Discovering Distant RR Lyrae Stars in the Milky Way Halo with Sparsely Sampled Photometry Data

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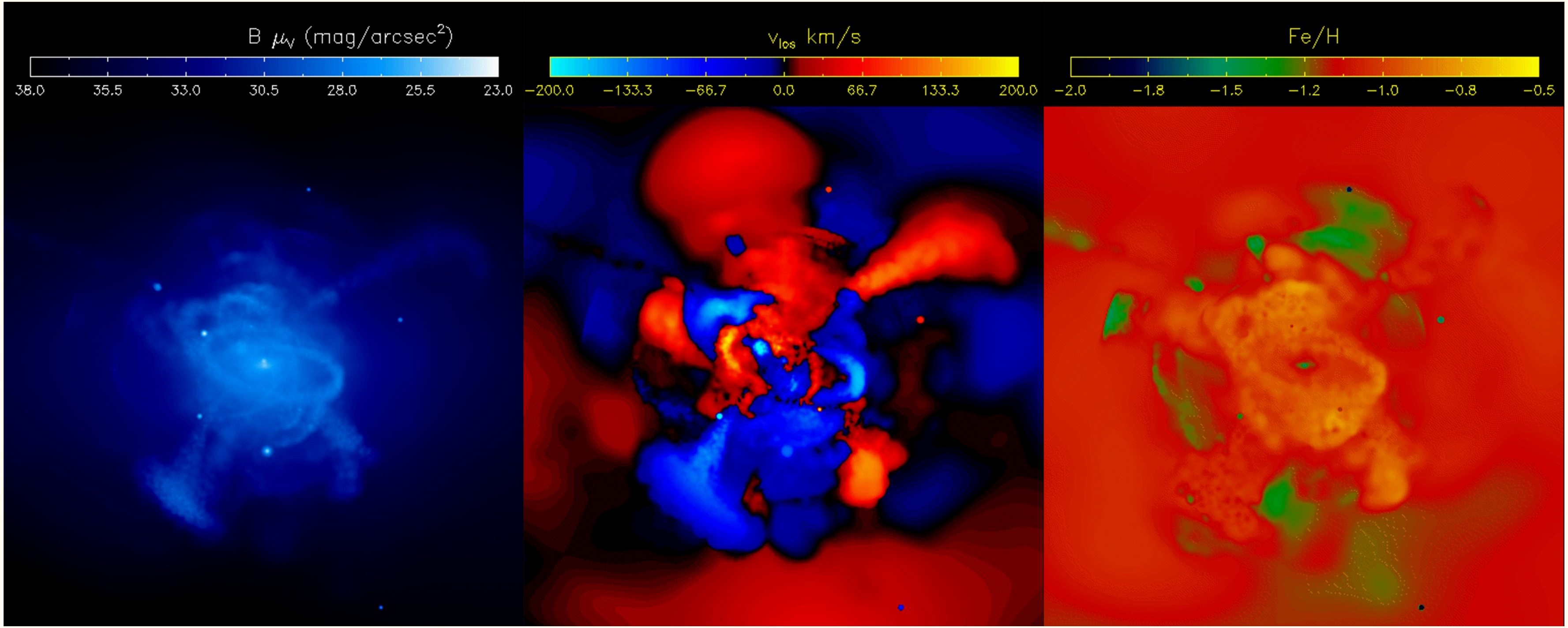
The Next Generation Virgo Cluster Survey

The NGVS as it would appear in the sky
Photo Jean–Charles Cuillandre (2010)

Scientific Motivation

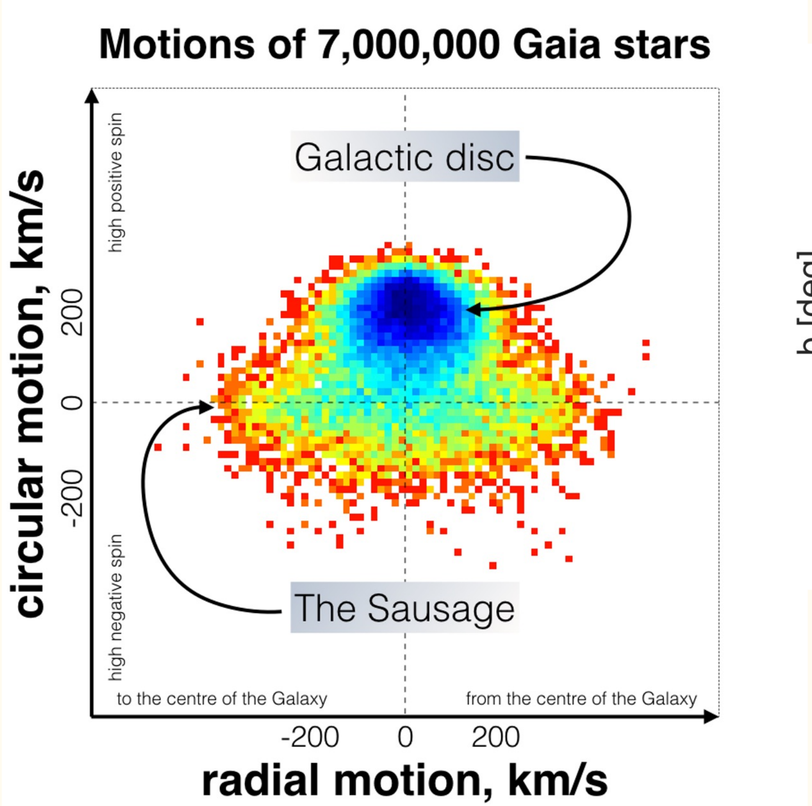
- Why study the distant halo?
- Why choose the RR Lyrae?

Why Stellar Halo?

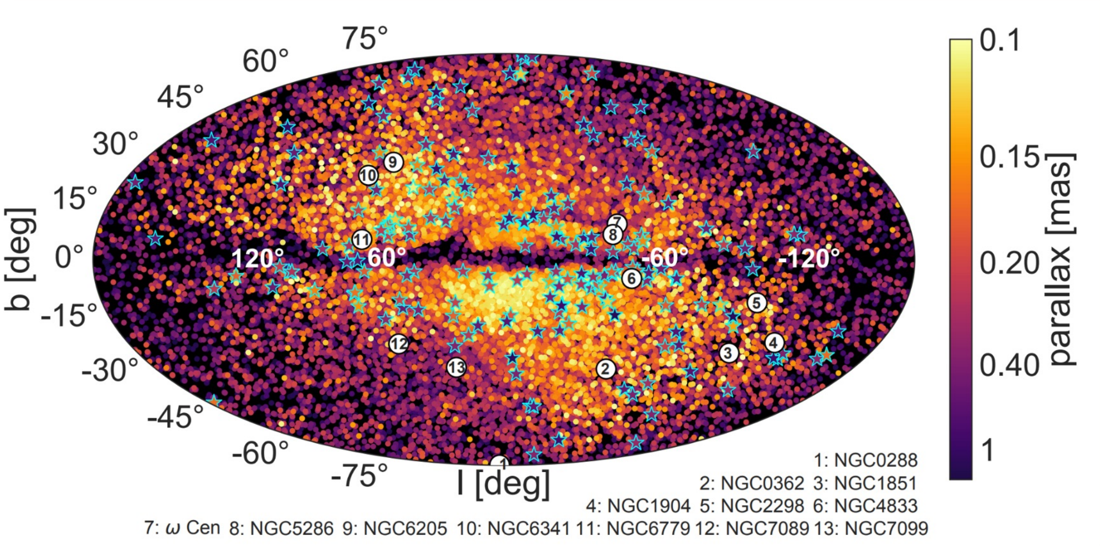


Bullock & Johnston, 2005

“Galaxy Renaissance”



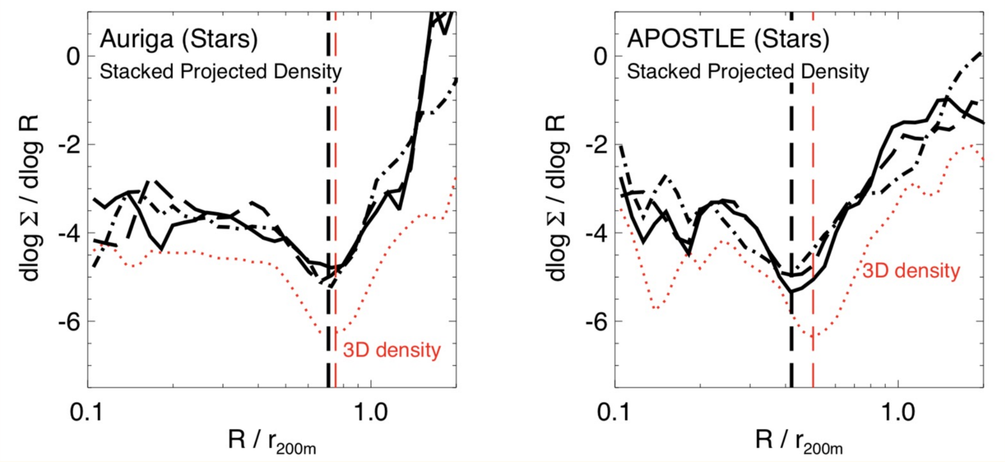
Belokurov et al. 2018



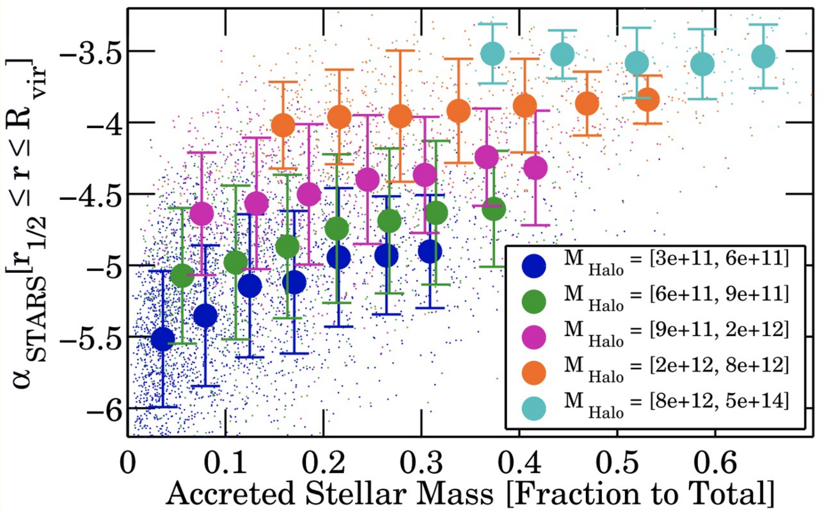
Helmi et al. 2018. Map of tentative stellar members of Gaia sausage.

< 10 kpc. In-situ

MW Halo: yet to be observed……



Deason et al. 2020



Pillepich et al. 2014

Splashback Radius
~ 0.8 R_200m

~ 300 kpc

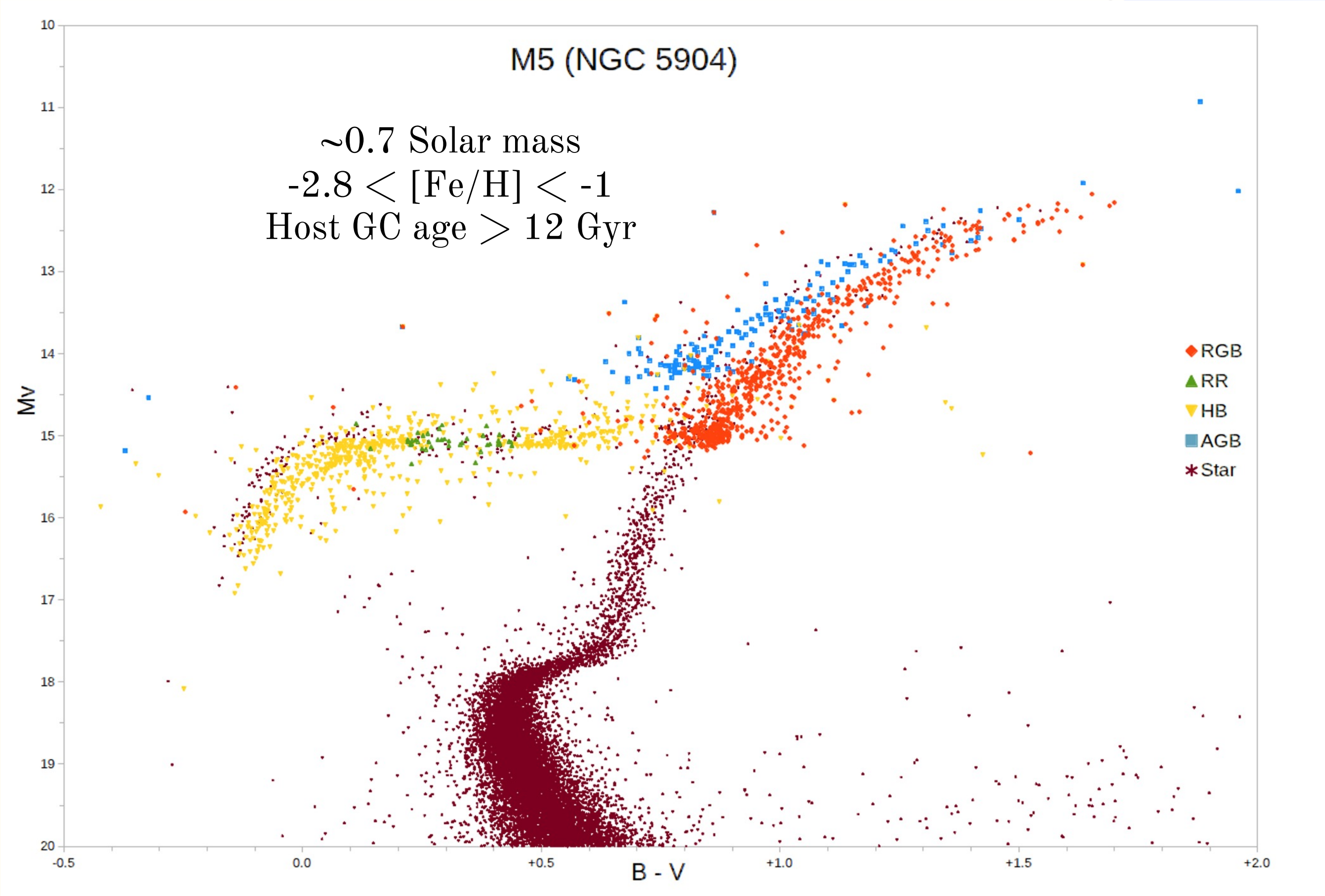
Slope of stellar density profile could serve as a probe of the MW halo mass, accreted mass fraction, and last merger time

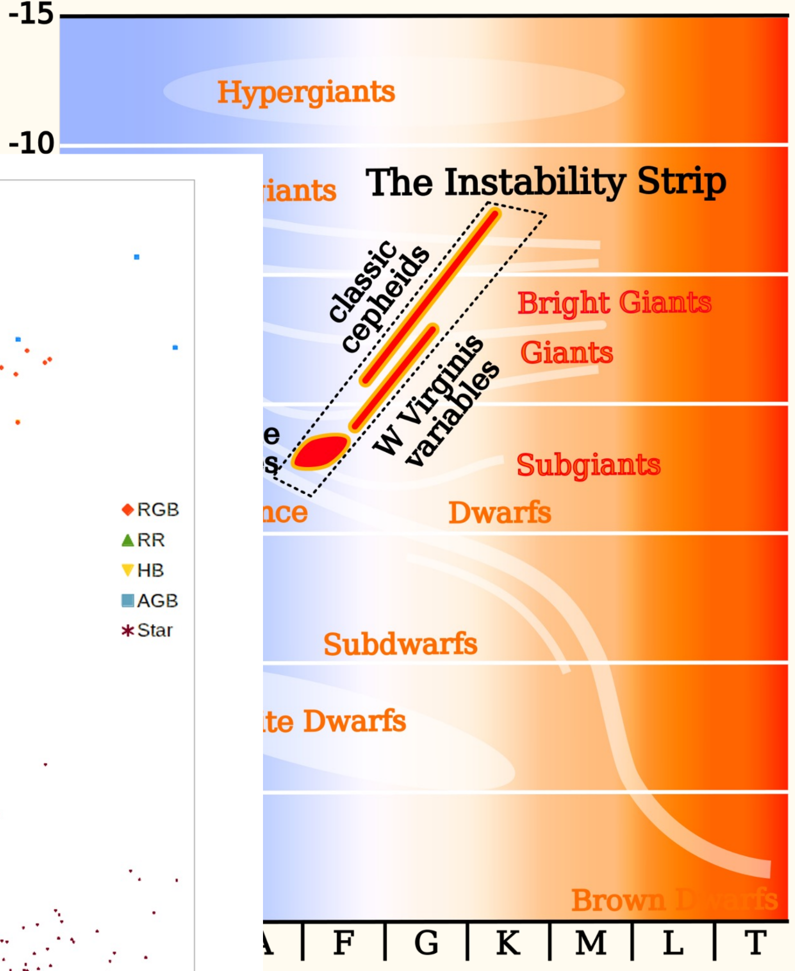
RR Lyrae

~0.7 Solar mass

$-2.8 < [Fe/H] < -1$

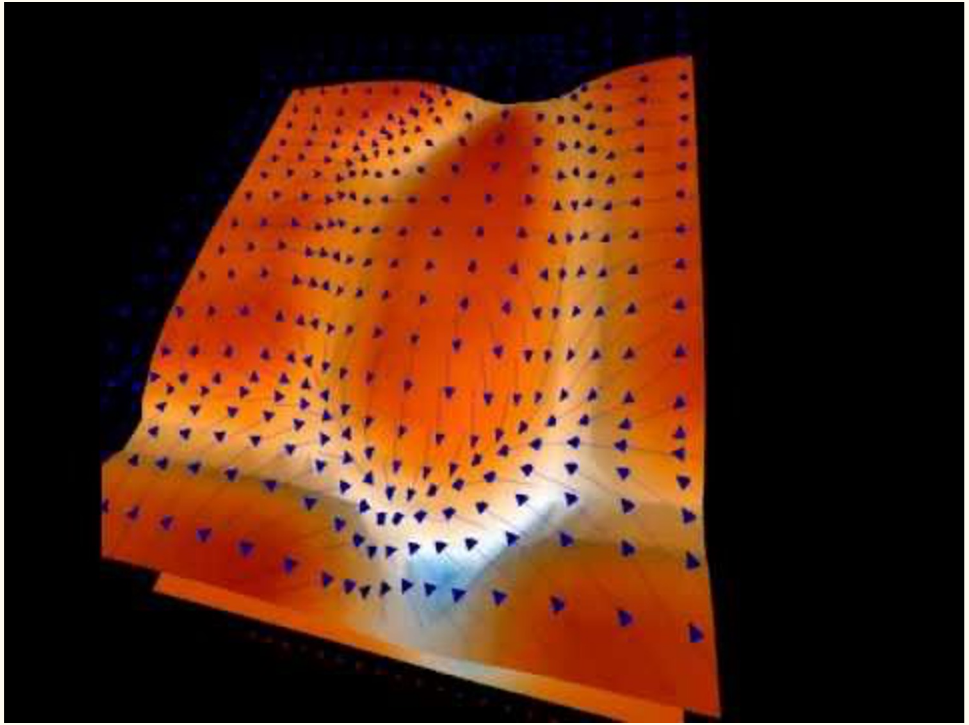
Host GC age > 12 Gyr





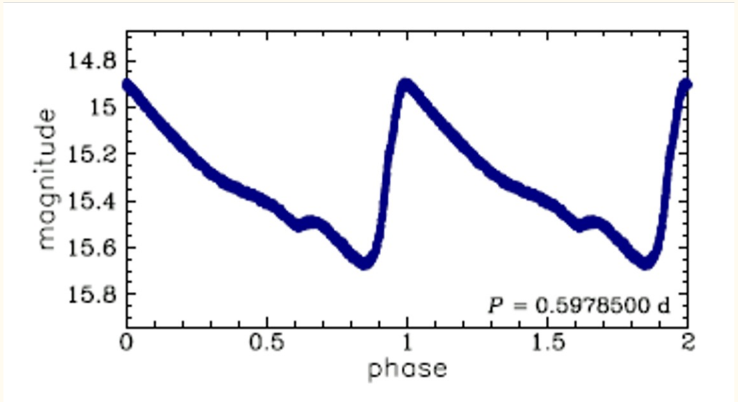
(from aavso.org)

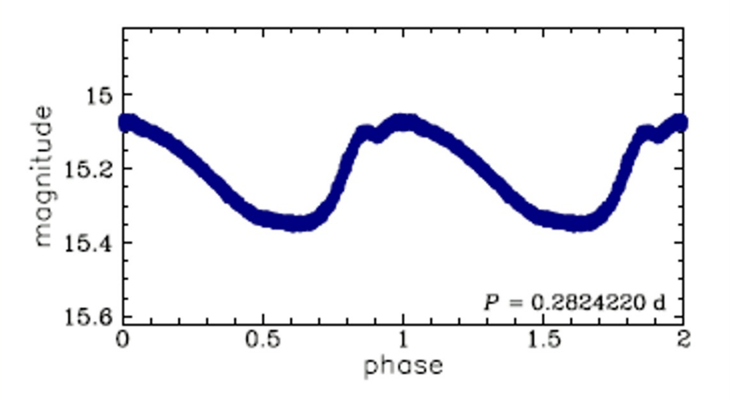
Light Curve Characteristics



RRab pulsation model, showing two temperature isosurfaces at 10,000 K and 30,000 K

Geroux et al. 2012

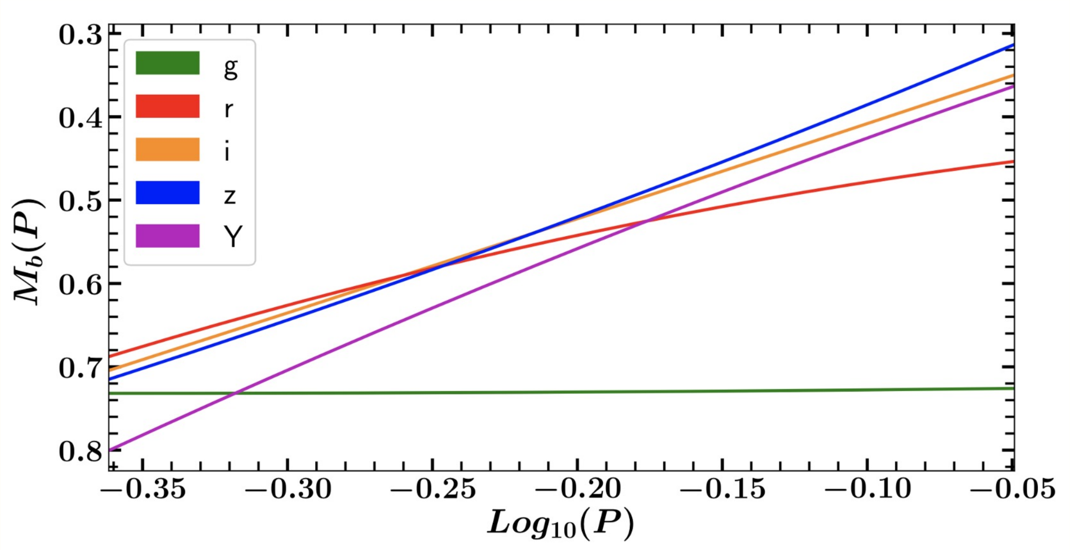




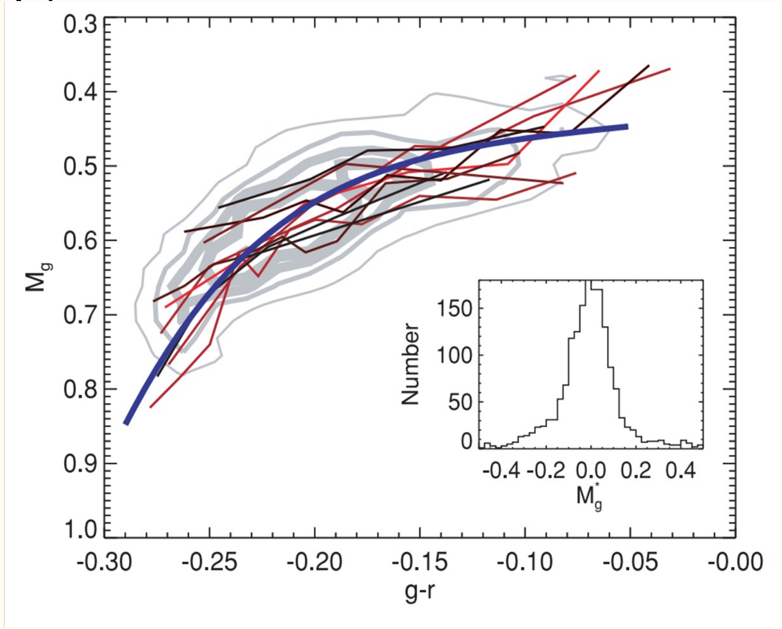
RRab vs RRc, densely sampled light curve from Soszynski et al. 2011

Short period variables, pulsate in specific pattern

Standard Candles (P-L-Z relationship)



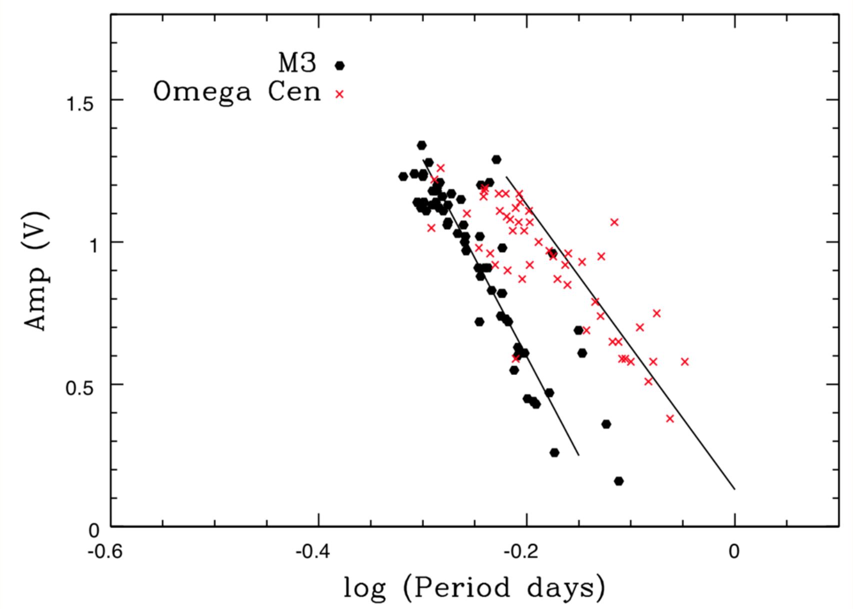
Period-luminosity (PL) relationship of RR Lyrae in different bands
(Stringer et al. 2019, calibrated with Catalina RRL in DES Y3)



BHB stars' g band absolute magnitude vs (g-r) relationship, fitted by data from 10 star clusters. Deason et al. 2013

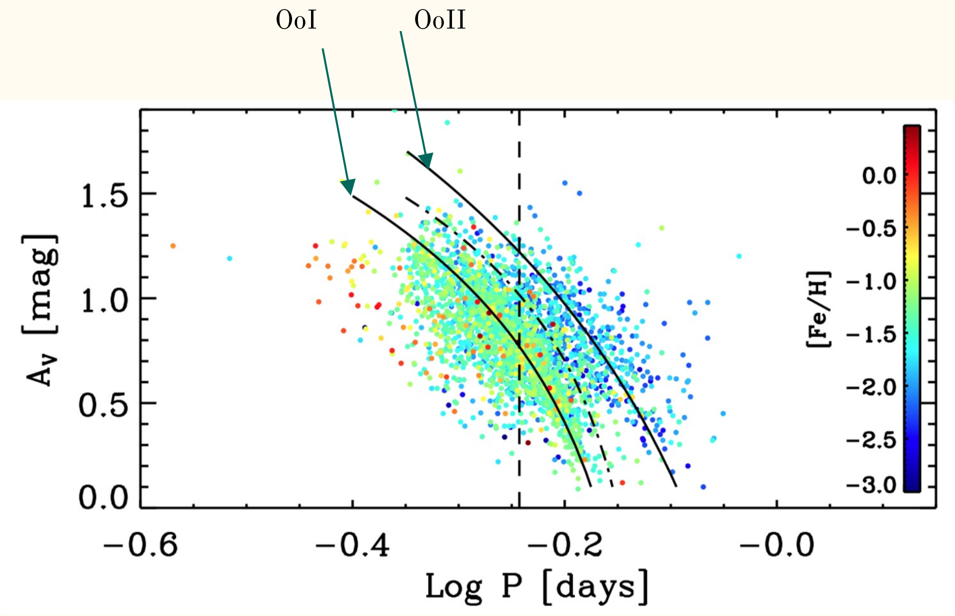
~ 5% systematic distance error at 300 kpc
vs
~ 25% systematic distance error at 50 kpc

Bailey Diagram



From Cacciari et al. 2005. Comparison between RRab in M3 (Oo I) and Omega Cen (Oo II)

Δlog P = 0.116[Fe/H] + 0.173, sigma = 0.4 (Sandage et al. 1983)



M. Fabrizio et al. 2019. All spectroscopically confirmed field RRab from literature.

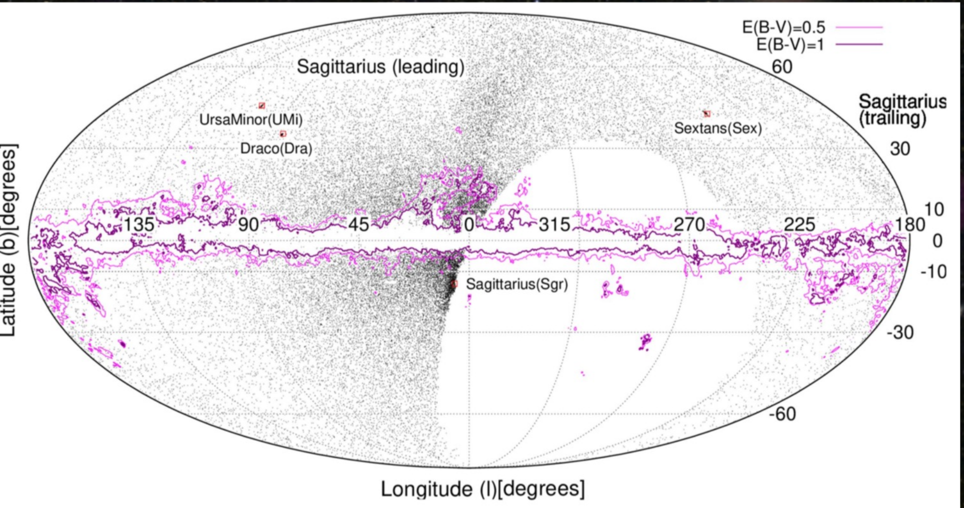
Statistically, RRL with longer periods are more metal-poor

Our Data

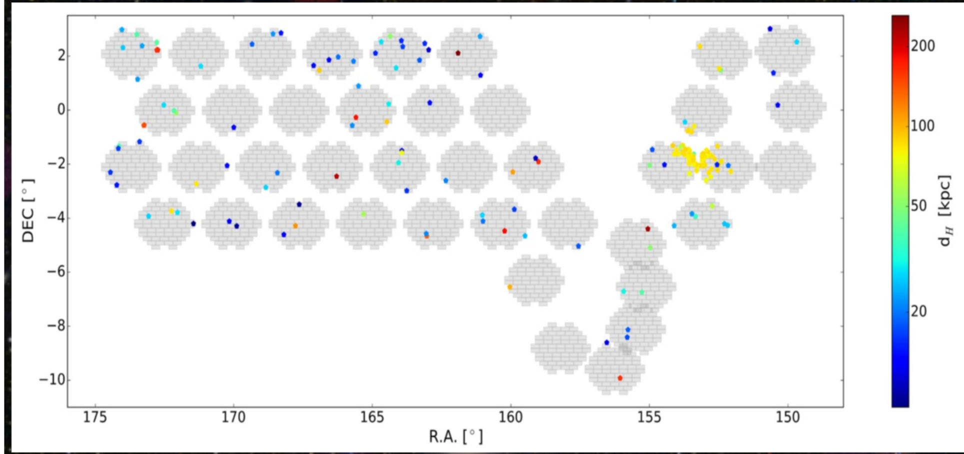
The Next Generation Virgo Cluster Survey (NGVS)

- DECam Surveys: State-of-the-Art
- NGVS Time Domain

Predecessors



Sesar et al. 2017

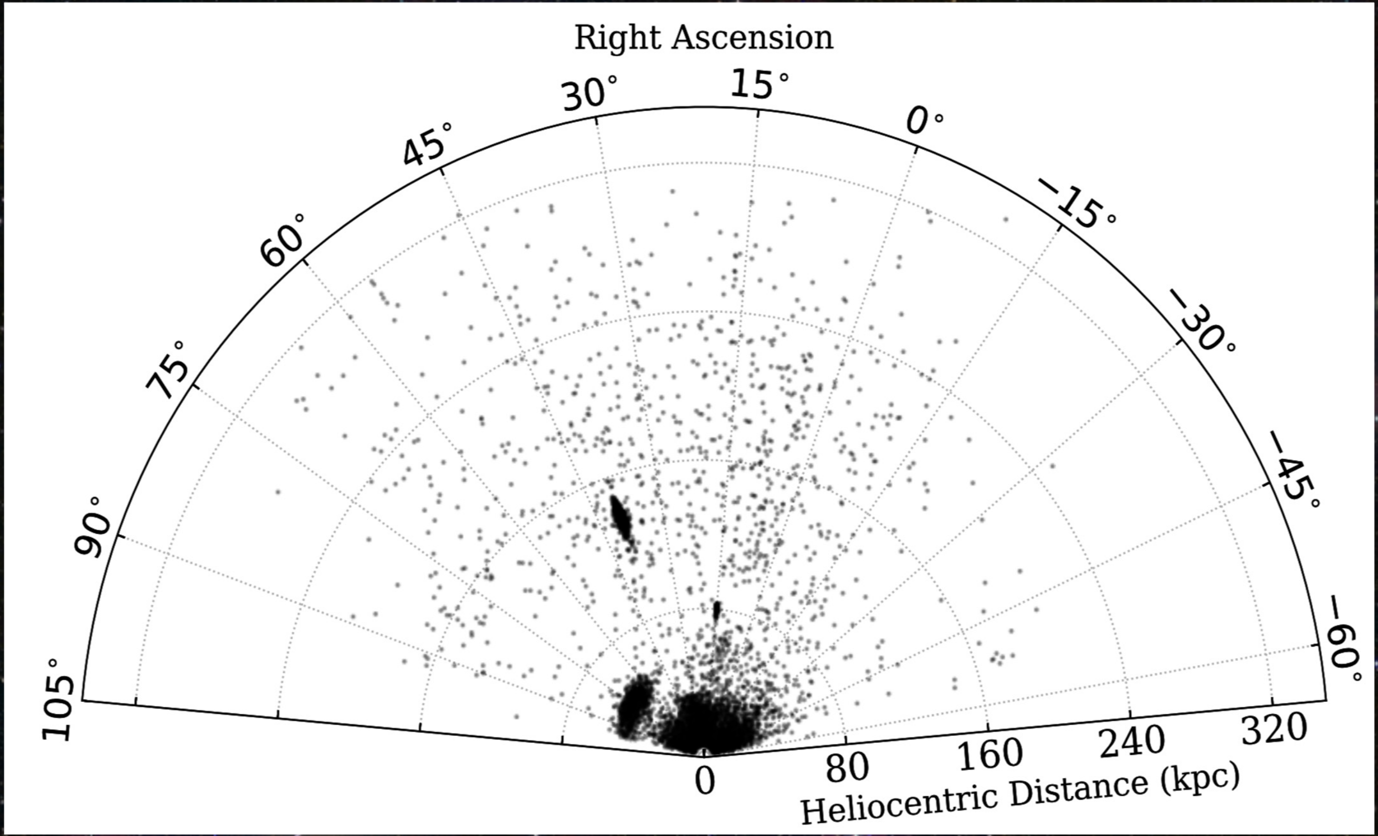


Medina et al. 2018

Pan-STARRS 1 3π Survey(PS1)
43,000 RRL in ~30,000 deg^2
~70 epochs in SDSS grizY
5σ g depth = 22.0
RRL out to 110 kpc
Covers Virgo field, 84 overlapping RRL

High Cadence Transient Survey (HiTS) using DECam
173 RRL in ~120 deg^2
~25 epochs in SDSS g
5σ g depth = 23.0
RRL out to 210 kpc

State-of-the-Art



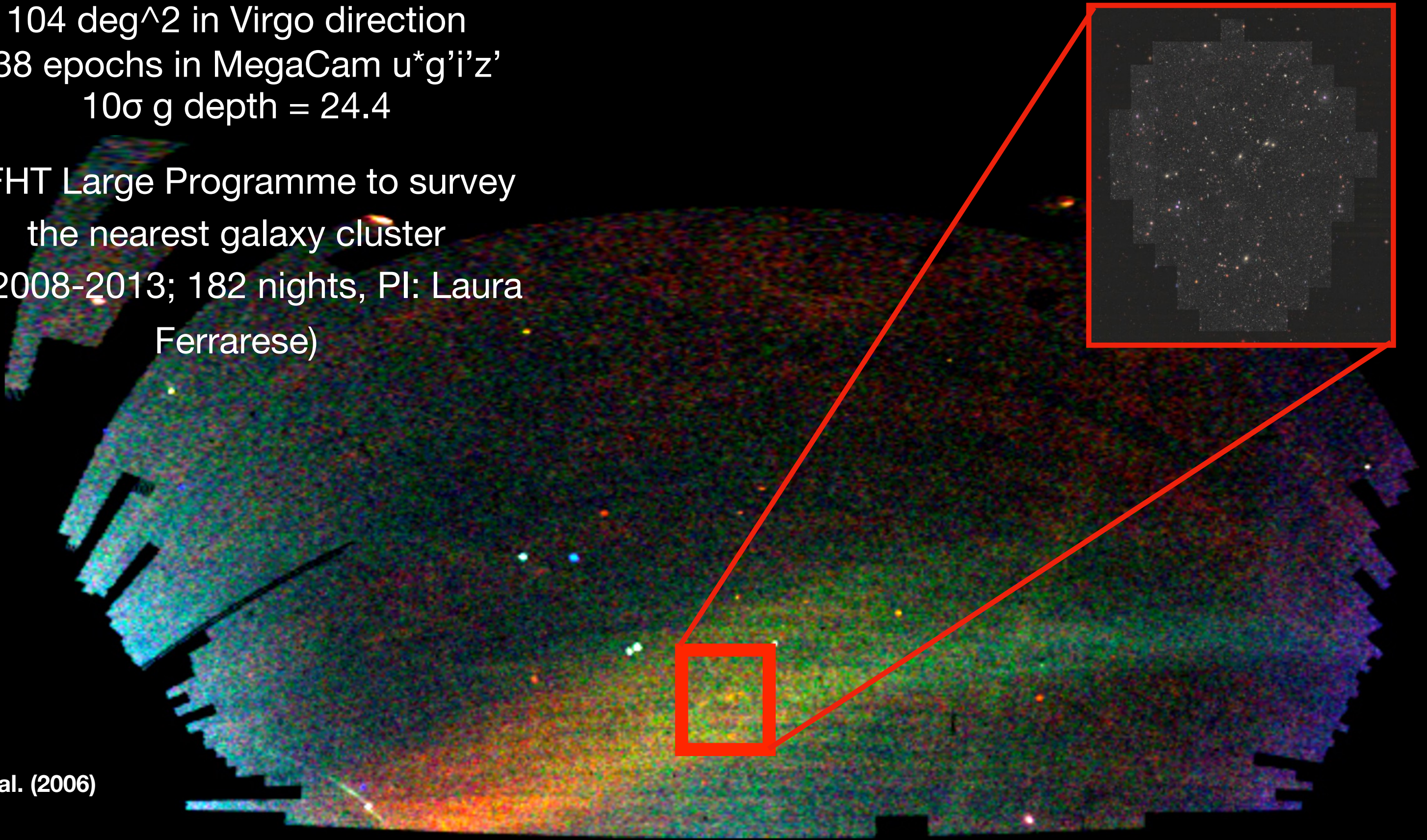
Stringer et al. 2021

Dark Energy Survey
6971 RRL in ~5000 deg^2
~30 epochs in SDSS grizY
RRL out to 330 kpc

The NGVS and the Milky Way Stellar Halo

104 deg^2 in Virgo direction
~38 epochs in MegaCam u*g'i'z'
10σ g depth = 24.4

CFHT Large Programme to survey the nearest galaxy cluster (2008-2013; 182 nights, PI: Laura Ferrarese)



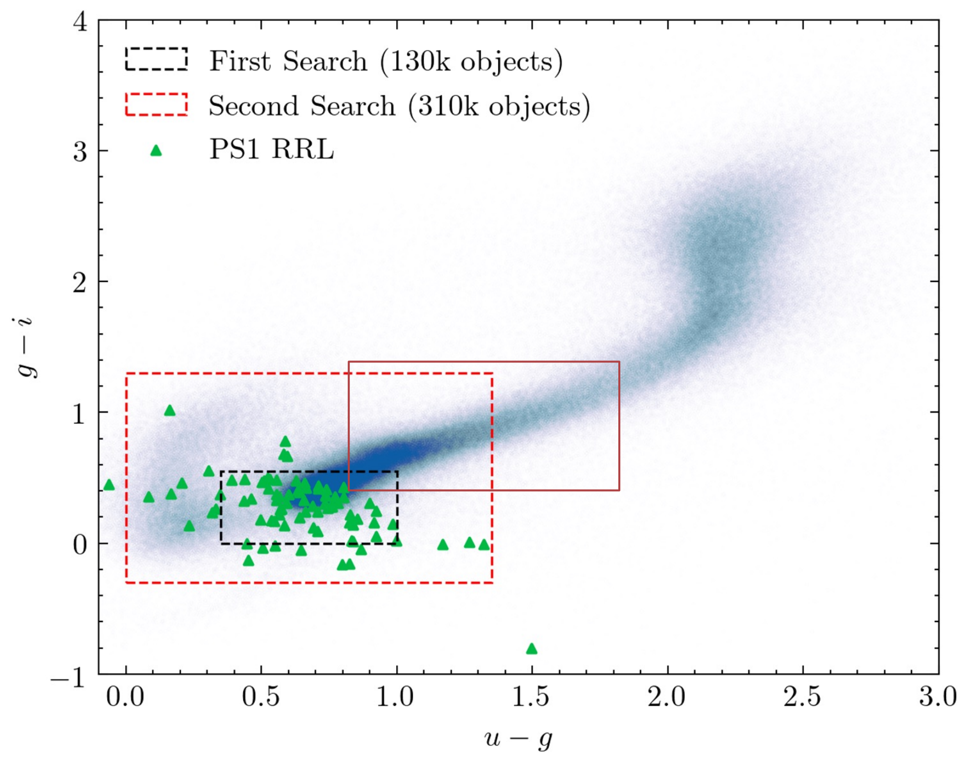
Belokurov et al. (2006)

Method

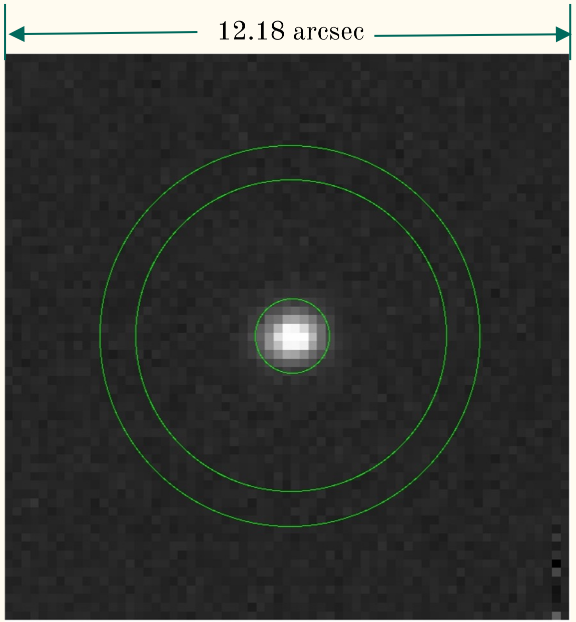
for RR Lyrae identification

- Aperture Photometry
- Fitting to Empirical Light Curve Templates

Aperture Photometry

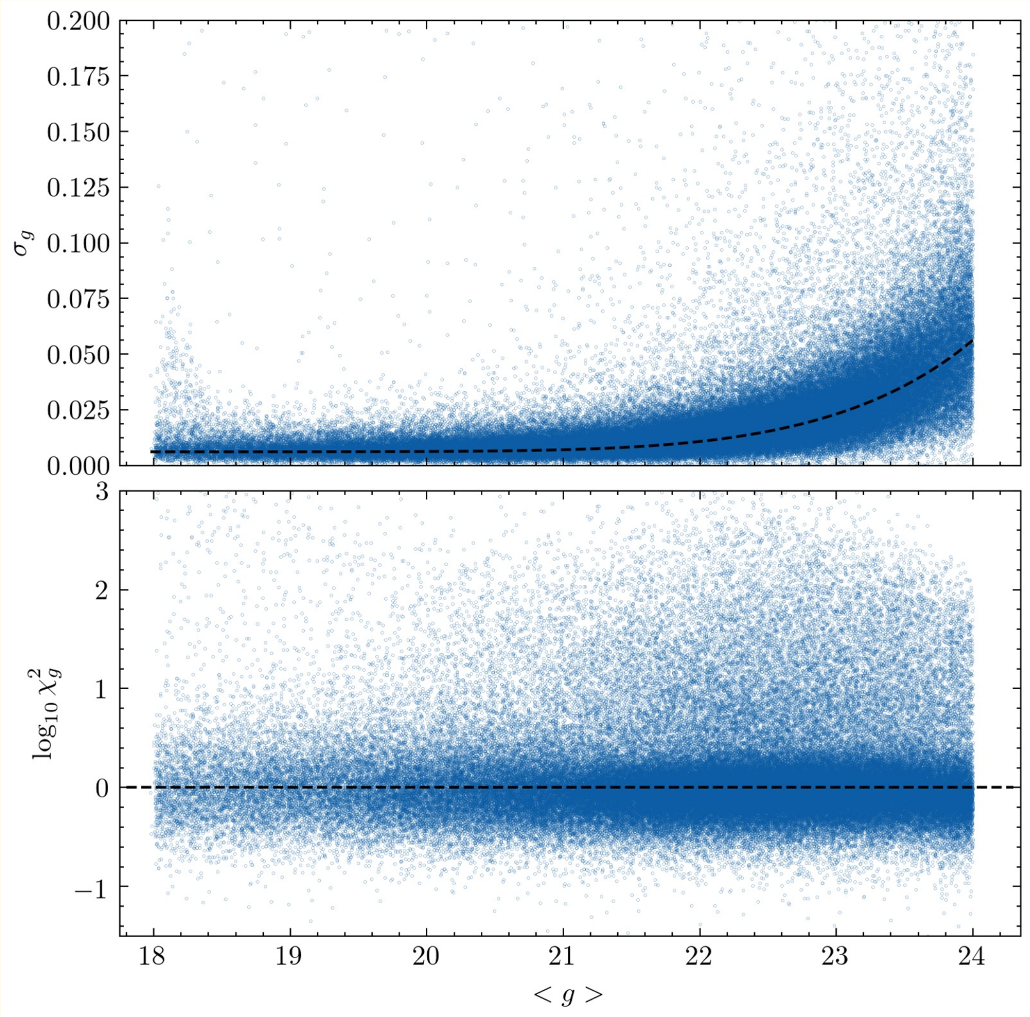


Dashed: search region for variables
Solid: Bright, reference non-variables for photometric calibration (Feng et al. in prep)



Astrometric solution & best-fit psf from Megapipe

For each exposure, calibrate to minimize the difference between the apparent magnitude and catalog magnitude of bright non-variables



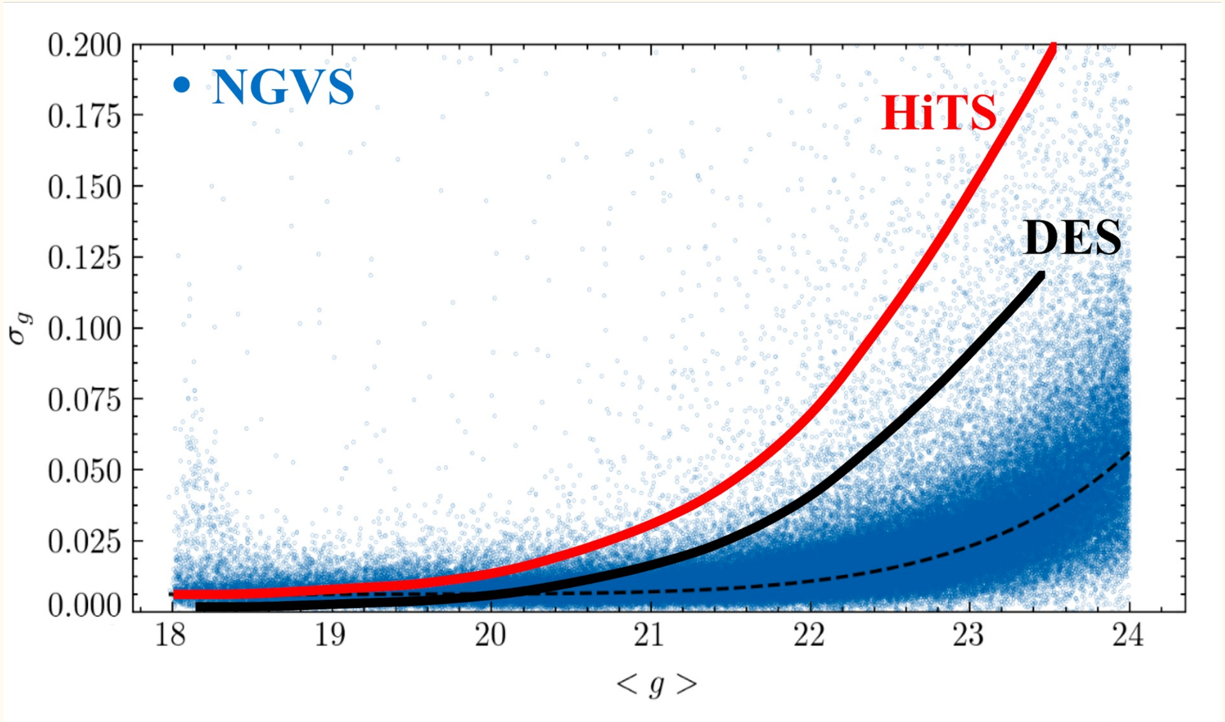
Standard deviation (<=> empirical photometric uncertainty) of our g' measurements, for 400k NGVS point sources

Chi-square statistics, with our calibrated error model

$$\chi^2_{\nu,b} = \frac{1}{N_b-1}\sum_{1}^{N_b}\frac{(m_{i,b}-\overline{m_b})^2}{\sigma^2_{i,b}}$$

$$\sigma_{i,b} = \sqrt{\sigma^2_{i,b,\mathrm{Poisson}} + \sigma^2_{sys,b}}$$

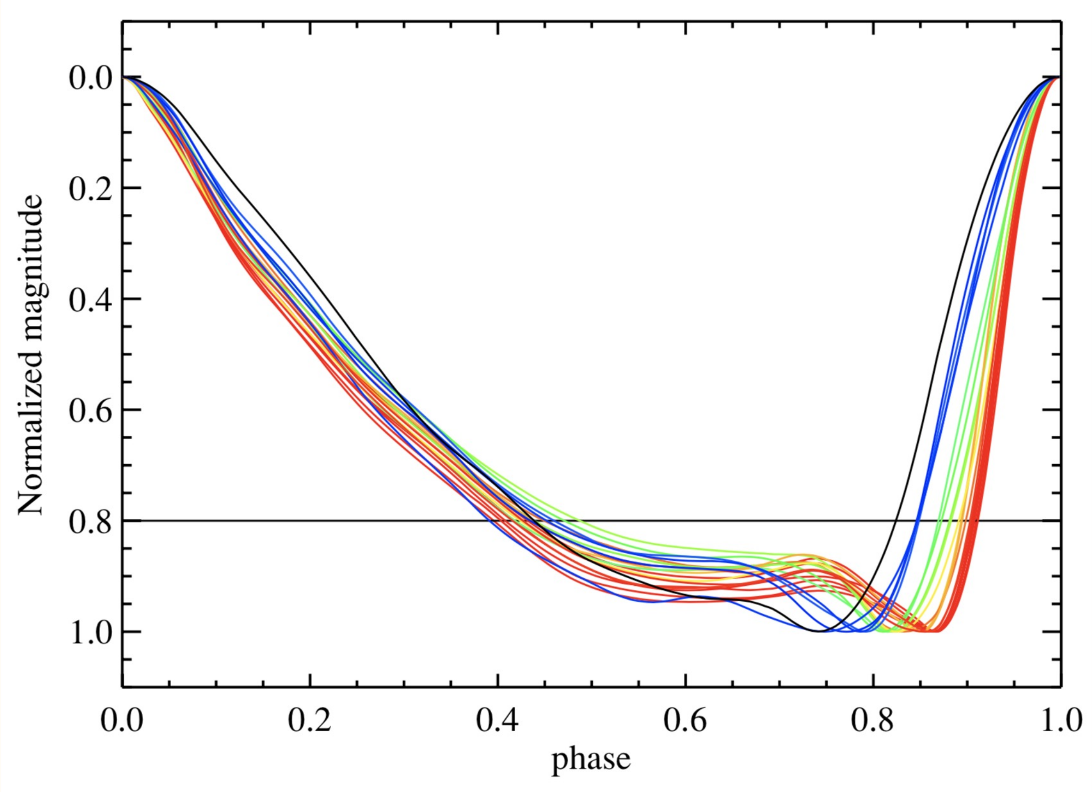
Single Epoch Photometry of NGVS



NGVS single epoch photometry is:

- 1.5 mag deeper than DES (Stringer et al. 2019)
- 2.3 mag deeper than HiTS (Medina et al. 2018)

Template Fitting Method



24 RRab g band reduced and normalized templates, color-coded by their shape, from SDSS S82 data (Sesar et al. 2010).

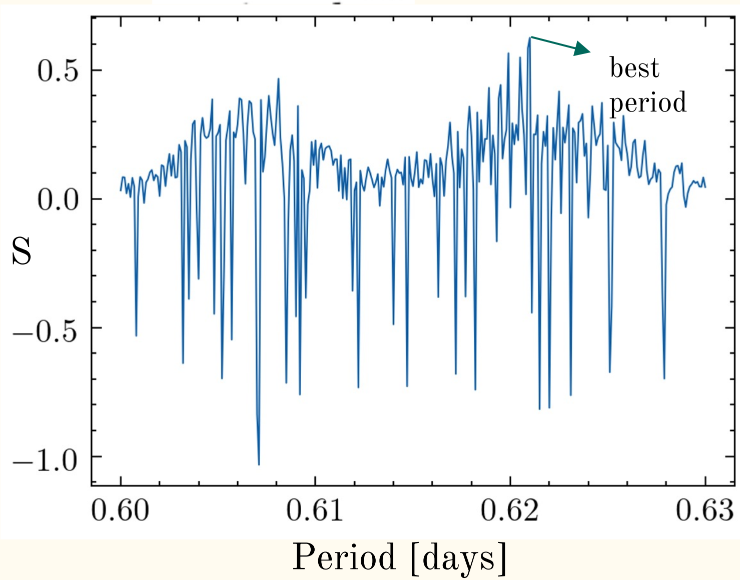
$$m_b(\phi) = a_b T_{b,k}(\phi) + m_{0,b}$$

$$\phi(t \mid P,\ \phi_0) = \frac{t \text{ modulo } P}{P} + \phi_0$$

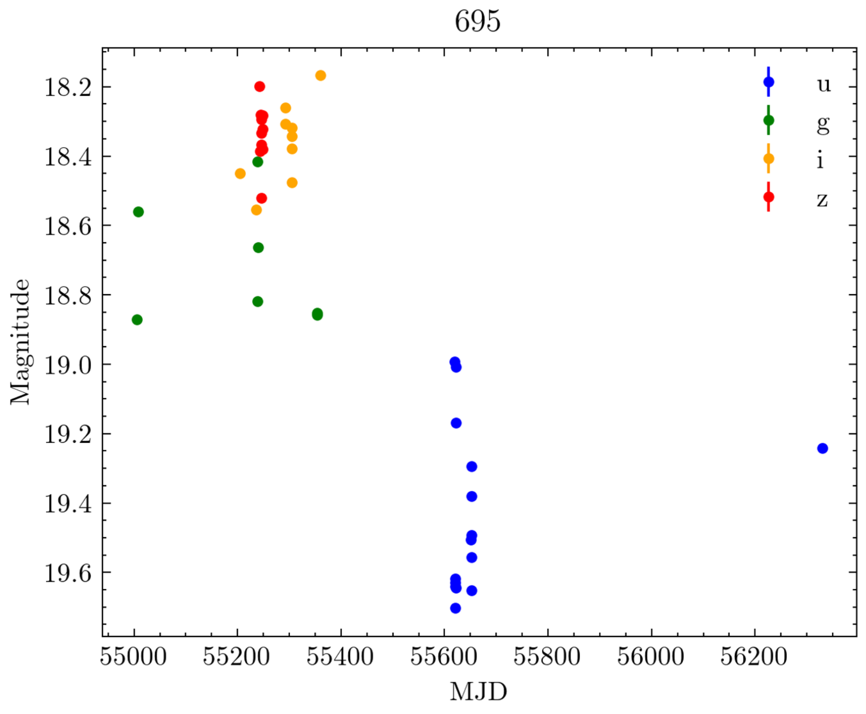
$$\chi^2 = \sum_{b=u,g,i,z} \sum_{n=1}^{N_{b,obs}} \left(\frac{m_{b,n} - m_b(\phi(t_{b,n}|P,\ \phi_0))}{\sigma_{b,n}} \right)^2$$

$$s_{\text{fitting}} = \frac{\chi^2}{\chi_0^2}$$

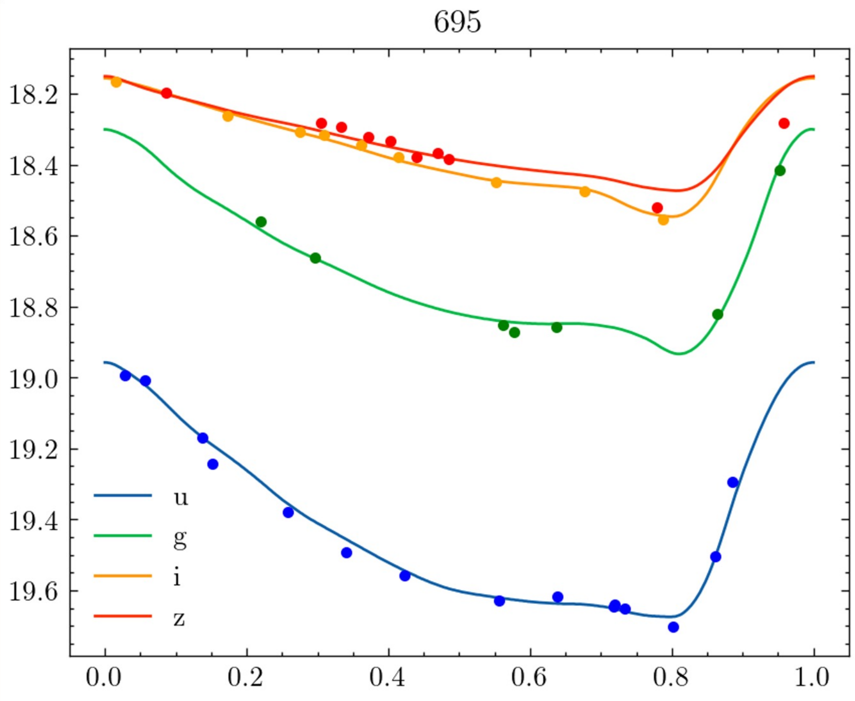
optimize



Template Fitting Method: Example

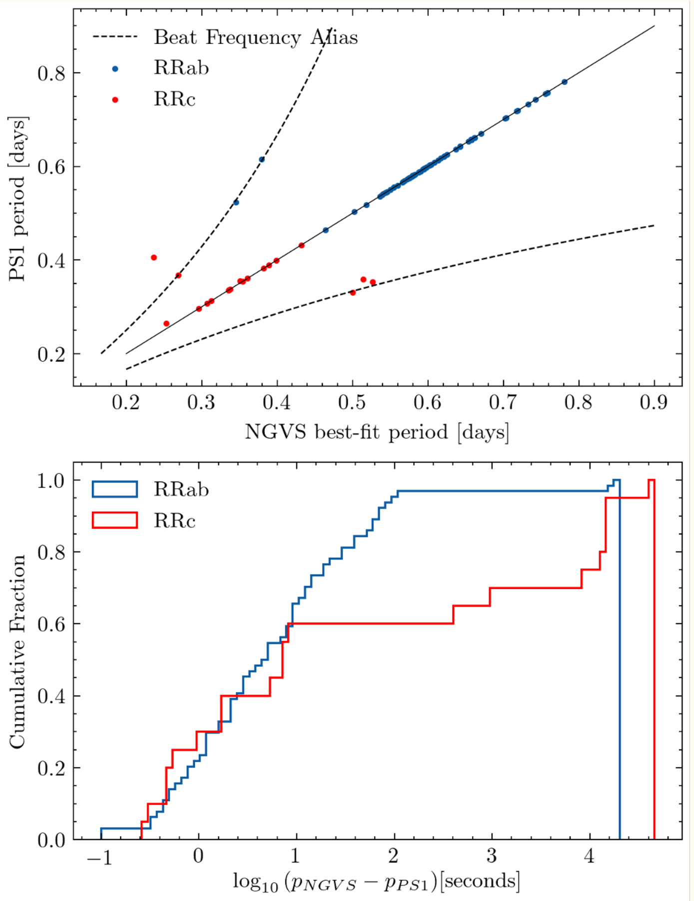


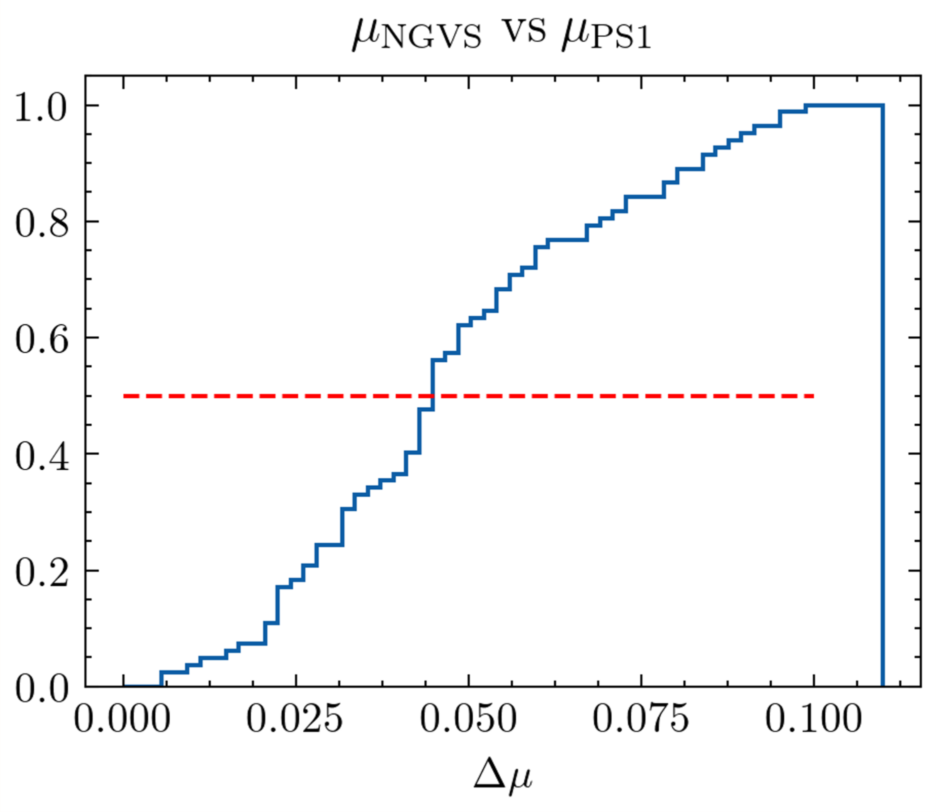
P=0.622 day



Our observation spans more than 1400 days, while the true period is 0.622 day
Successfully folded over 2250 pulsation cycles with only 40 measurements across 4 bands

Robustness Test on PS1 RRL





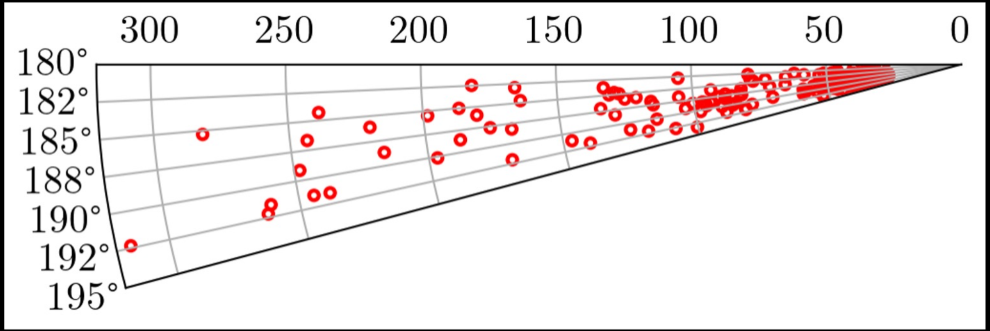
Feng et al. in prep

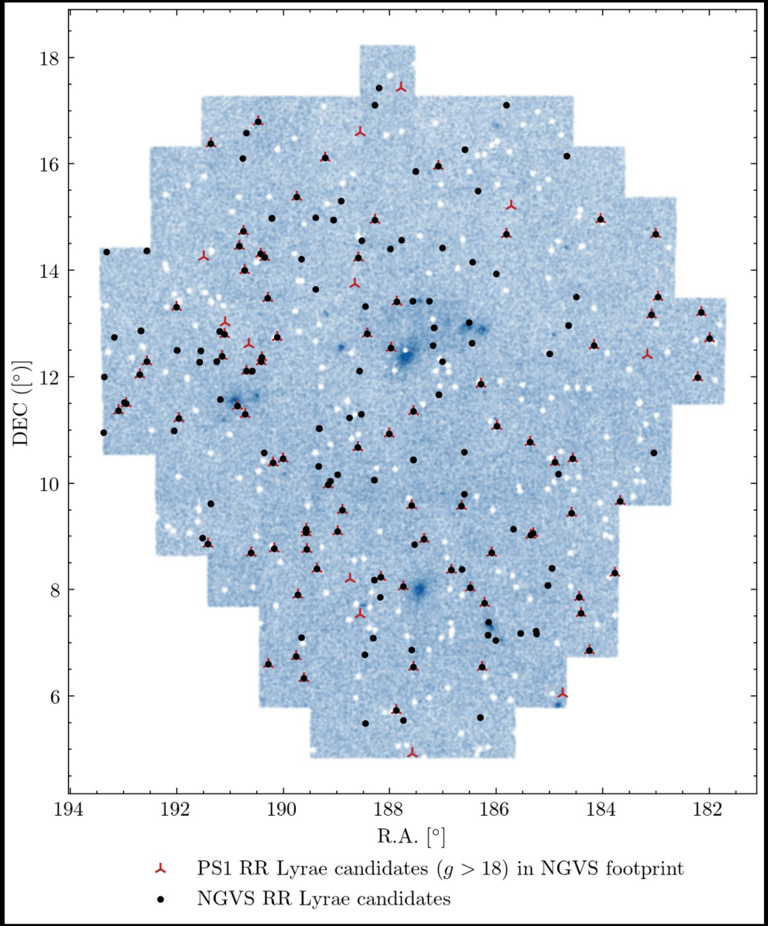
Period measurements agree within 2 minutes, if not affected by beat alias

NGVS RR Lyrae

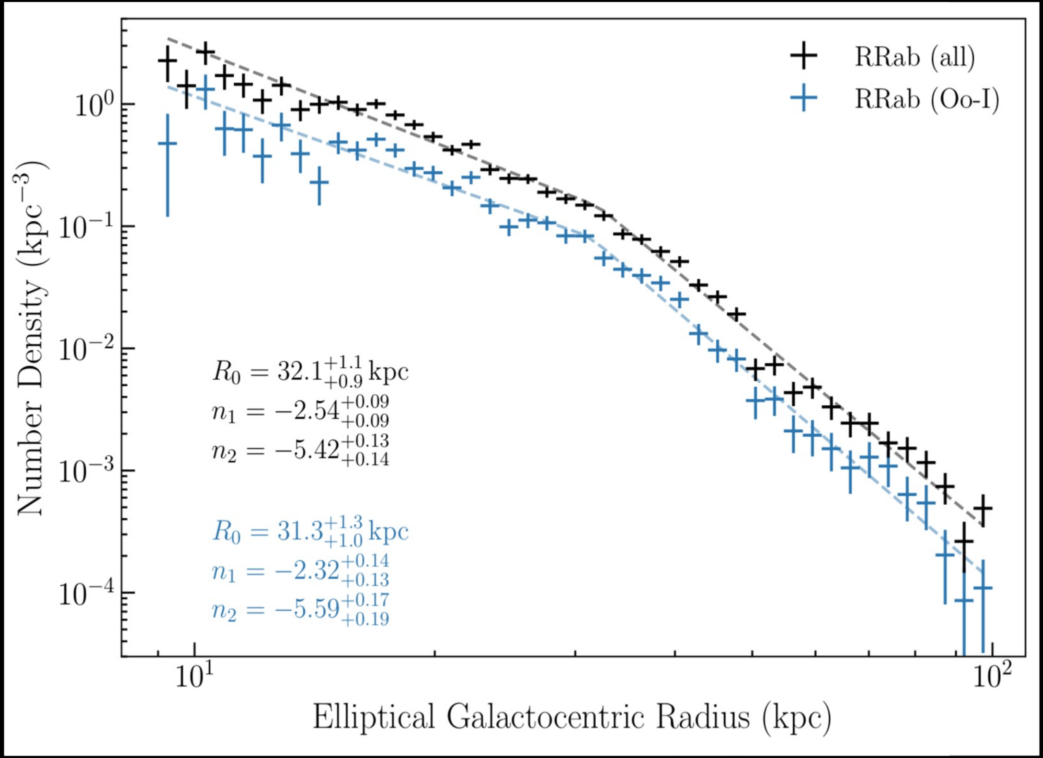
Heliocentric distance / kpc

RA

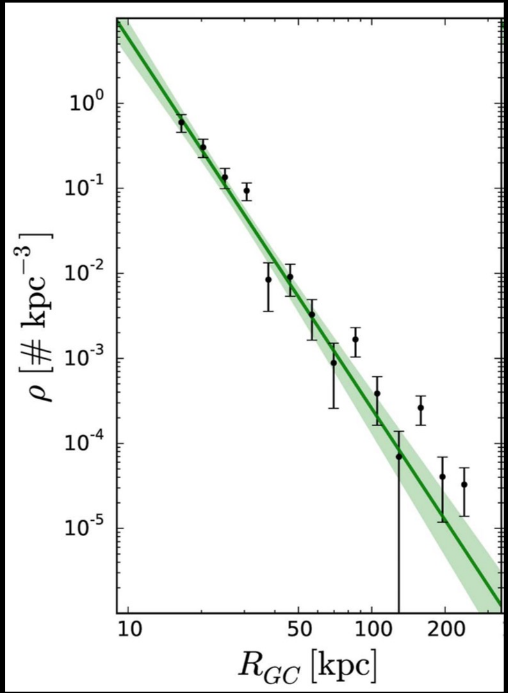




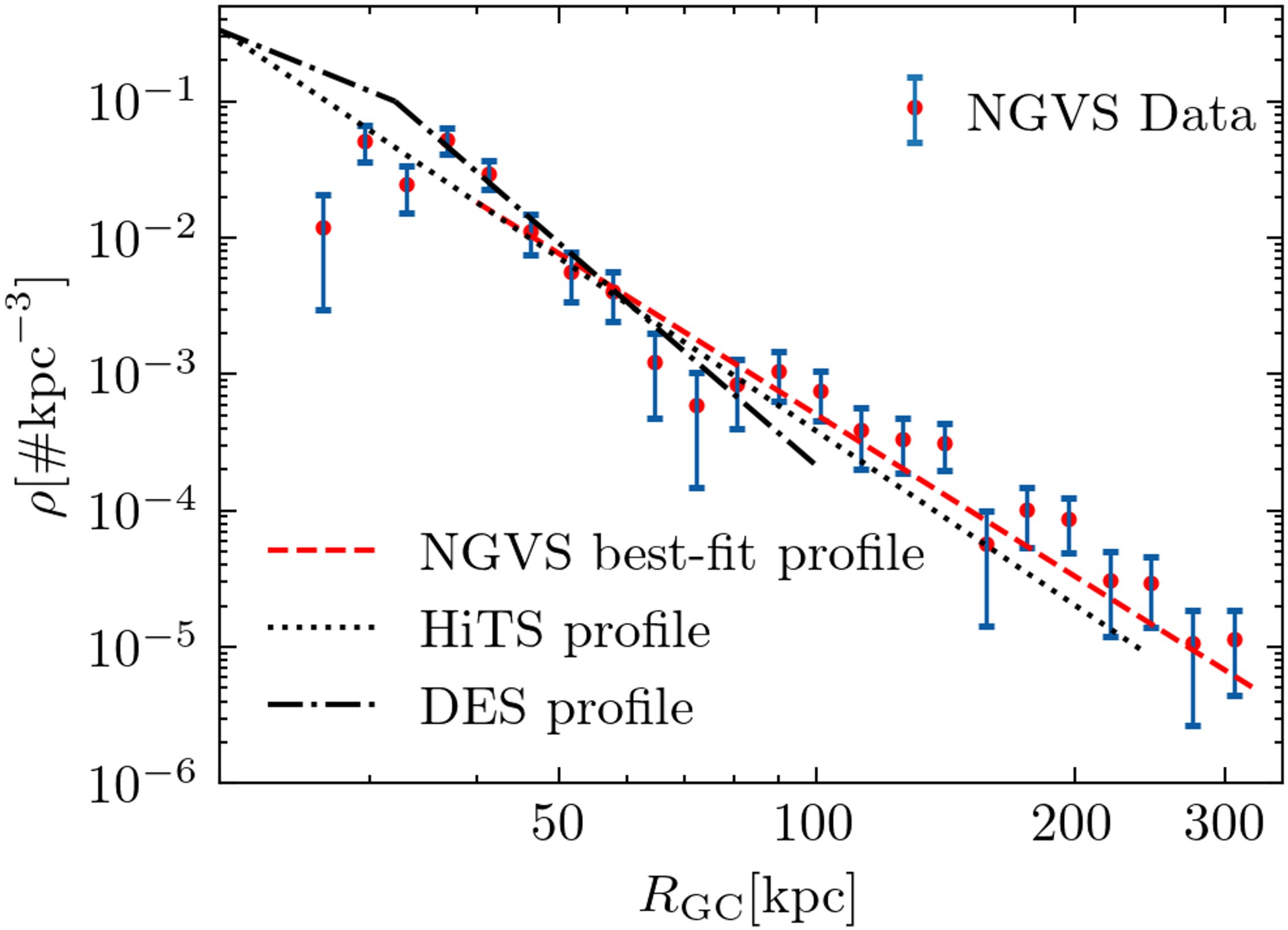
Literature Results: from 2 DECam Surveys



DES Y6 RRL, broken-power-law profile
(Stringer et al. 2020)



HiTS RRL
power-law profile with n = -4.2 +/- 0.32
(Medina et al. 2018)



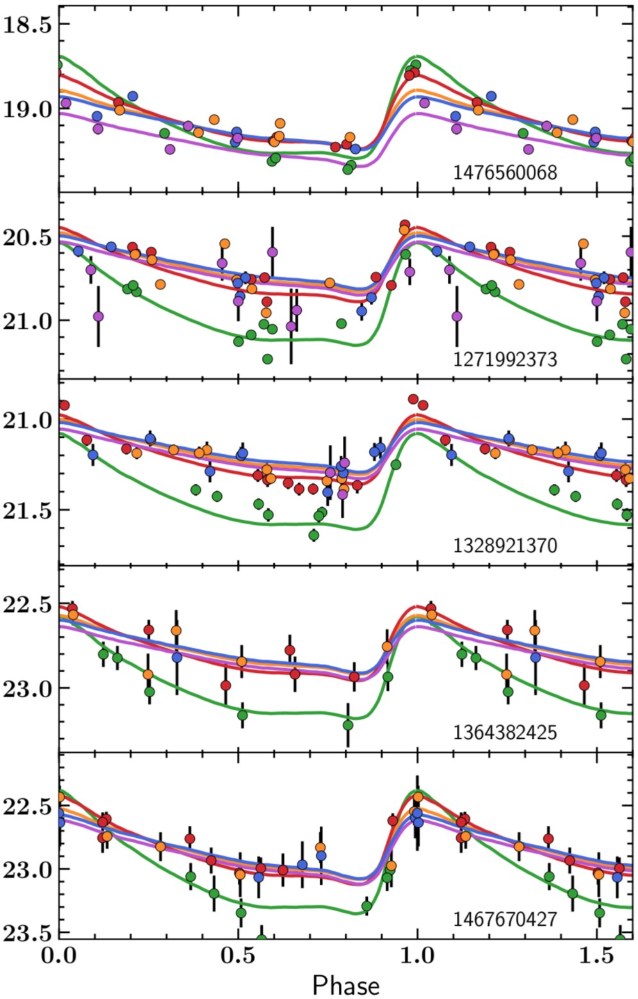
Outer Halo slope: n = -3.93 +/- 0.33

starts from 40 kpc (Feng et al. in prep)

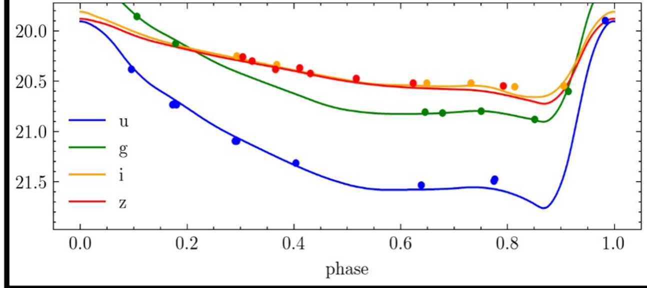
More Literature Results

Model	Slope	R_b (kpc)	Inner Slope	Outer Slope	Range (kpc)	Tracer Used	Paper
Broken Power Law							
	⋯	23	−2.4	−4.5	5–100	RRLs	Watkins et al. (2009)
	⋯	27 ± 1	-2.3 ± 0.1	$-4.6^{+0.2}_{-0.1}$	1–40	BHB and BS stars	Deason et al. (2011)
	⋯	28	-2.6 ± 0.04	-3.8 ± 0.1	12–40	near MSTO stars	Sesar et al. (2011)
	⋯	24	-2.8 ± 0.5	-5.4 ± 0.5	5–60	RRLs	Zinn et al. (2014)
	⋯	20	-2.5 ± 0.4	-4.9 ± 0.4	10–60	F-type stars	Pila-Díez et al. (2015)
	⋯	18 ± 1	-2.1 ± 0.3	-3.8 ± 0.1	10–80	K giants	Xue et al. (2015)
	⋯	$29.87^{+2.80}_{-3.55}$	$-3.61^{+0.15}_{-0.16}$	$-4.75^{+0.30}_{-0.28}$	10–70	BHB stars	Das et al. (2016)

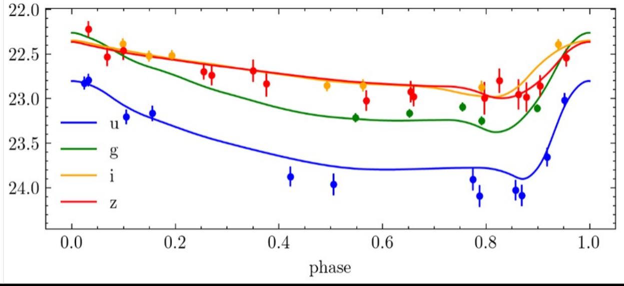
DES Y6 RRL Examples



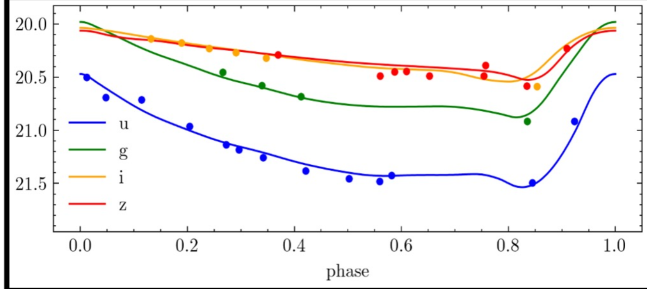
NGVS RRL Examples



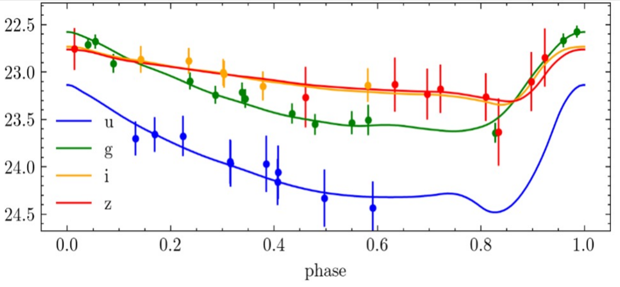
~50kpc



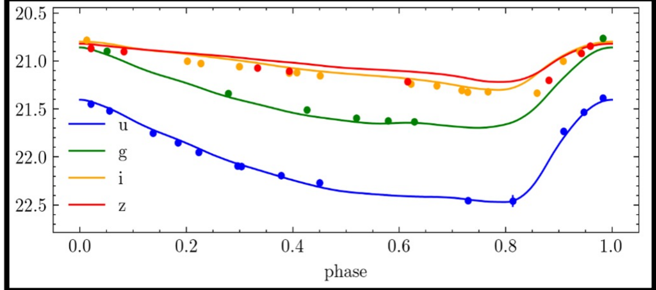
~220kpc



~80kpc

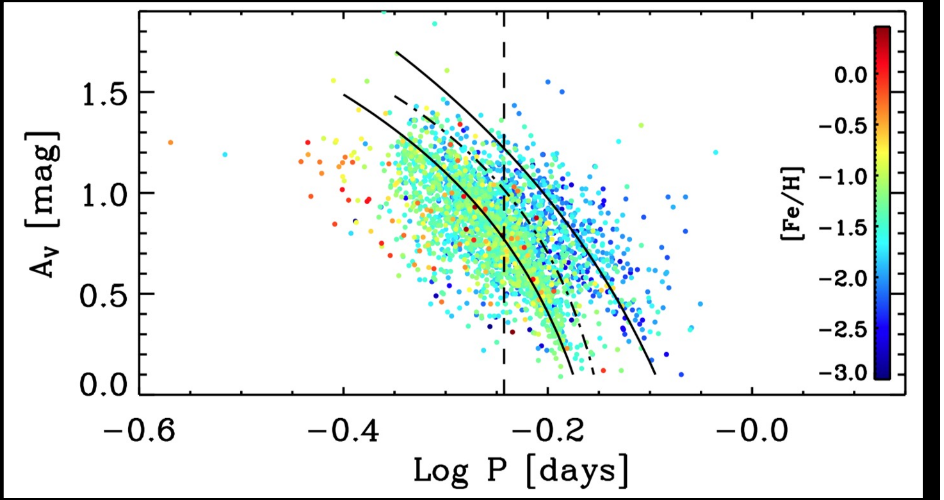


~300kpc

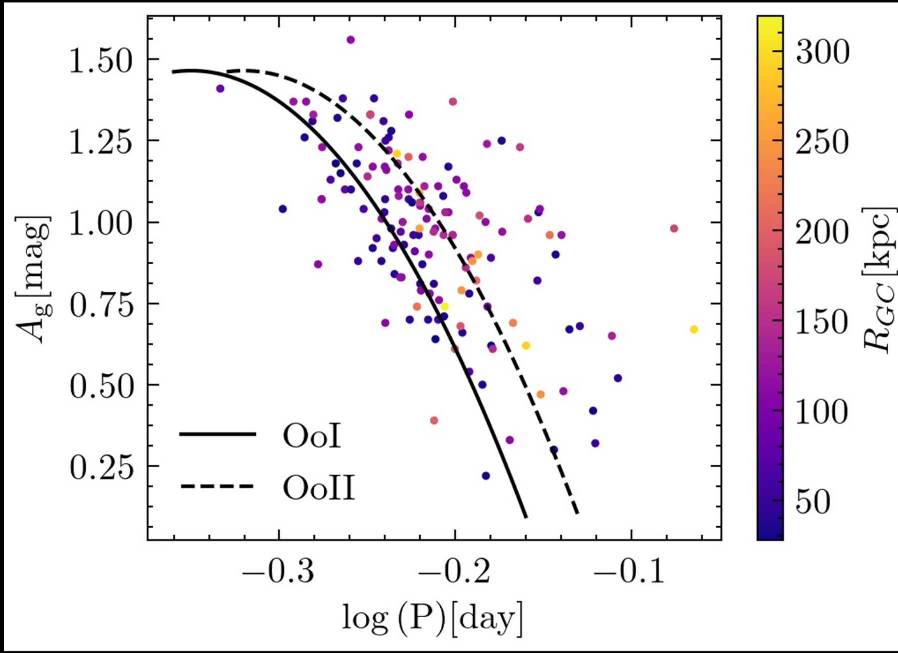


~120kpc

The Bailey Diagram



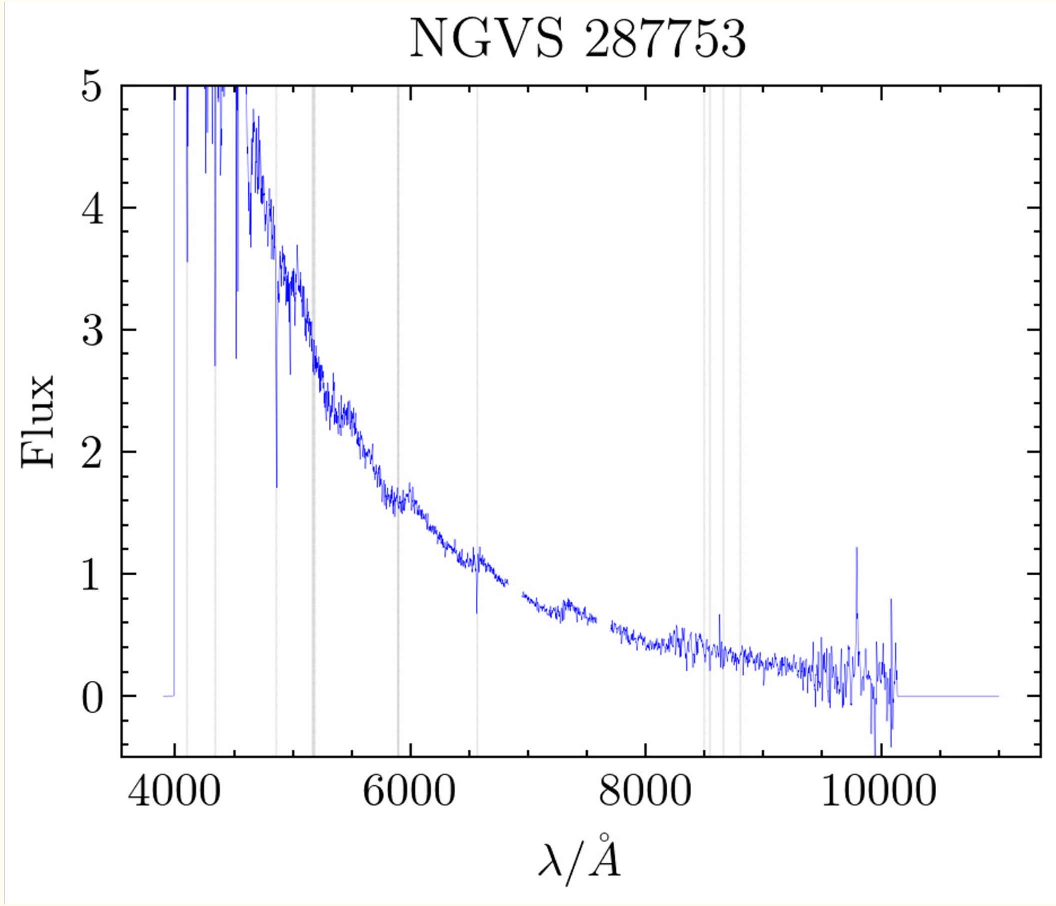
M. Fabrizio et al. 2019



Feng et al. in prep

Distant halo (>100 kpc) RRL are likely from a metal poor environment.

Spectroscopic Follow-Up...



~10 nights of Keck ESI

Targeting RRab stars from 90 to 150 kpc for kinematical information

Summary

- RR Lyrae are powerful halo tracers; we also discovered RRL out to 300 kpc like DES
- A robust estimation of the slope of stellar density in outer halo
- Distant halo RRL (over 100 kpc) are likely from metal-poor environments
- Kinematics of RRL from Keck ESI to come