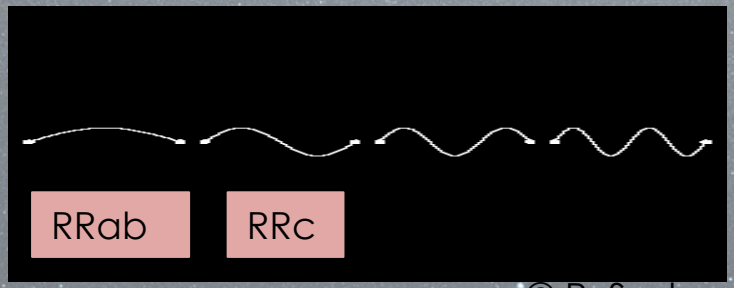
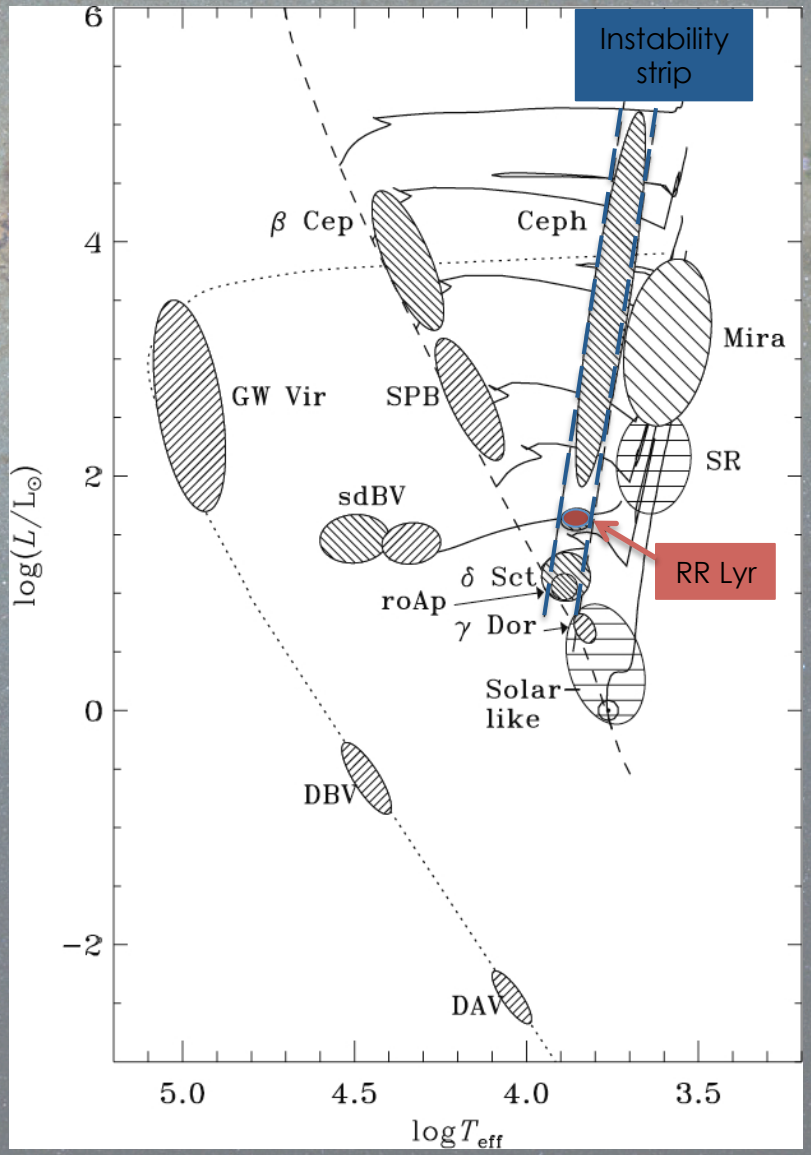
RR Lyrae stars:



© R. Szabo



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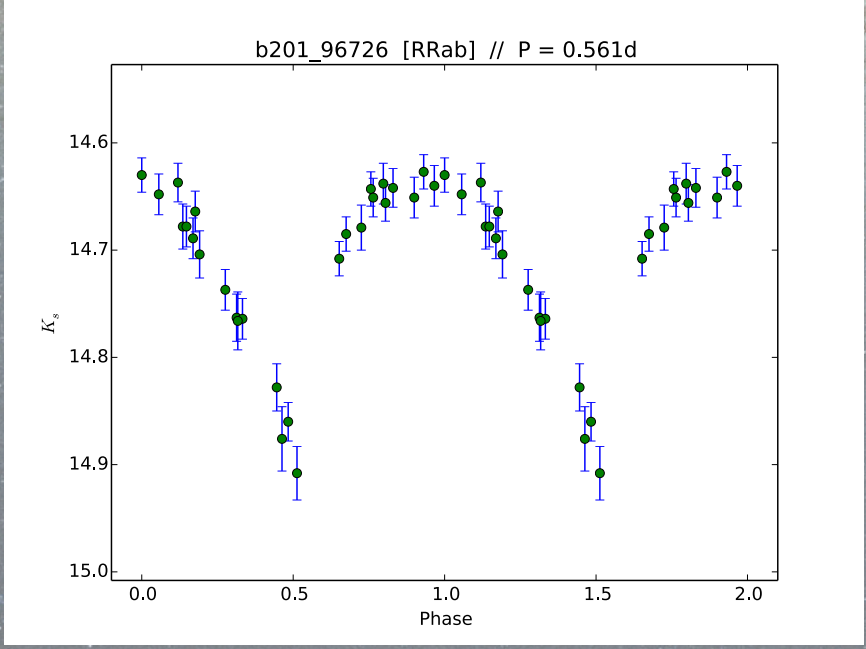
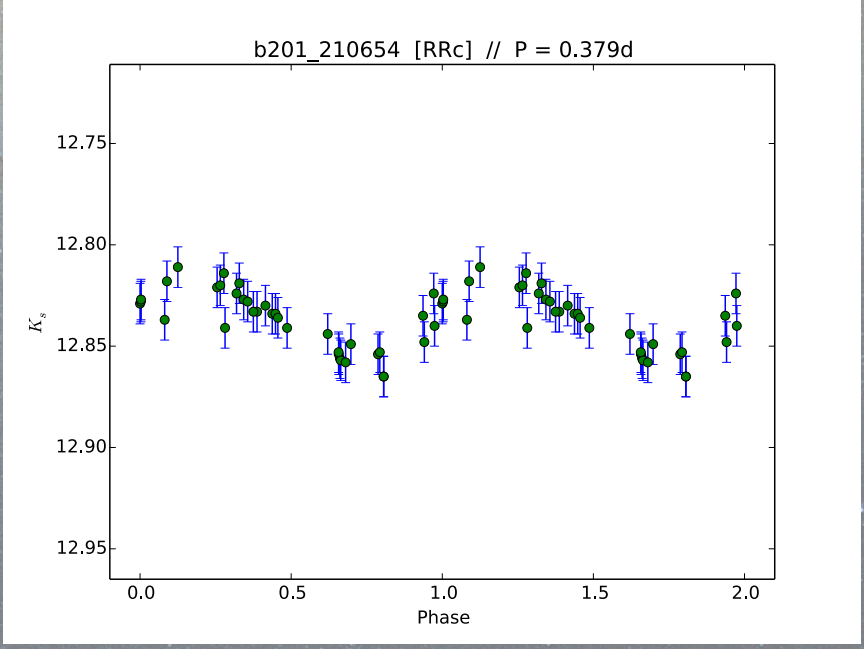
Introduction

★ Variable stars

RR Lyrae stars:





RRab
P = 0.561 days

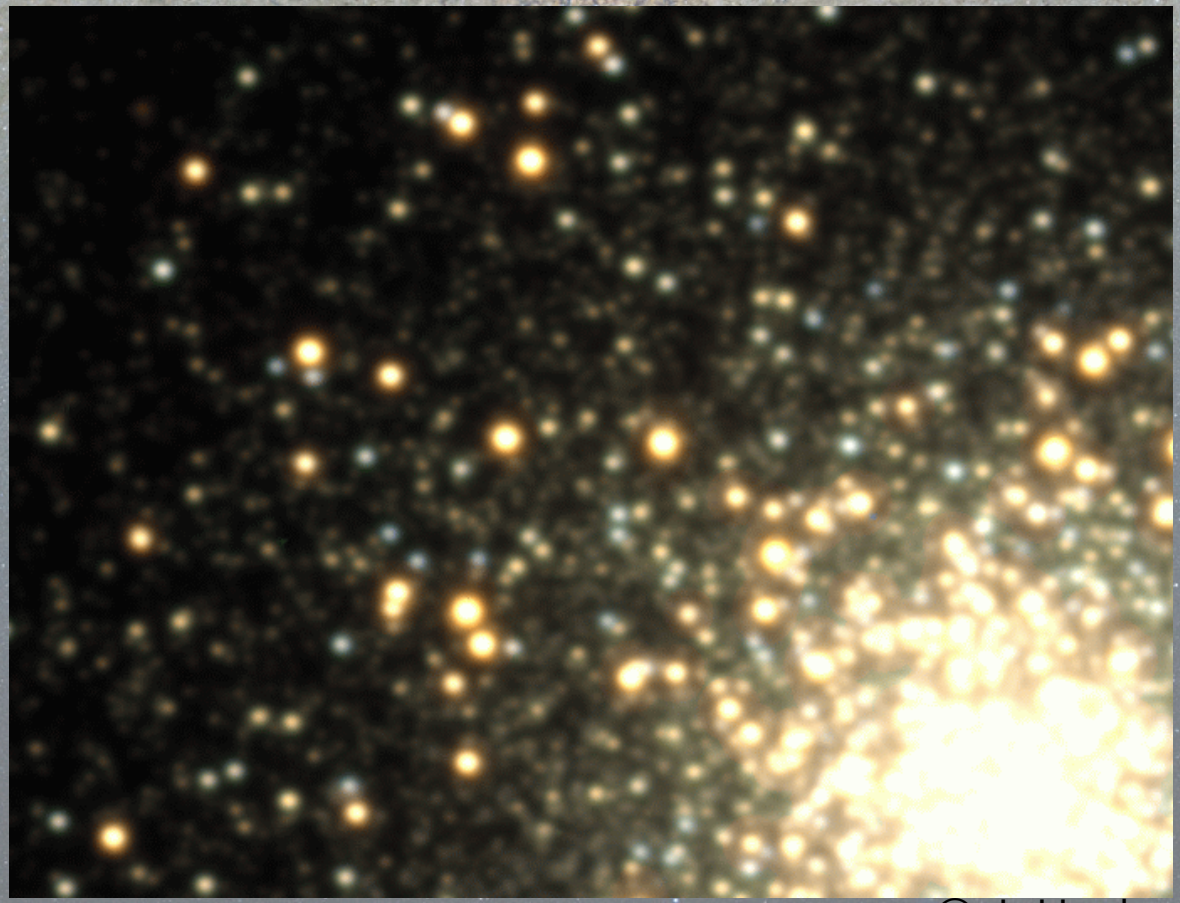
RRc
P = 0.379 days

Gran et al. 2015

Introduction

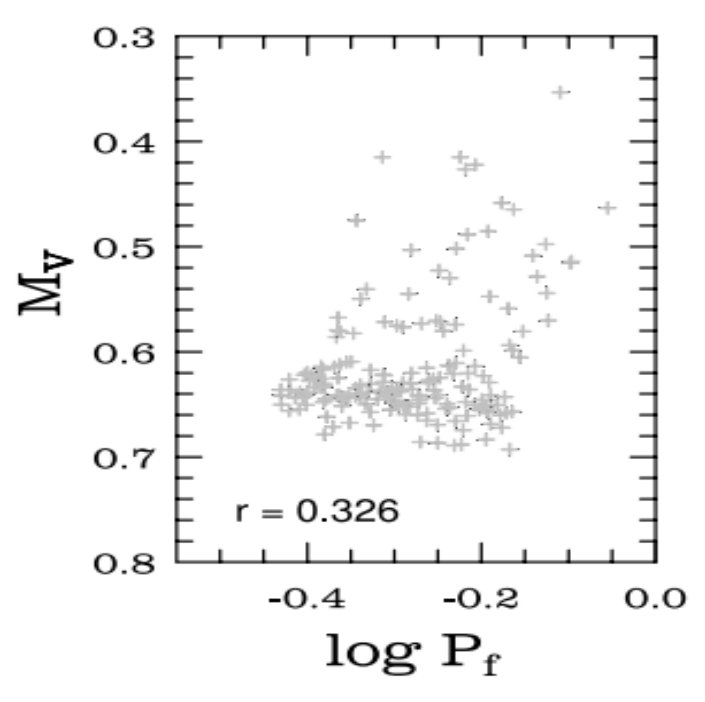
★ Variable stars

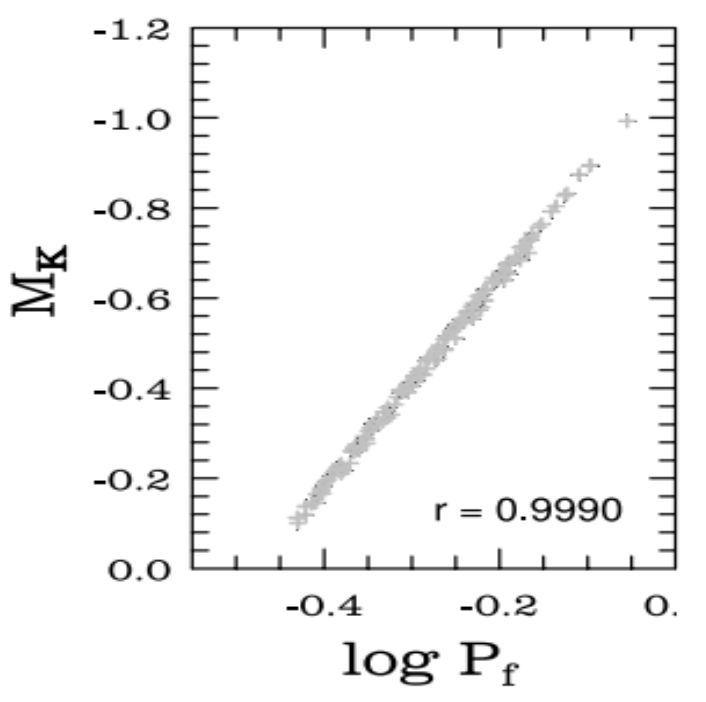
RR Lyrae stars:



Introduction

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





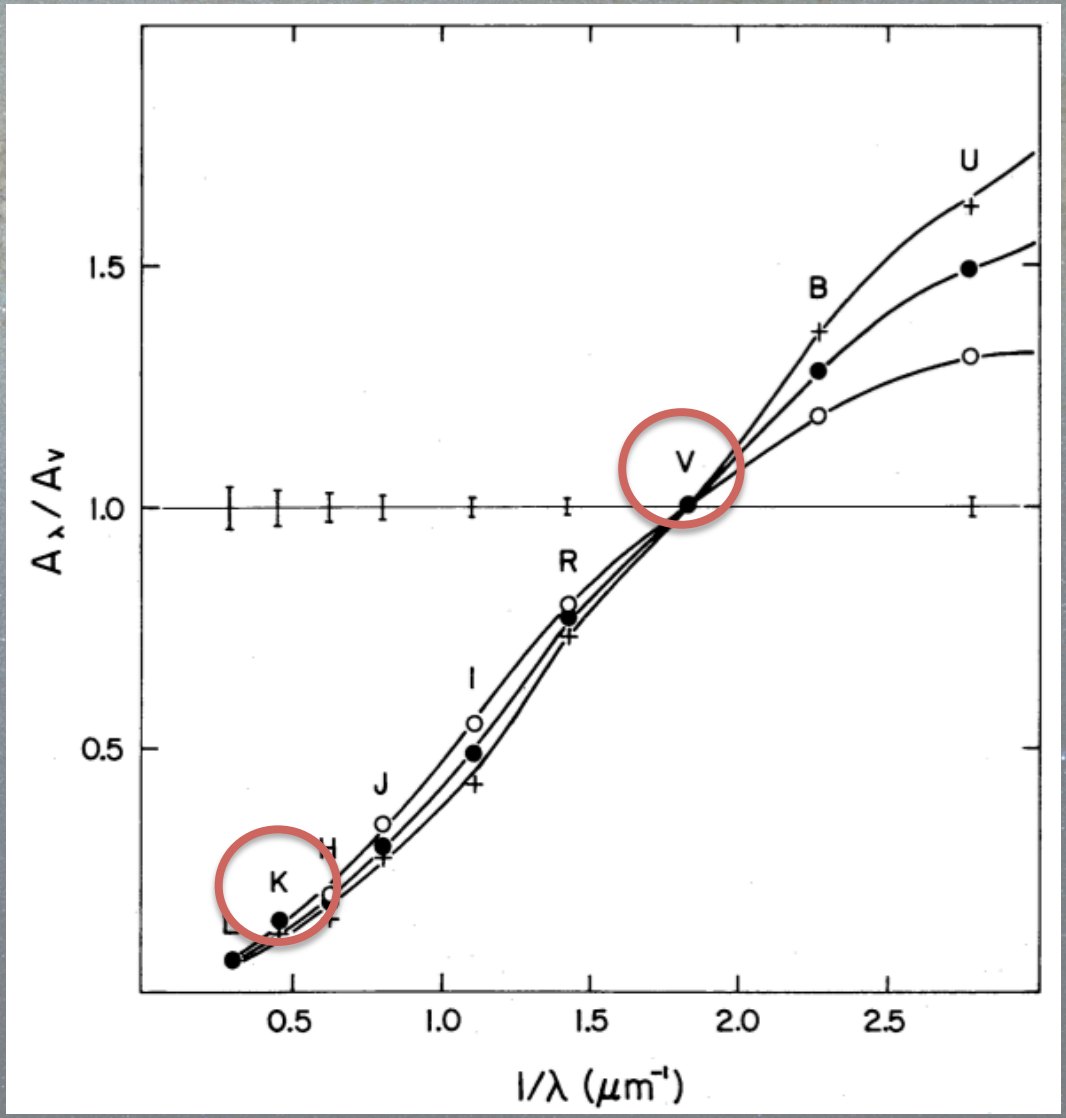
Optical (V) v/s near-IR (K)

Catelan et al. 2004

Introduction

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

Lower interstellar extinction

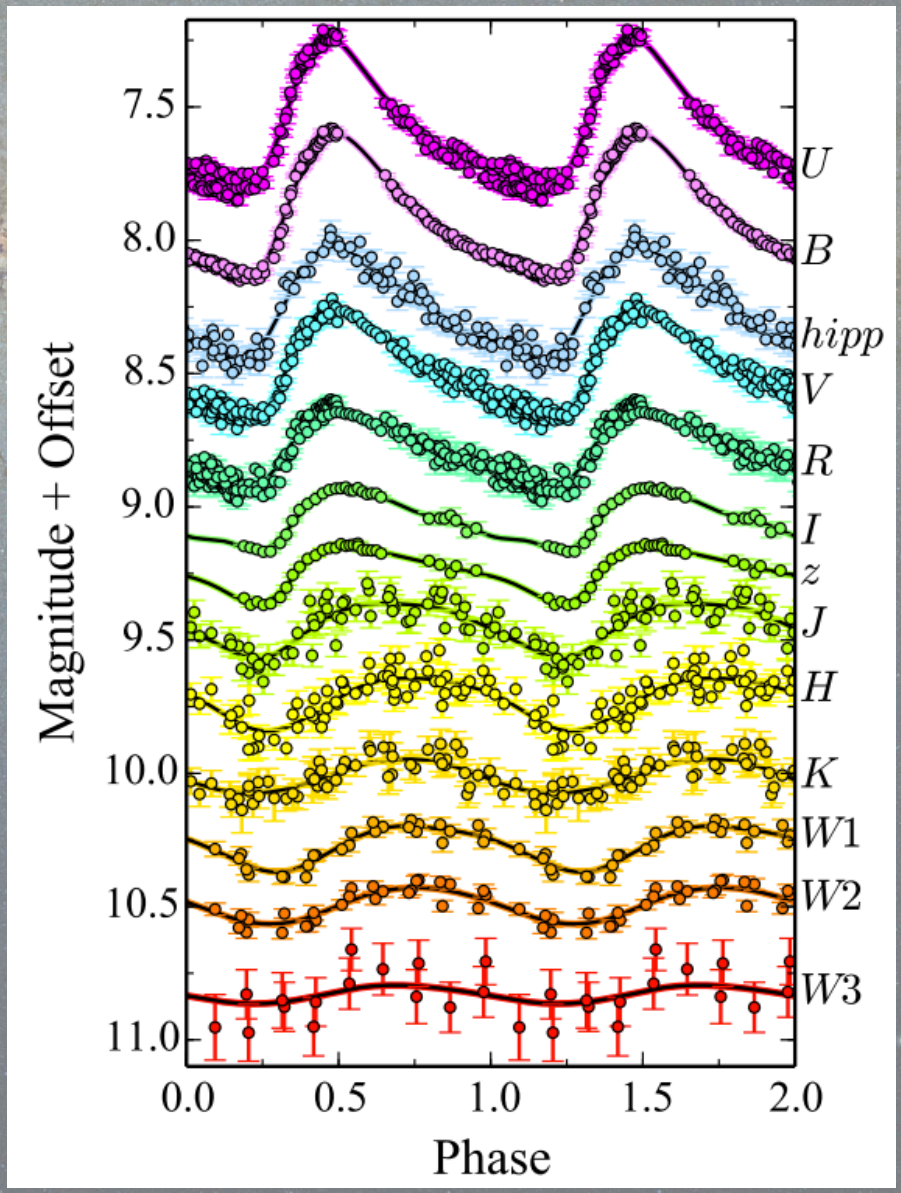


Comparison between the optical/near-IR extinction laws. (Cardelli et al. 1989)

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 ≈ 0.6 days; Klein et al. 2014)


© ESO/VVV Survey/I. Toledo/D. Minniti
Full moon size

Motivation

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

★ VVV uses **near-IR filters**(ZYJHK$_s$) to observe ~300 deg^2 in the Galactic bulge

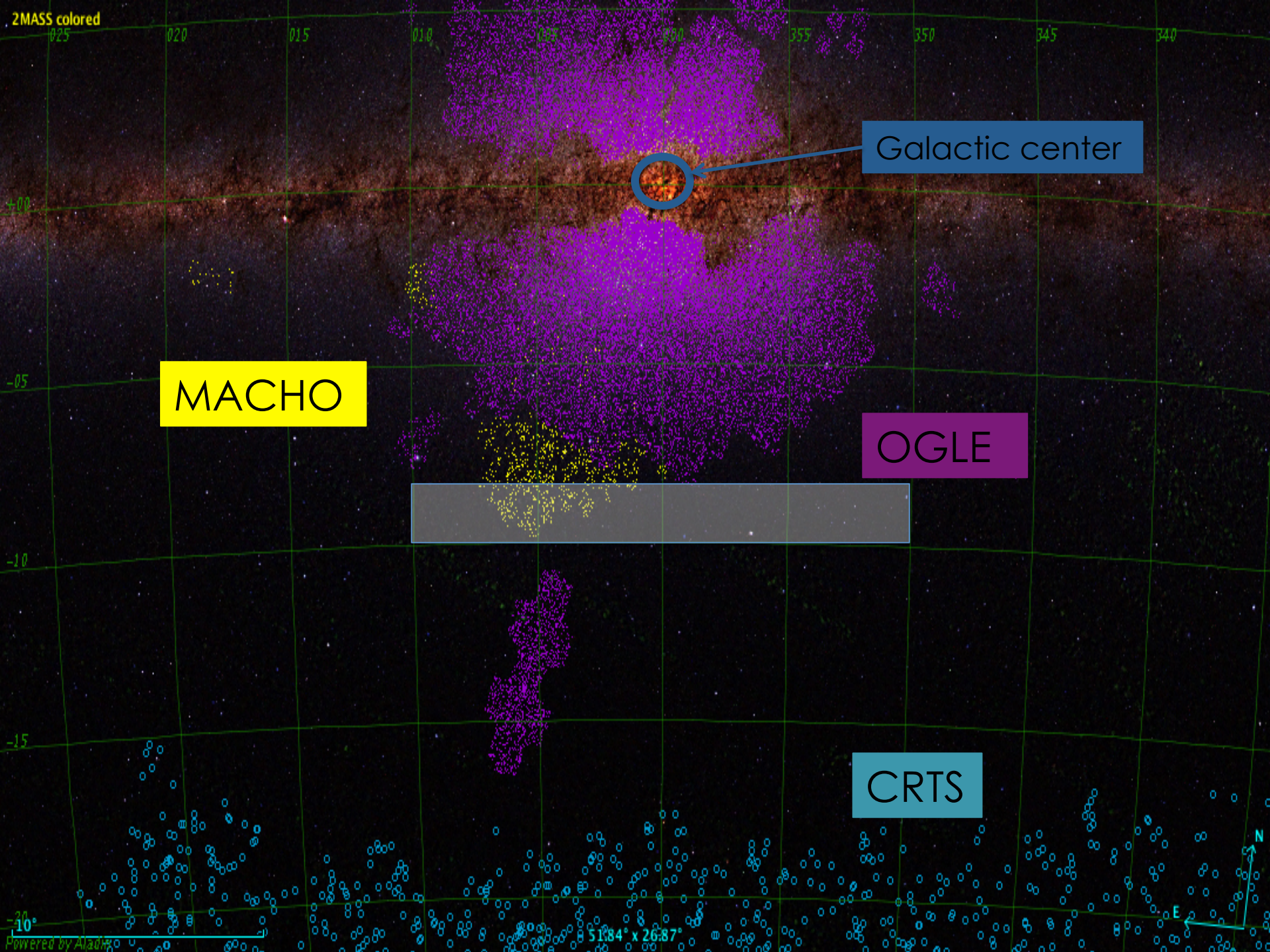
- ★ZYJH one epoch at the first year of operation
- ★K$_s$-band variability survey: ~100 epochs

★ "Outer bulge" avoided by other variability surveys:

- ★OGLE, MACHO, EROS
- ★Explore Sgr dSph RR Lyr candidates

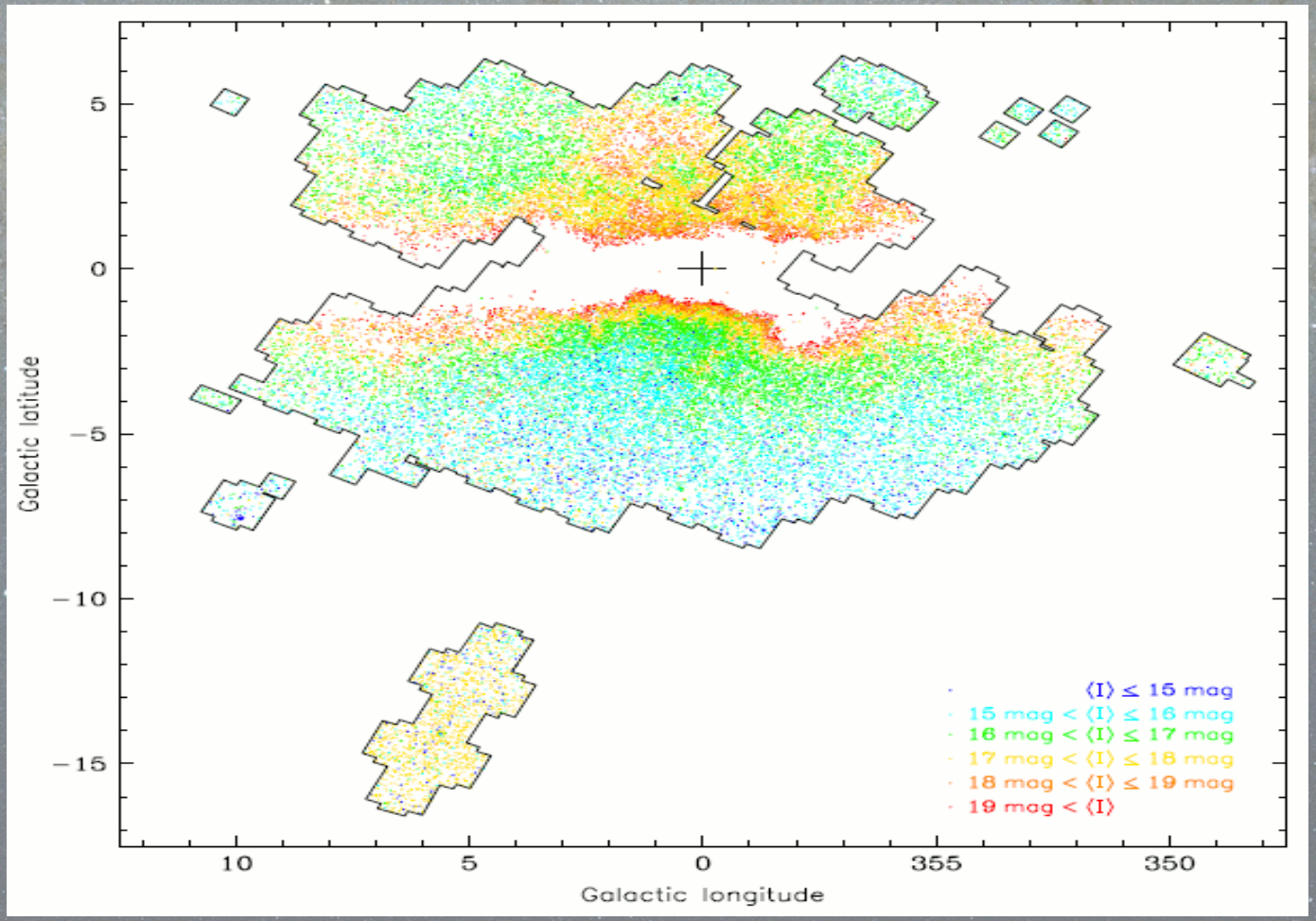
$l \leq -8$ deg

M54: (l, b) ~ (5, -14) deg, d ~ 25 kpc


2MASS colored
Galactic center
MACHO
OGLE
CRTS
N
E
10°
51.84° x 26.87°
Powered by Aladin

Motivation

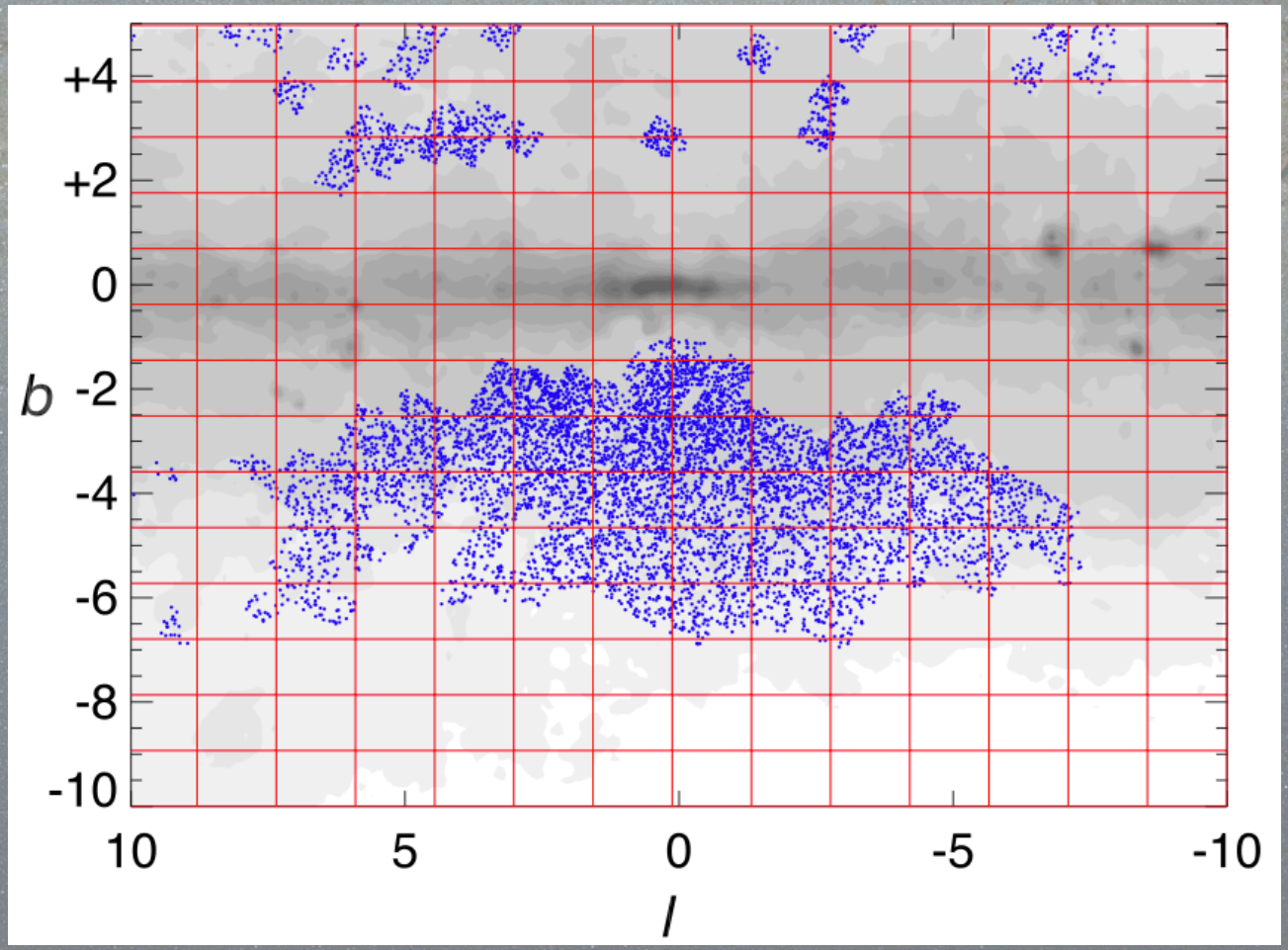
OGLE IV – 36257 bulge + 2000 Sgr dSph RR Lyr stars



Soszyński et al. 2014 + Pietrukowicz et al. 2014

Motivation

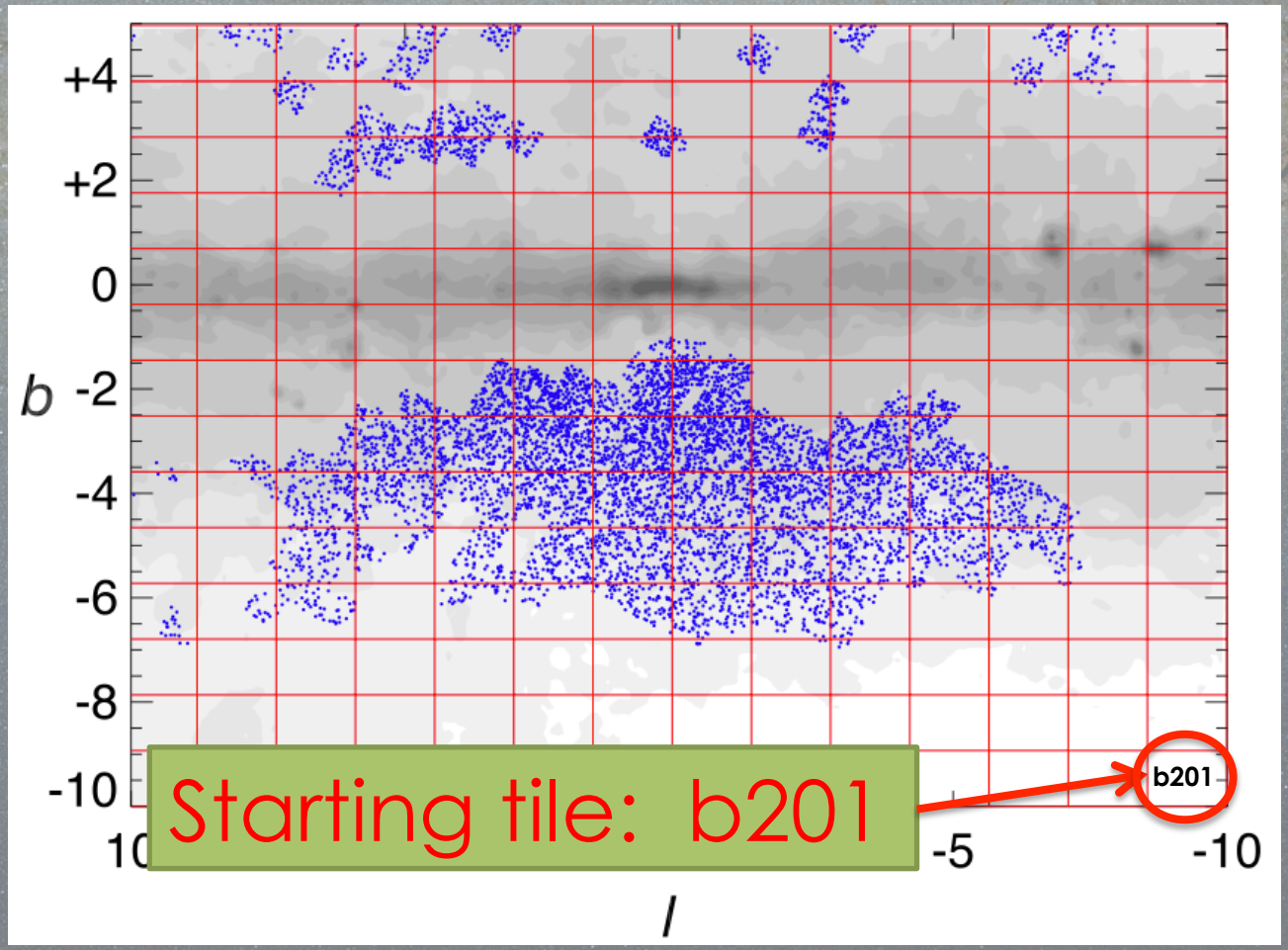
VVV – 7663 bulge RR Lyr stars



Dékány et al. 2013

Motivation

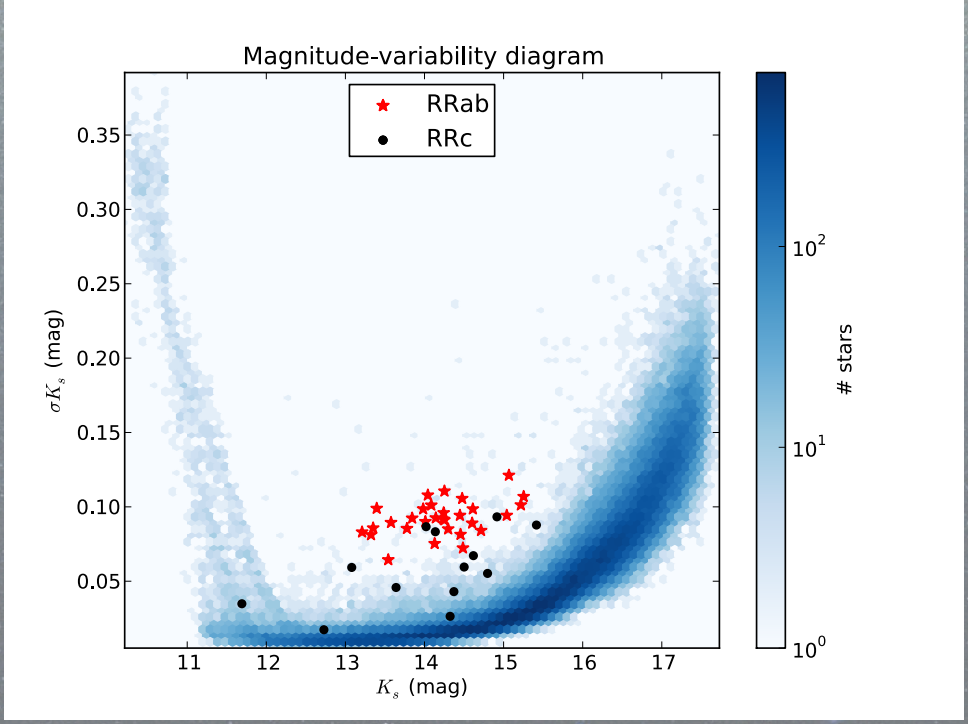
VVV – 7663 bulge RR Lyr stars



Dékány et al. 2013

Analysis

- ★ Variable discrimination:
  - ★ RMS – χ^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⋆

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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 $(\ell, b) \sim (-9°, -9°)$, 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 χ^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
extinction toward all the RRab stars in this tile were derived, and distance estimations wer
relation. Despite the limited amount of RR Lyrae stars studied, our results
around ~ 8.1 and ~ 8.5 kpc. for either the Cardelli or Nishiyama
Nevertheless, a larger area must be analyzed to definiti

Key words. Galaxy: bulge – Galaxy:

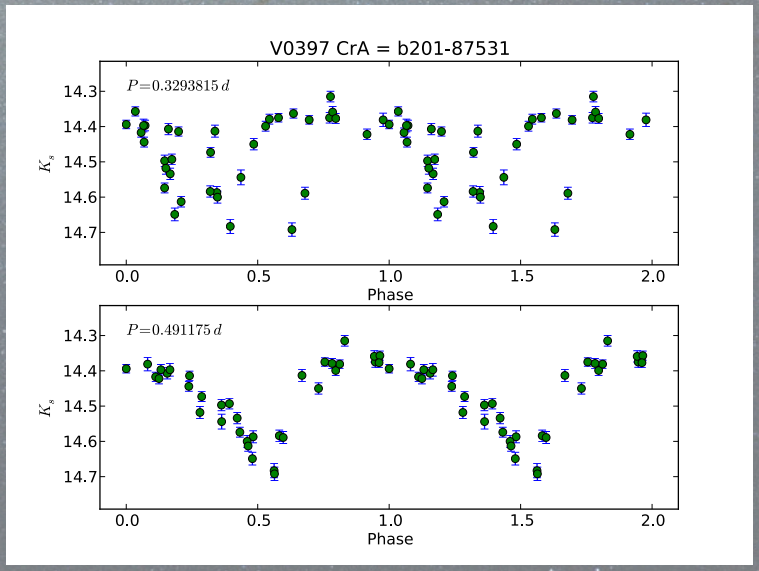
Published !!

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

"Bulge RR Lyrae stars in the tile b201"

- ★Optical works found 10 RR Lyr in the field
- ★39 RR Lyr stars: 27 ab- and 12 c-type
- ★New periods for MO, V397 and V467 CrA
- ★$\Delta P = P_{Lit} - P_{VVV} \sim 10^{-3}$ days

GCVS	P_{Lit} (days)	P_{VVV} (days)	d (")
MO CrA	---	0.657005	0.475
V397 CrA	0.3293815	0.491175	0.771
V463 CrA	0.6040585	0.604052	0.139
V467 CrA	0.4480160	0.359989	1.931
V475 CrA	0.5119430	0.511933	17.41
V482 CrA	0.5417140	0.541714	2.725
V483 CrA	0.4850490	0.485059	0.105
V486 CrA	0.4601694	0.460161	0.573
V493 CrA	0.5194291	0.519429	31.26



★ Completed:

- ☑ *b201*

★ To analyze:

- ☐ 195 bulge tiles (b202 – b396)

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☑ *b201*

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☐ 195 bulge tiles (b202 – b396)

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

η Sgr
K_s = -1.5

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:

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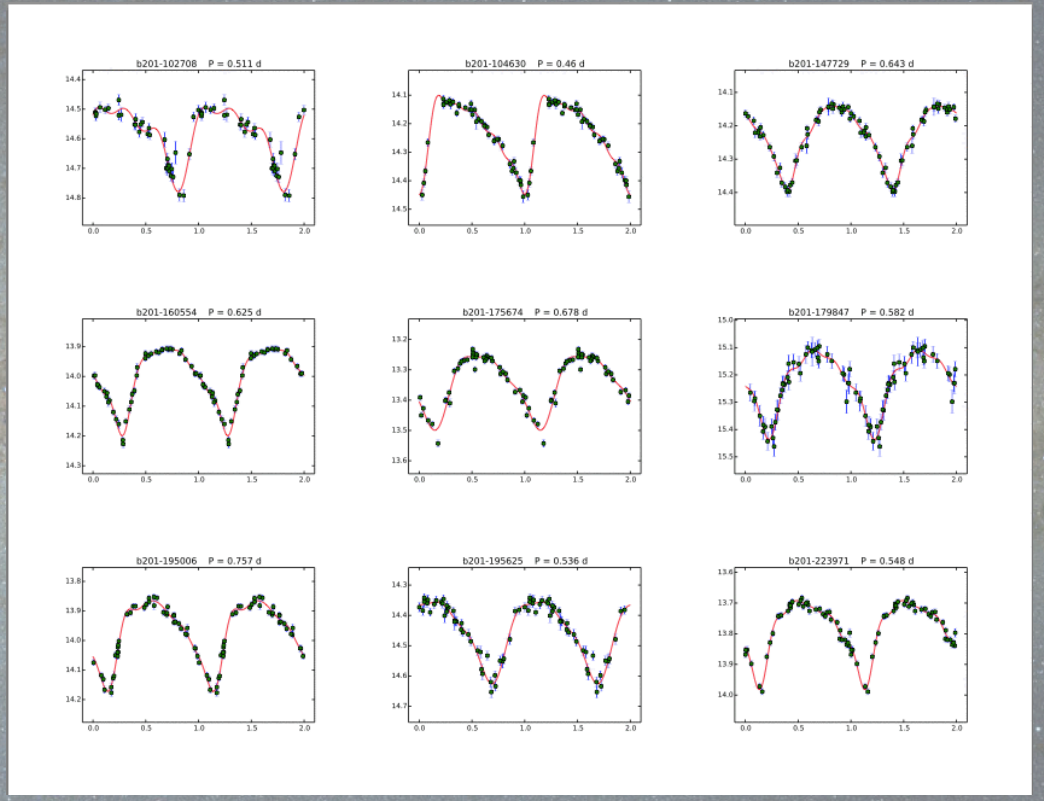

η Sgr
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b228 ✓	b227 ✓	b226 ✓	b225 ✓	b224 ✓	b223 ✓	b222 ✓	b221 ✓	b220 ✓	b219 ✓	b218 ✓	b217 ✓	b216 ✓	b215 ✓
b214 ✓	b213 ✓	b212 ✓	b211 ✓	b210 ✓	b209 ✓	b208 ✓	b207 ✓	b206 ✓	b205 ✓	b204 ✓	b203 ✓	b202 ✓	b201 ✓

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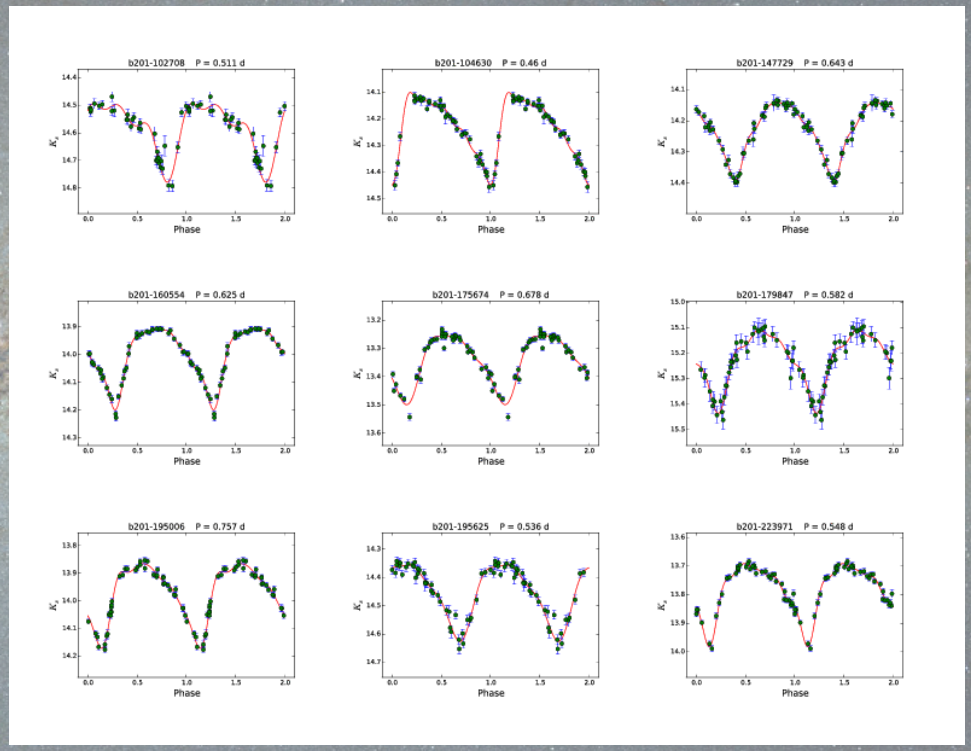
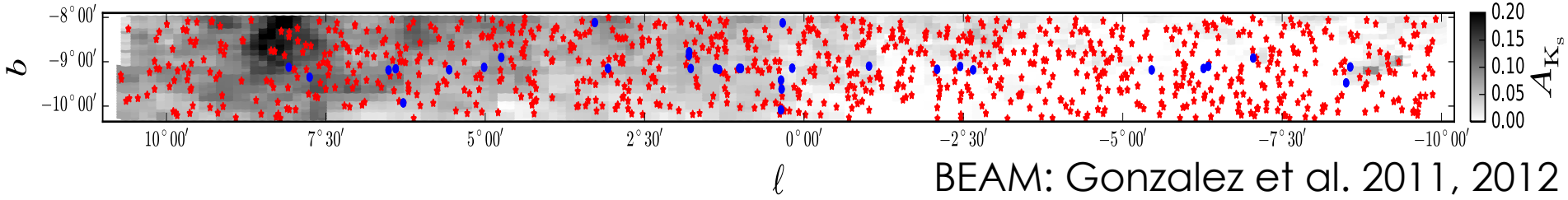
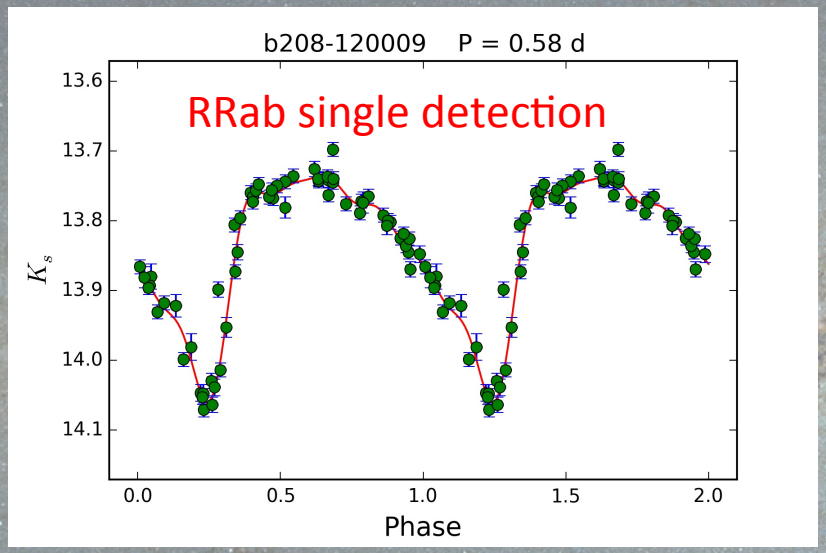


Colors { RRab double detection
RRab single detection



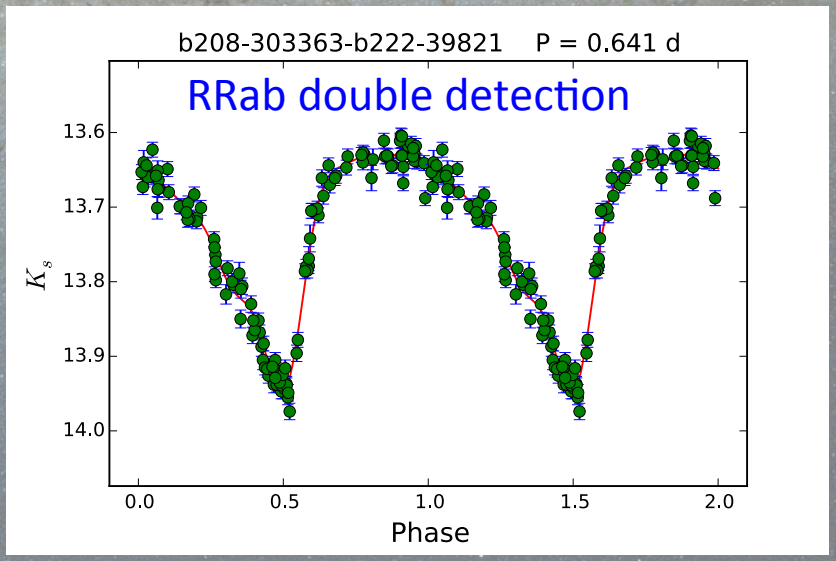
BEAM: Gonzalez et al. 2011, 2012



Tiling pattern

~7% of overlapping areas
(Saito et al. 2012)

epochs x 2



Colors { RRab double detection
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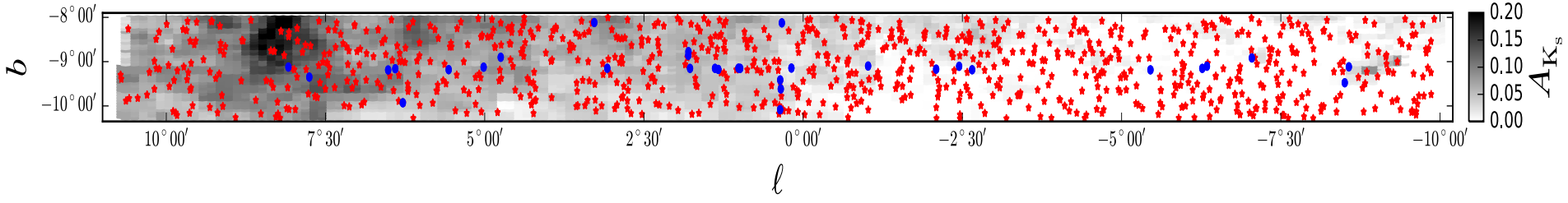
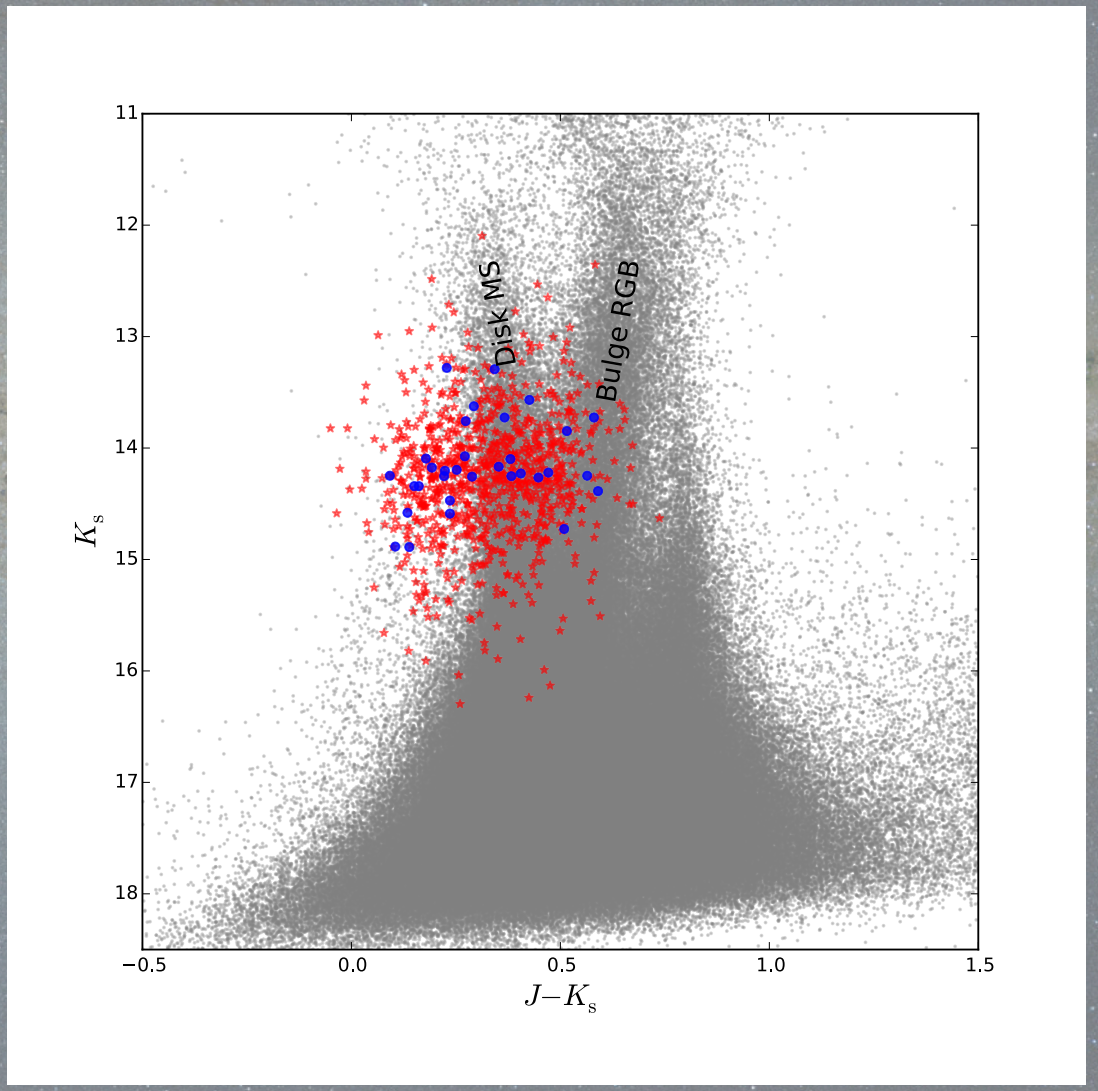
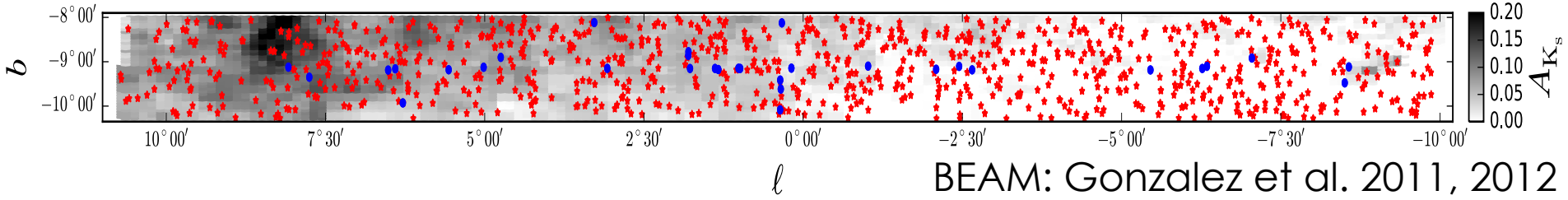


Colors { RRab double detection
RRab single detection

J x (J-K_s) color-magnitude diagram of the RR Lyrae found and the tile *b201* as a background.

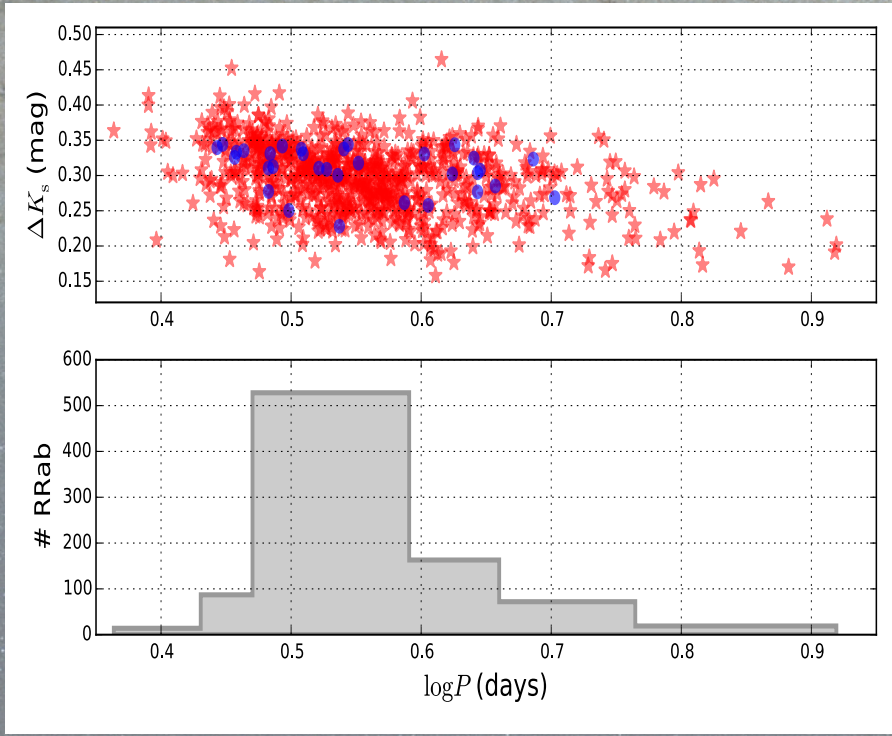




BEAM: Gonzalez et al. 2011, 2012

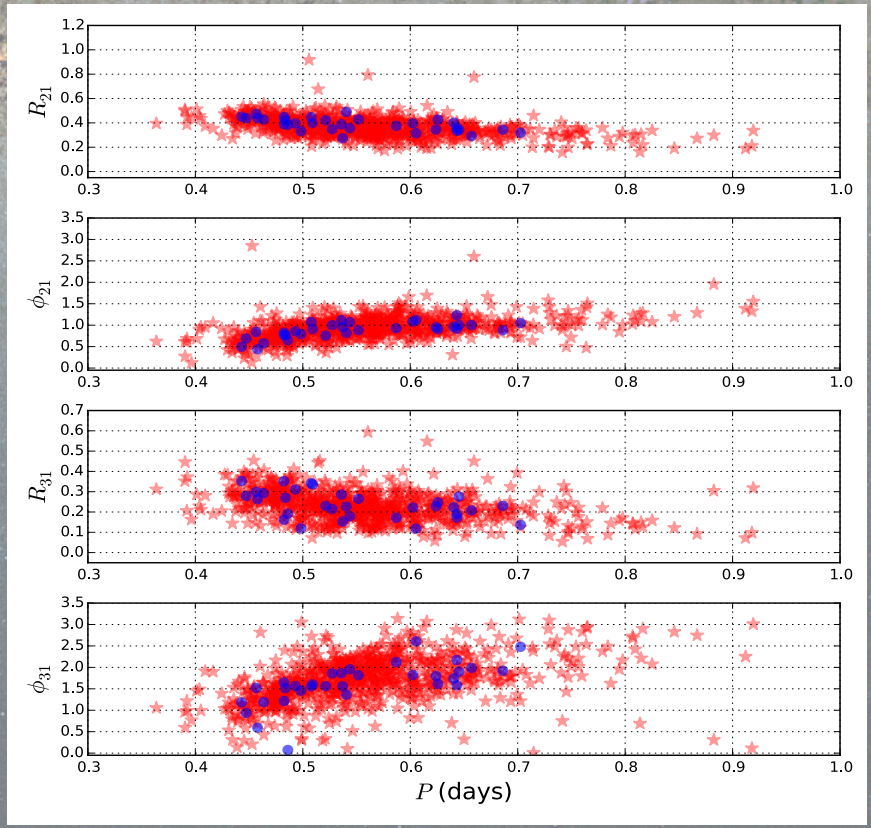
Results

In 28 tiles, 883 RRab stars were found.



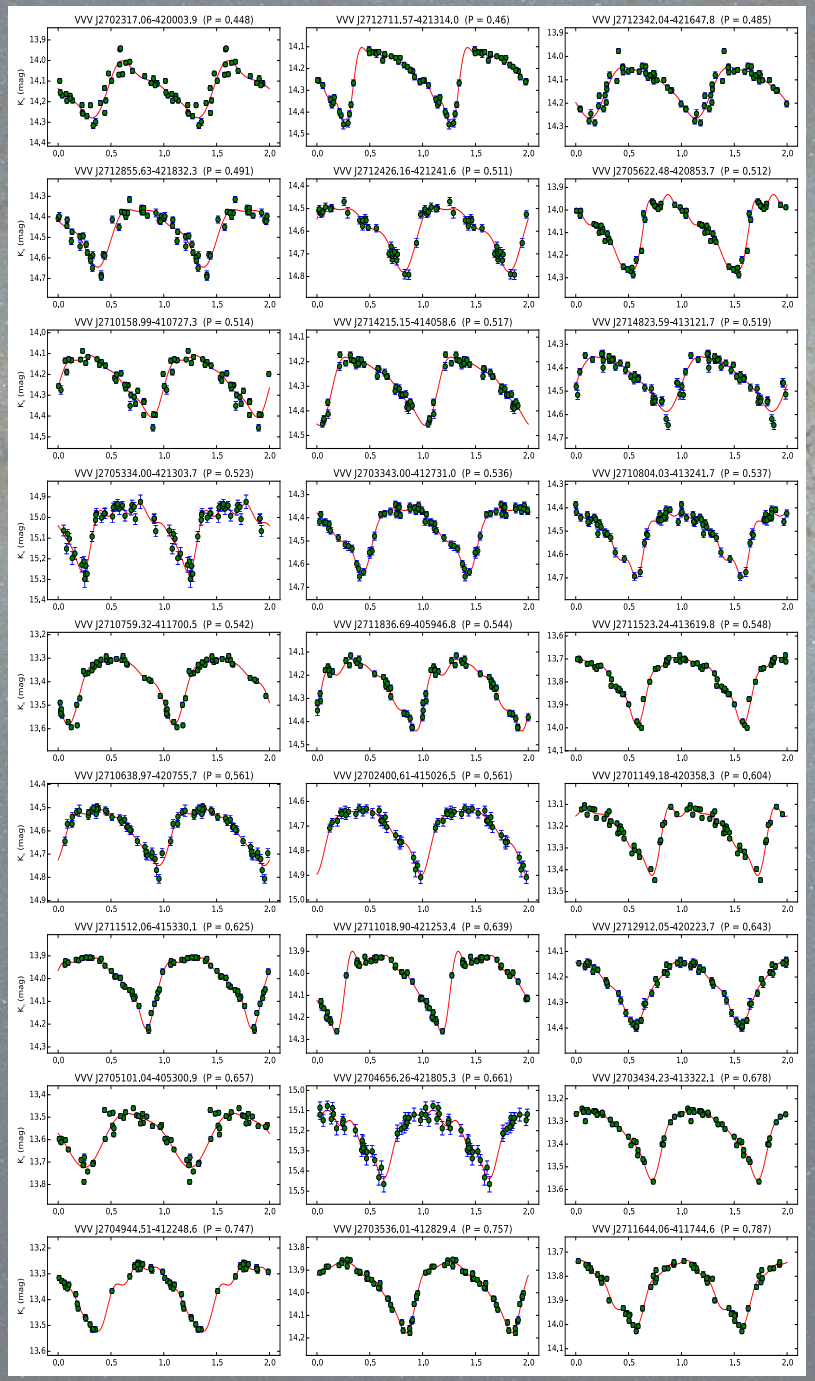
Bailey diagram + Period histogram

(astroML Bayesian blocks;
Scargle et al. 2013, Vanderplas et al. 2012)



Coefficients of the
Fourier decomposition

Kovacs & Kupi (2007)



+ $E(J-K_s)$ ⟷ $(J-K_s) - (J-K_s)_0$

+ [Fe/H] ⟷ OGLE [Fe/H]~ -1

+ A_{K_s} ⟷ $0.698\ E(J-K_s)$
Cardelli et al. (1989)

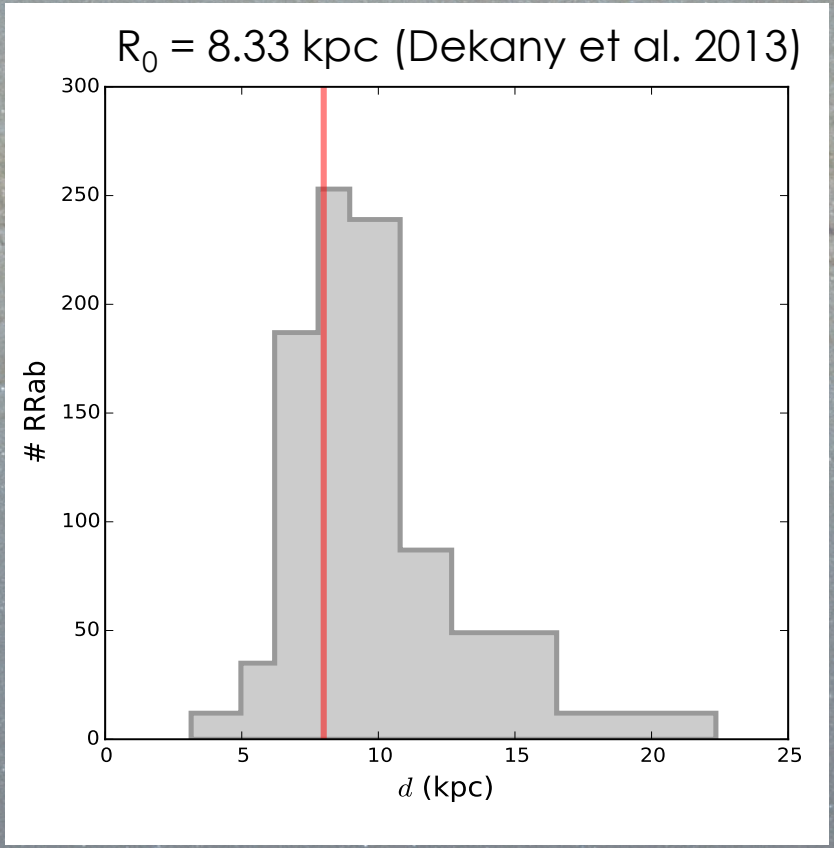
+ P-L Relation ⟷ Catelan et al. (2004)
Alonso-García et al. (2015)

=

DISTANCES

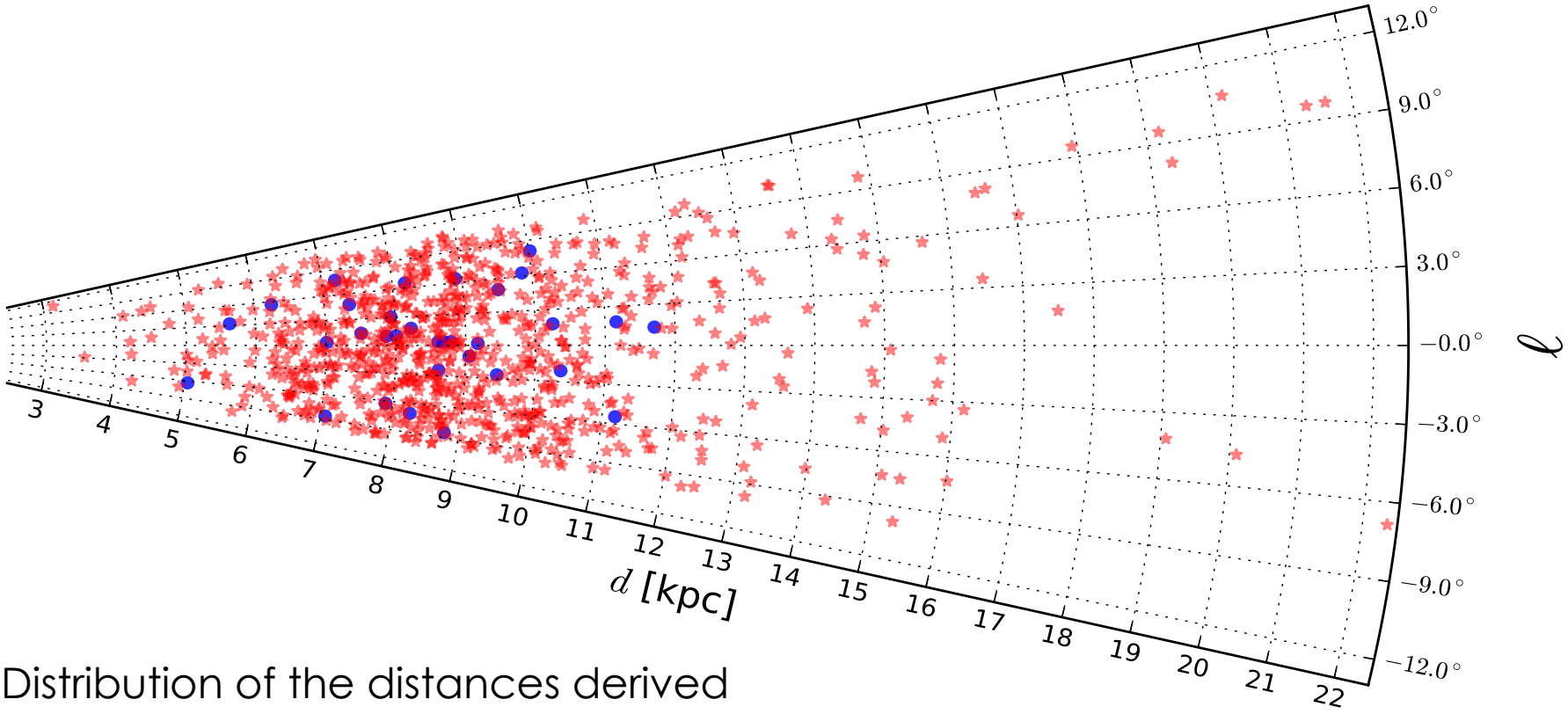
$$\log d = 1 + 0.2(K_{s,0} - M_{K_s})$$

Results



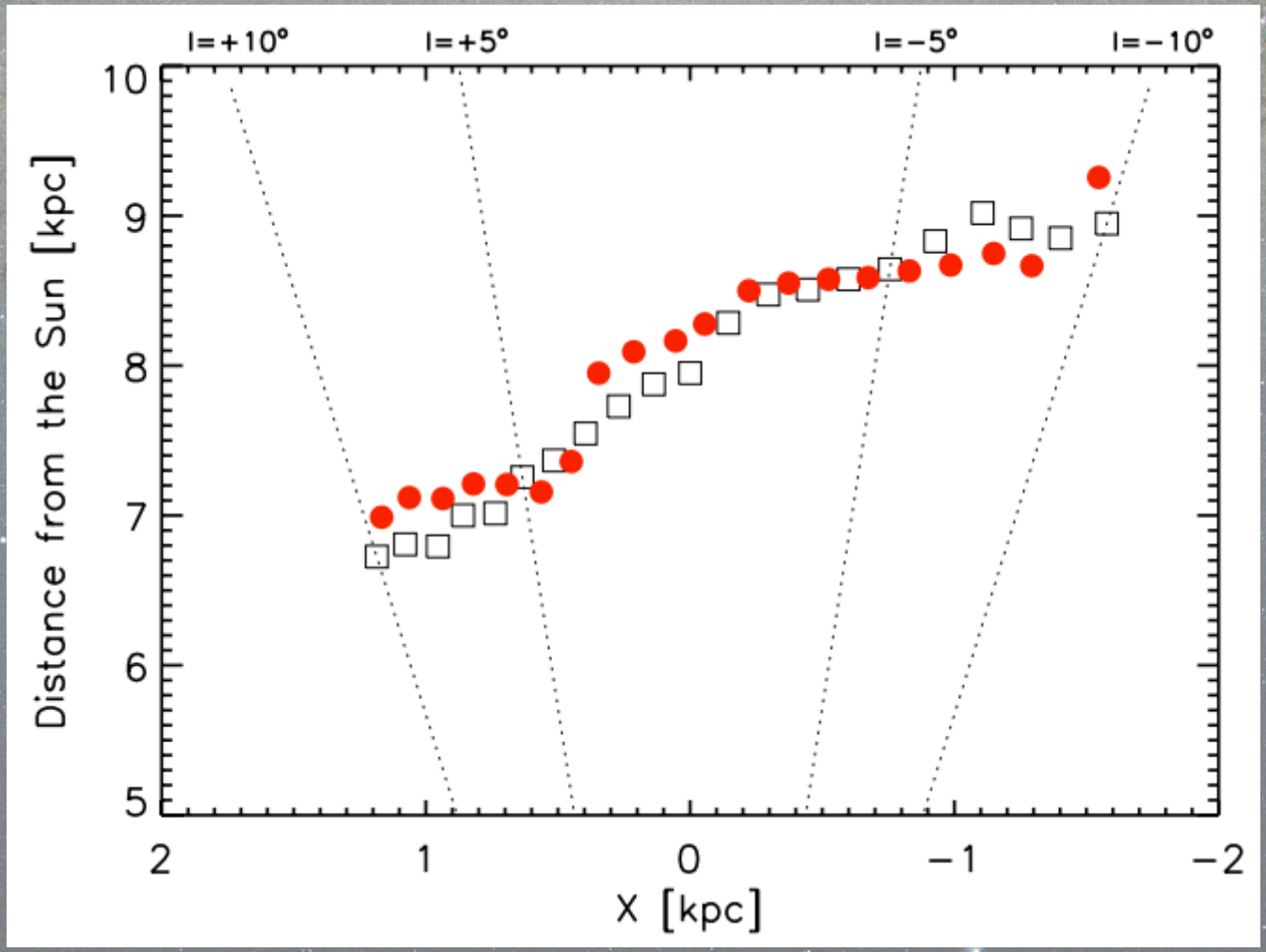
Distribution of the distances derived for the RR Lyrae stars in the complete *outer bulge*.

Results



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

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



Gonzalez et al. 2012

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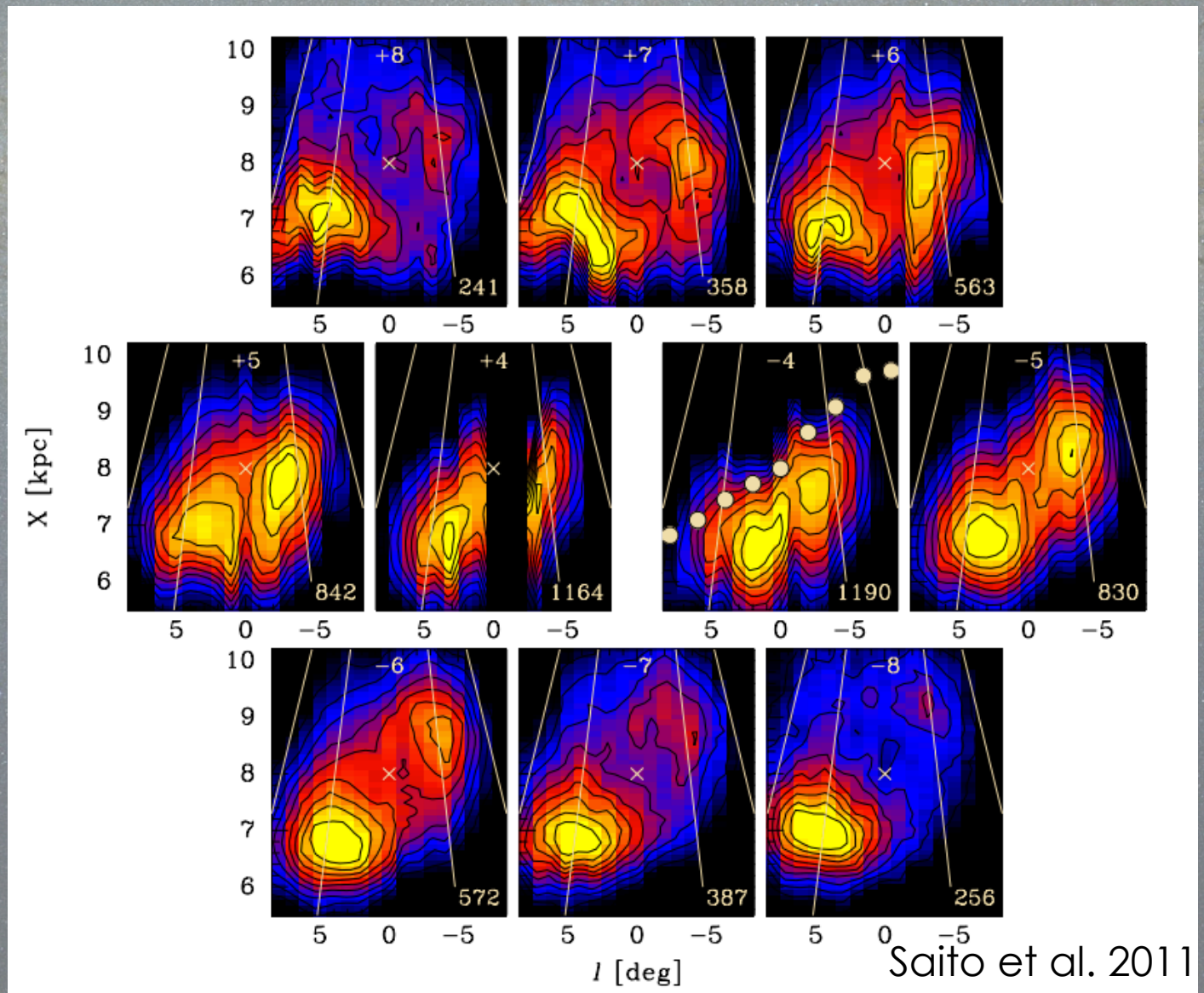

Saito et al. 2011

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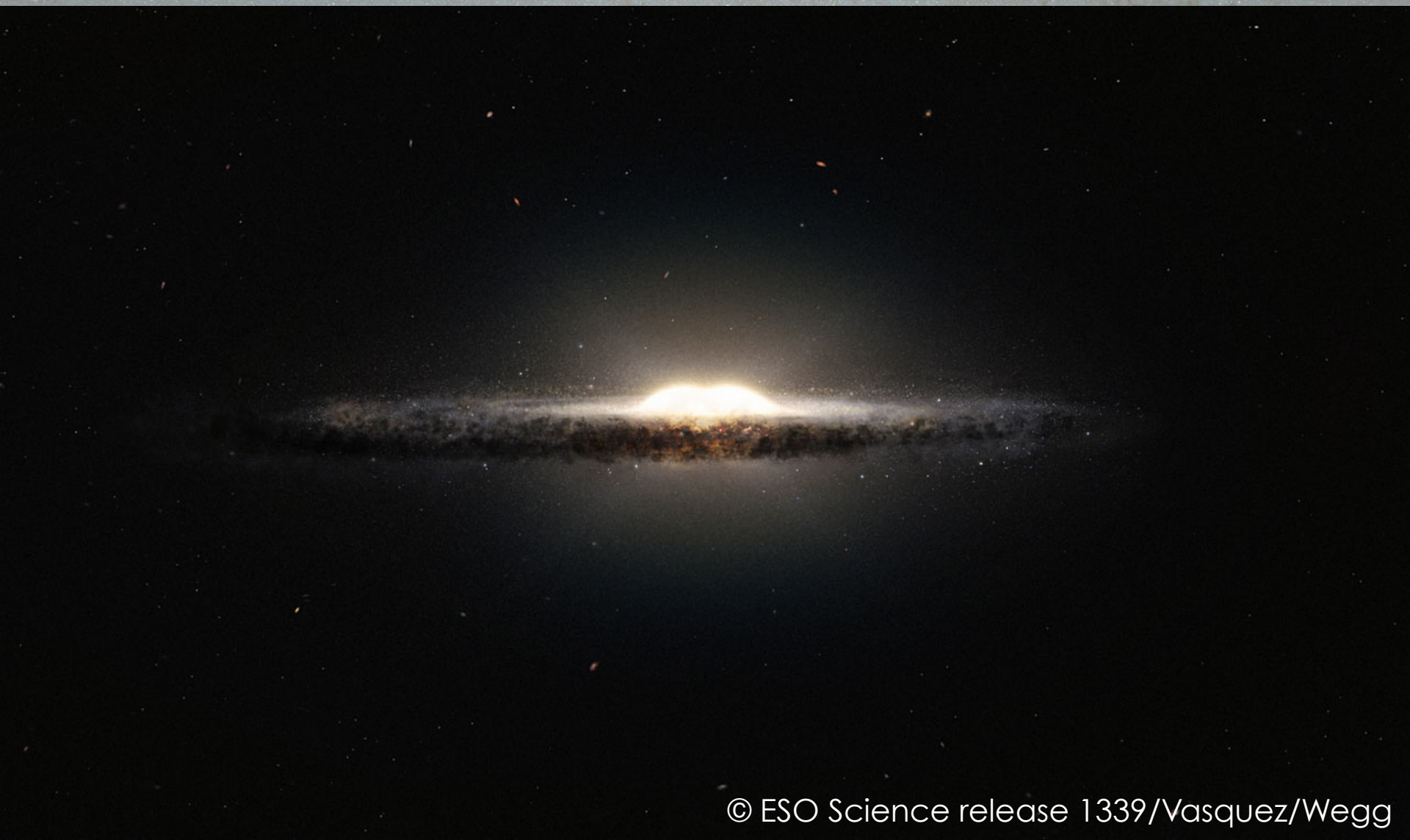
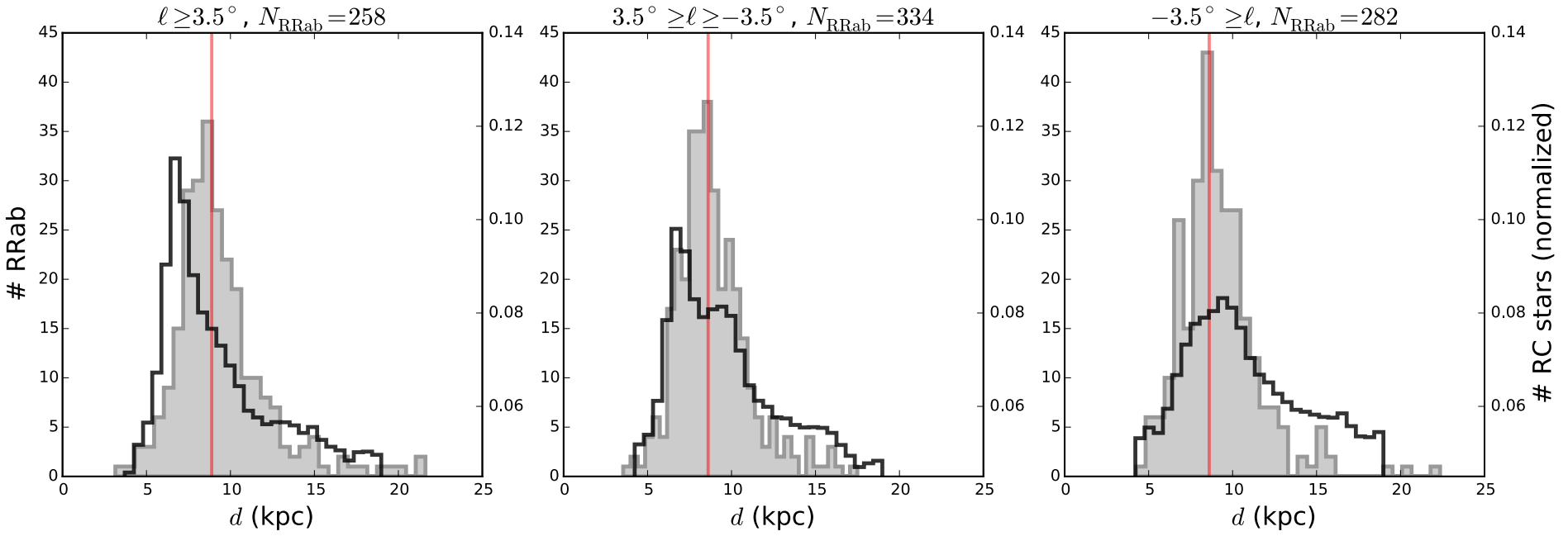
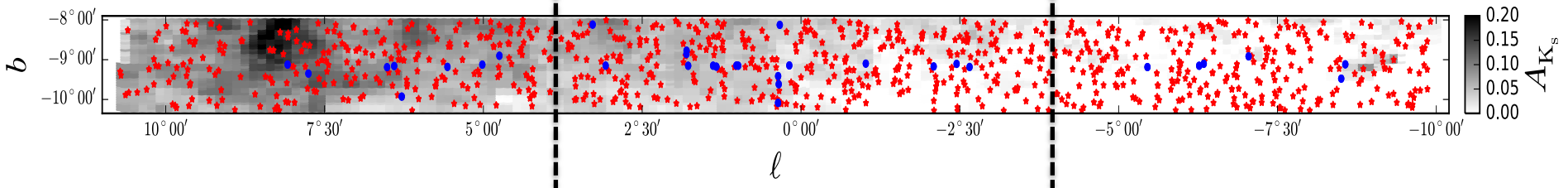


Results

RR Lyrae stars

Red clump stars

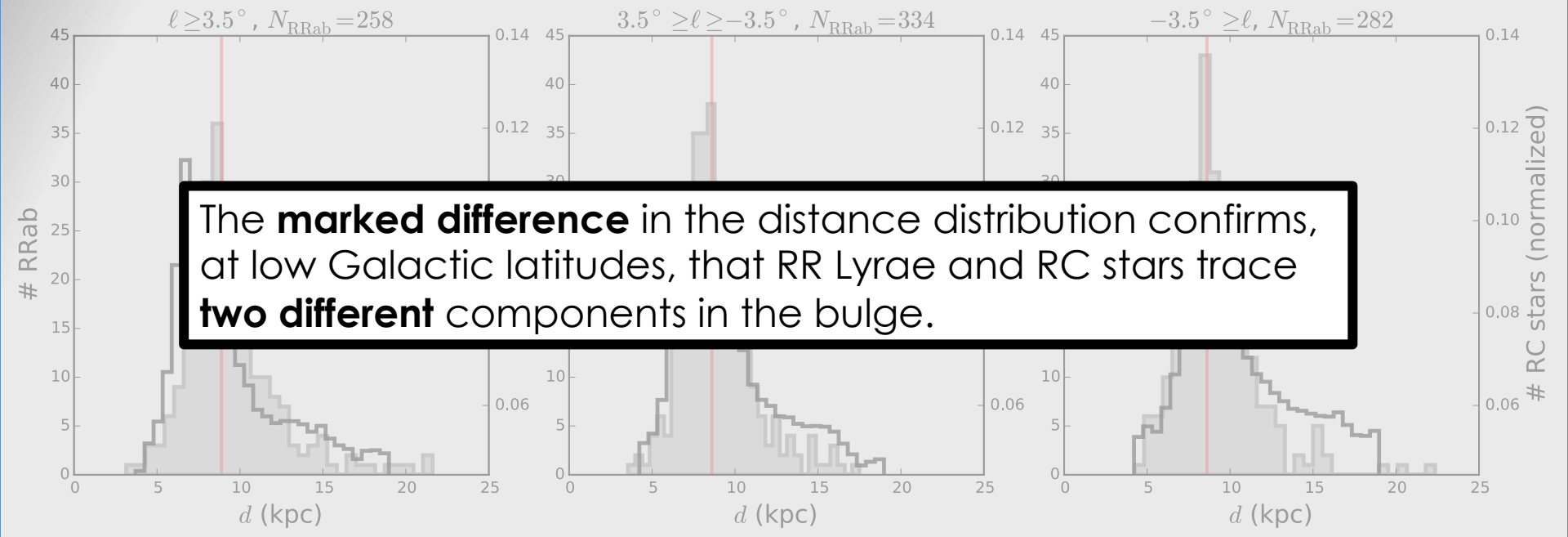




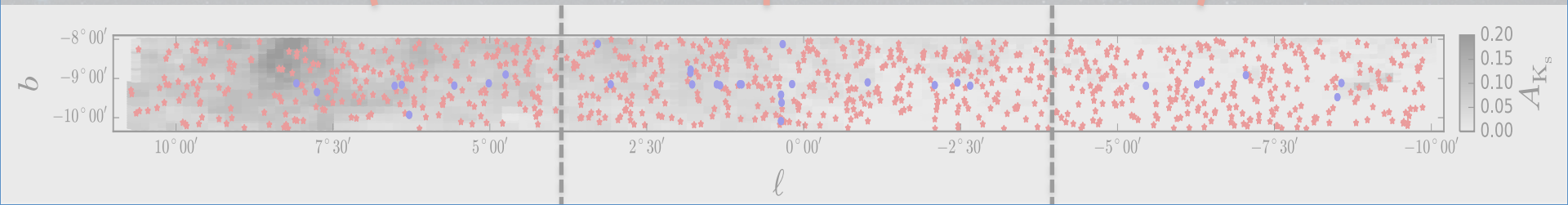
Results

RR Lyrae stars

Red clump stars



The **marked difference** in the distance distribution confirms, at low Galactic latitudes, that RR Lyrae and RC stars trace **two different** components in the bulge.



Summary & Future work

★ VVV is mapping the 3D structure of the Galaxy through RR Lyrae stars.

★ Reddening and distance were derived for RRab stars in the *outer bulge*.

★ A total of 883 RRab stars have been detected in 28 tiles of the outer bulge.

{ Periods
Amplitudes
Fourier Coeff.
Mean mags.
Distances }

★ RR Lyrae stars trace a centrally concentrated distribution, different to the one traced by red clump stars known to follow a bar (x-shape)

Thanks for your attention !!