Identifying RR Lyrae in the Dark Energy Survey

Katelyn Stringer

May 16th, 2019

LIneA Webinar

Collaborators

TAMU Advisors: Lucas Macri, James Long, Jennifer Marshall

DES: Milky Way Working Group + TMO, Calibrations, Science Release

Outline

- Motivation: Why Search for RR Lyrae?
- DES Data Set & Analysis
- Results & Continuing Work

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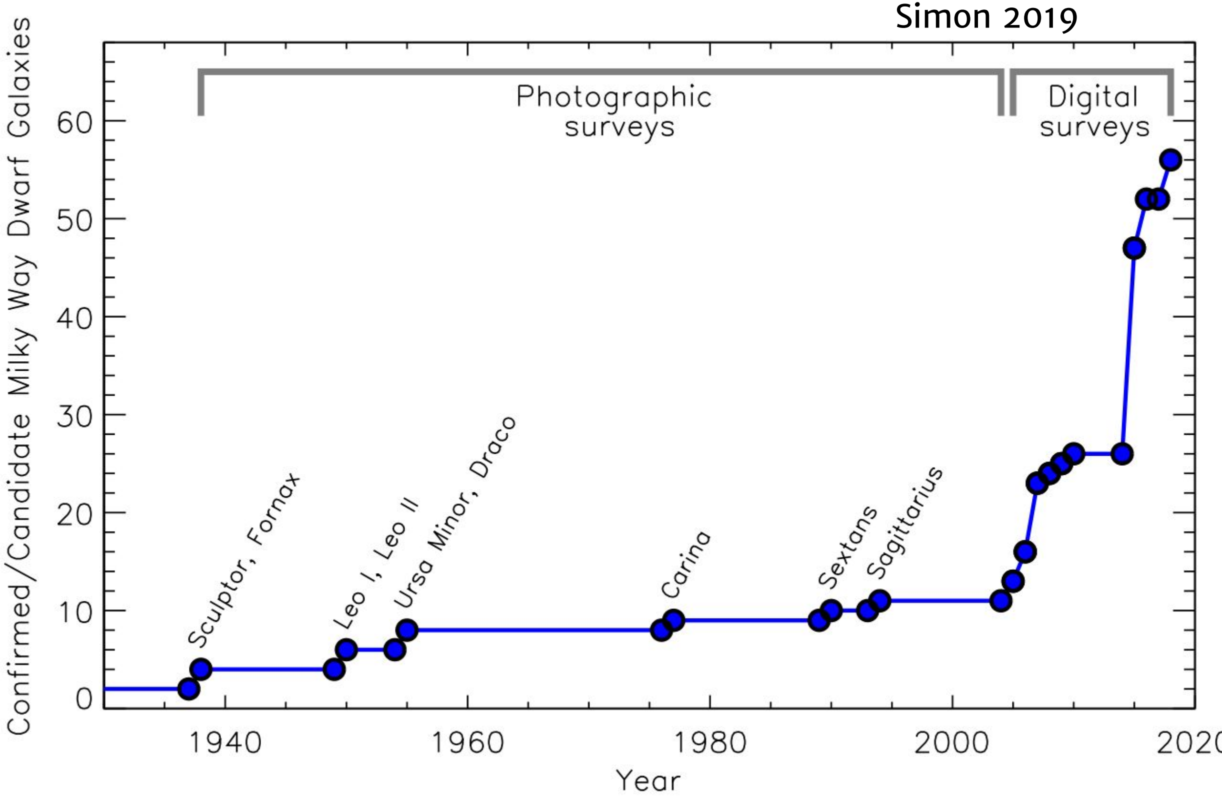
- **Motivation: Why Search for RR Lyrae?**
- DES Data Set & Analysis
- Results & Continuing Work

Galactic Satellites

- Building blocks of Milky Way (e.g. Bullock & Johnston 2000)
- Large scale surveys have increased the known census

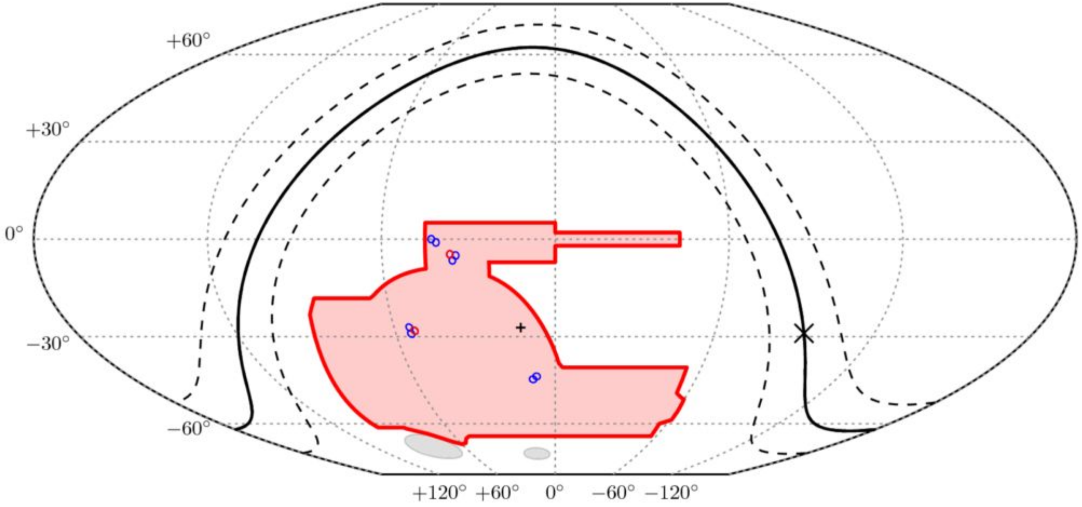
Simon 2019



Dark Energy Survey

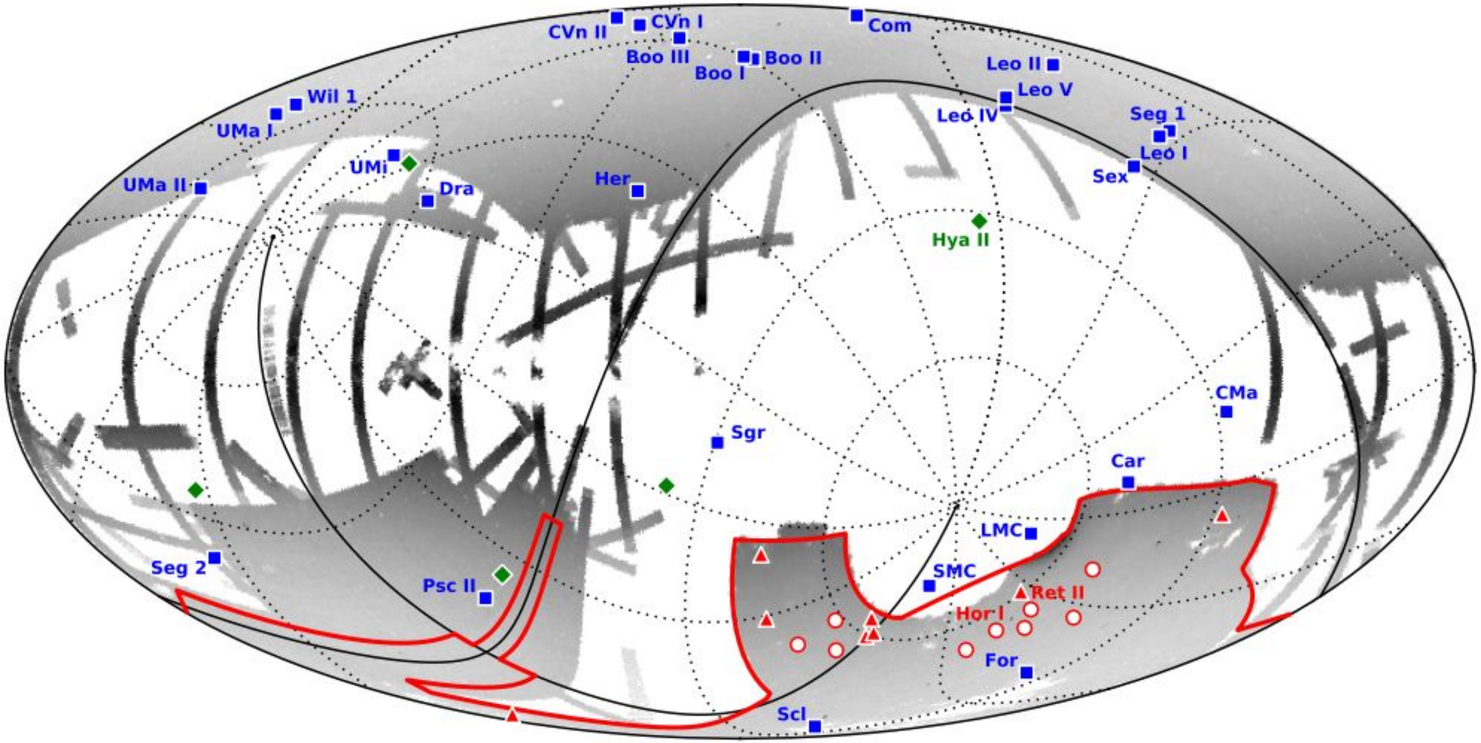
Deep (g~23.5 in single exposure) and wide (~5000 deg^2) photometric survey in Southern Celestial hemisphere

Photo Credit: H. T. Diehl, Fermilab



DES Collaboration 2018

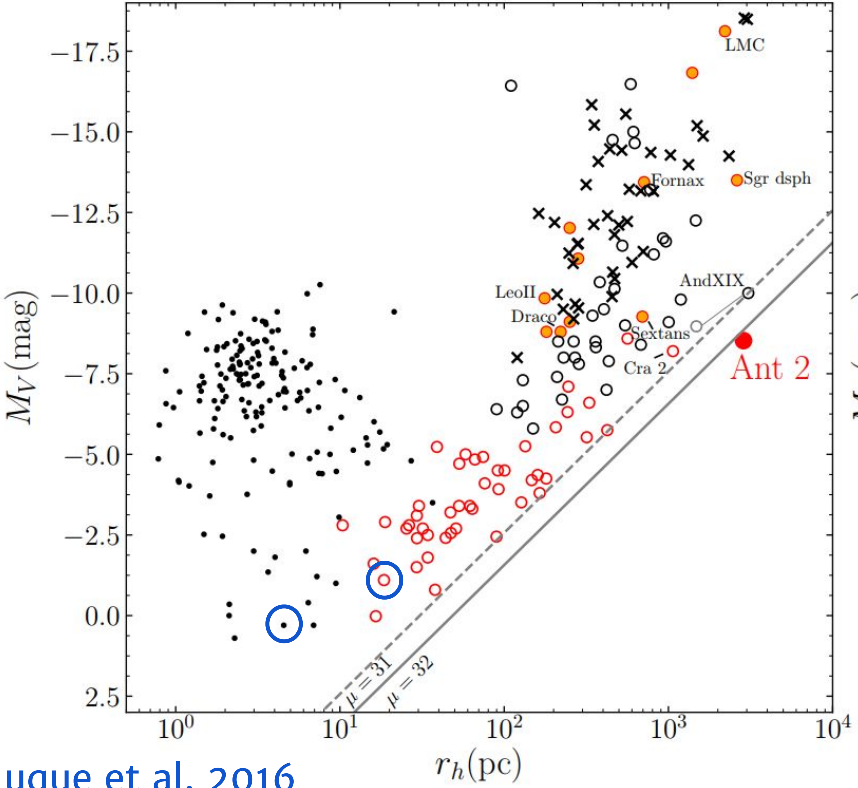
DES Satellite Candidates

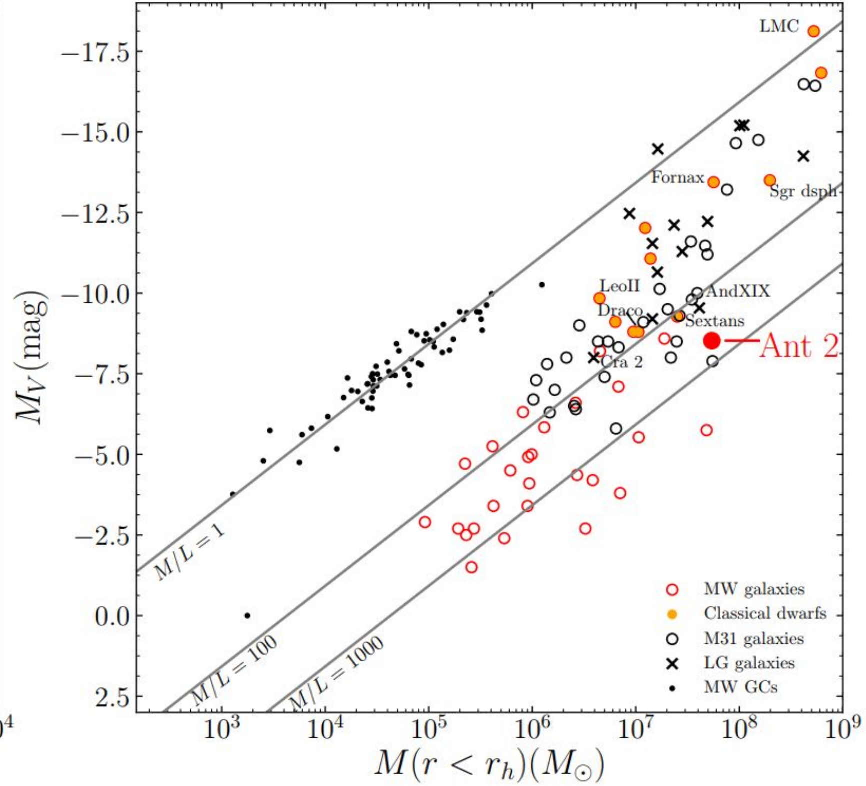


Drlica-Wagner et al. 2015

Galactic Satellites

Figure 11 from Torrealba et al. 2018



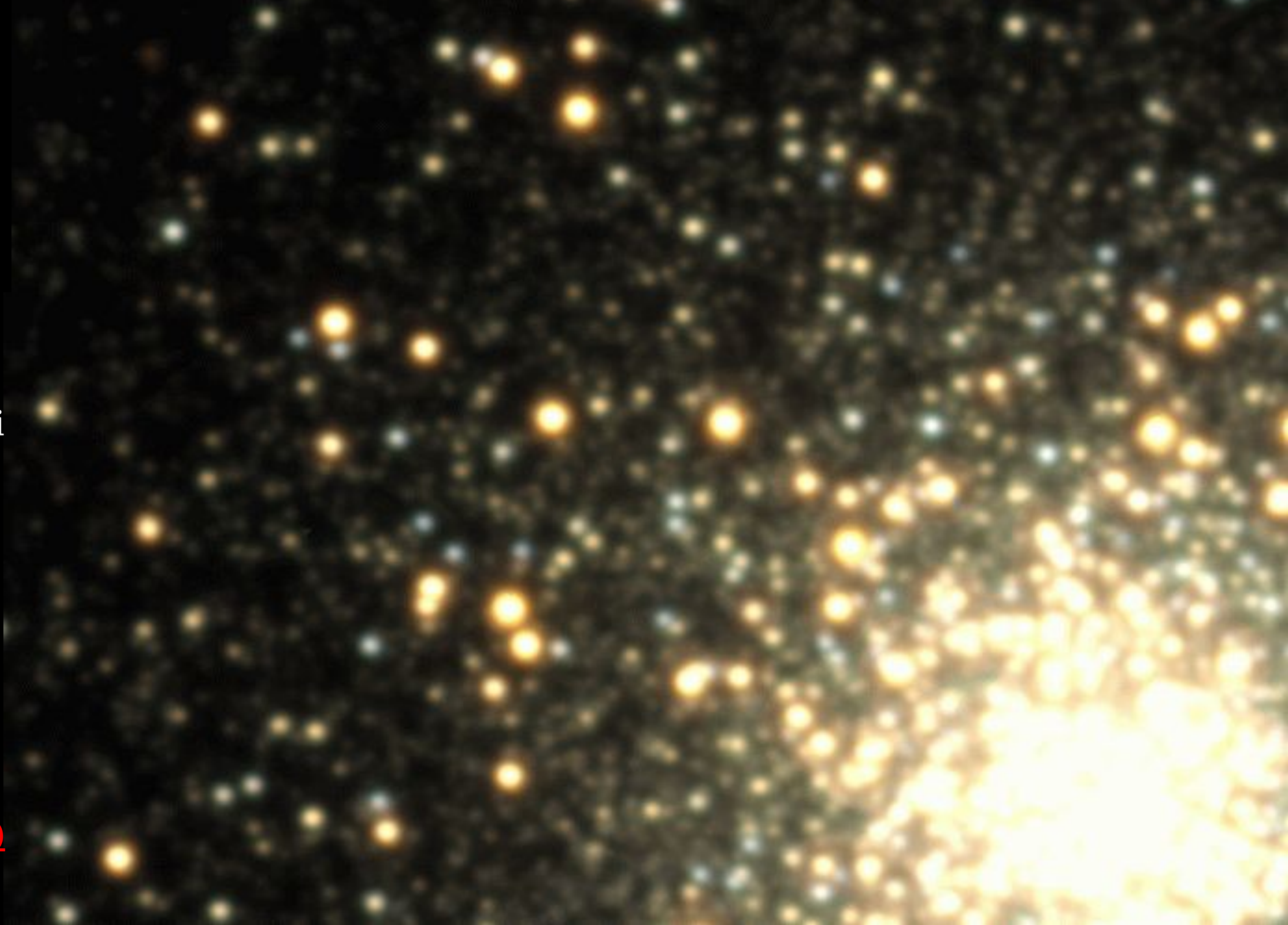


Luque et al. 2016

Variable Stars in M3

Observers:
Krzysztof Stanek &
Andrew Szentgyorgyi

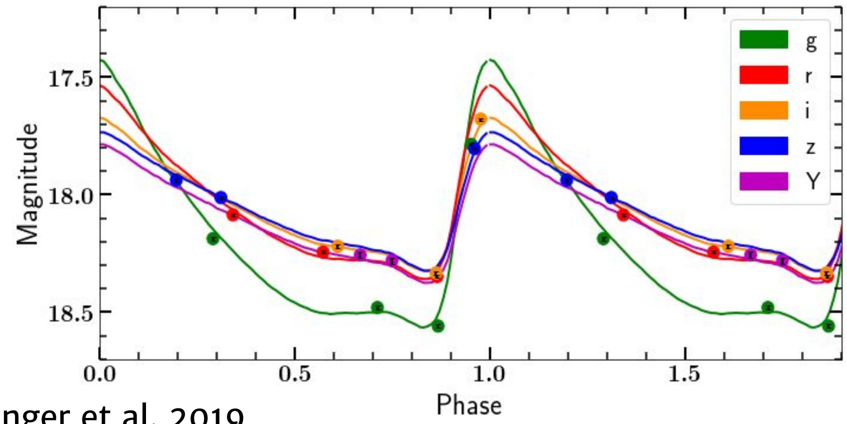
Video by:
Joel Hartman



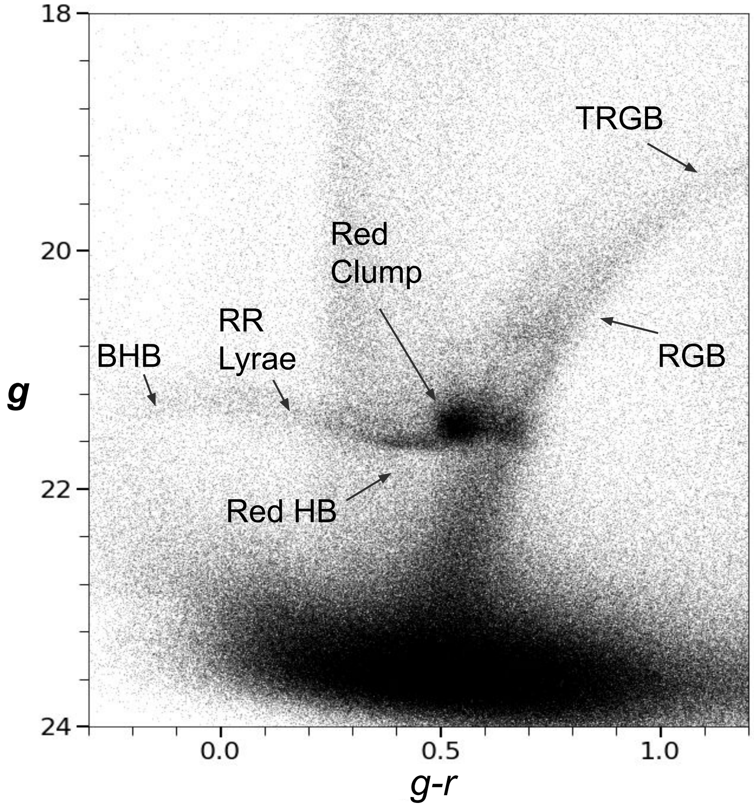
(Link for pdf version)

RR Lyrae (RRL) Stars

- Old pulsating ~solar-mass stars
- Identified by light curve shapes & periods
- Distance indicators (*PLZ* relation)



Stringer et al. 2019



CMD of Fornax dSph in DES Y3

RR Lyrae as Tracers

- Luminosities are perfect range to detect to edge of Galactic halo
- Small statistical distance uncertainty, ~3% (Sesar et al. 2017)
- Can be used to trace structure

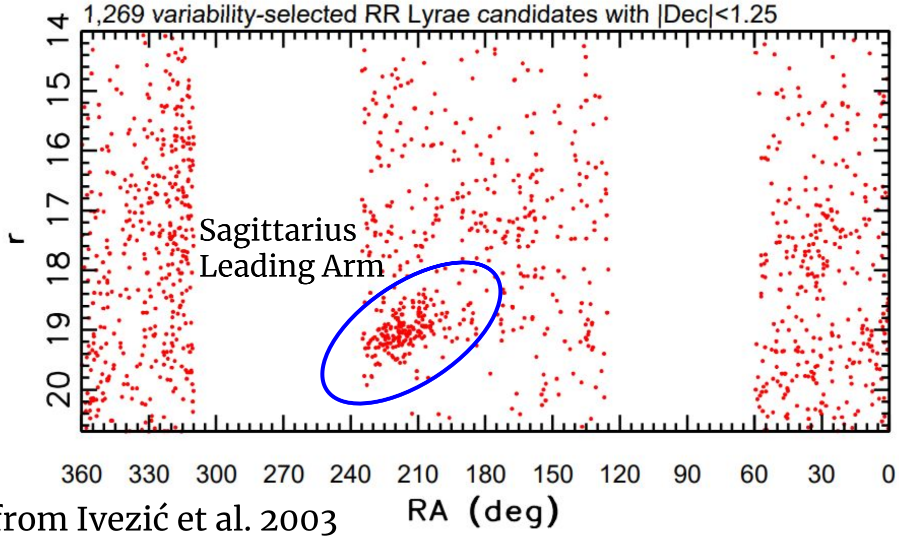
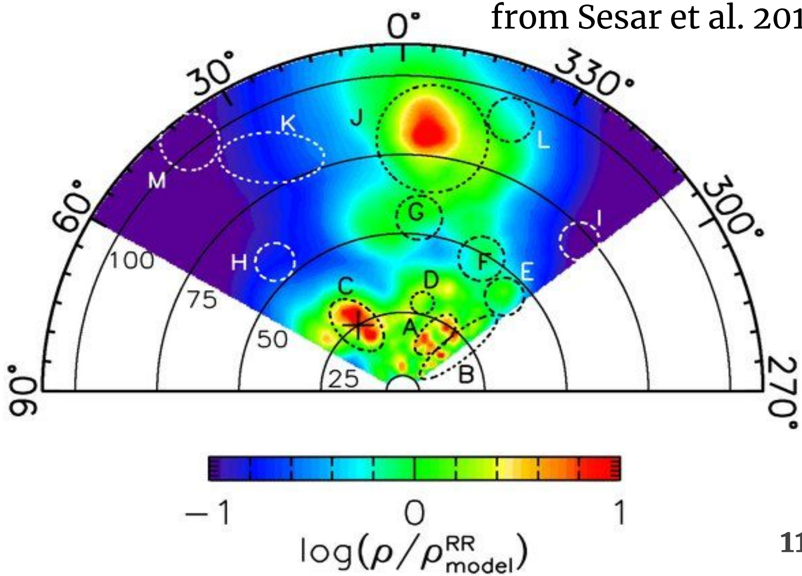


Fig. 1 from Ivezić et al. 2003

Portion of Fig. 11 from Sesar et al. 2010



Detection with RRL Groups

- $\geq$ 1 RRL has been found in every satellite with published time-series data (except Carina III)
- Baker & Willman 2015: 2 RRL within 500 pc indicates stellar structure

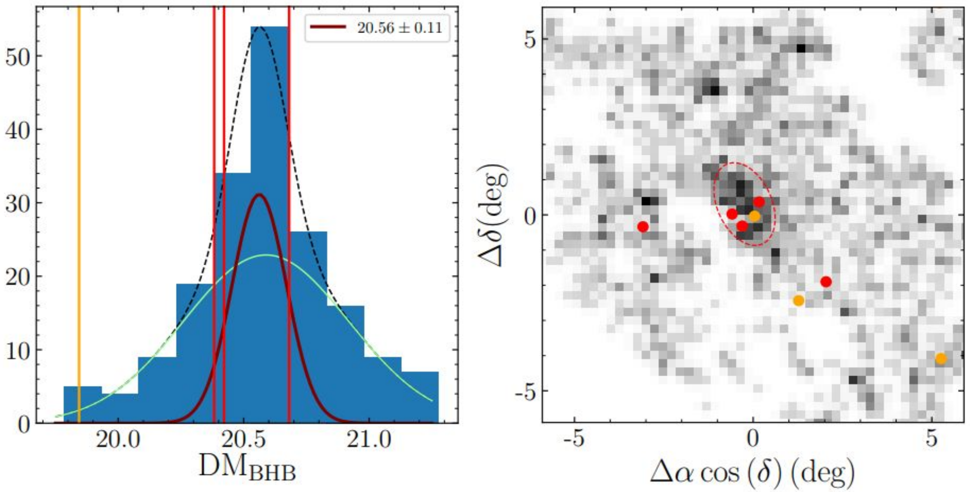
MW Dwarf	N_{RRab}	N_{RRc}	RR_c/RR_{ab+c}	Reference
Fornax	396	119	0.23	Bersier & Wood (2002)
Sculptor	134	88	0.40	Kaluzny et al. (1995)
Draco	214	30	0.12	Kinemuchi et al. (2008)
Leo II	106	33	0.24	Siegel & Majewski (2000)
Ursa Minor	47	35	0.43	Nemec et al. (1988)
Leo I	47	7	0.13	Held et al. (2000)
Sextans	26	10	0.27	Mateo et al. (1995)
Canes Venatici I	18	5	0.22	Kuehn et al. (2008)
Bootes I	7	8	0.53	Siegel (2006)
Hercules	6	3	0.33	Musella et al. (2012)
Ursa Major I	5	2	0.29	Garofalo et al. (2013)
Leo IV	3	0	0.0	Moretti et al. (2009)
Coma Berenices	1	1	0.5	Musella et al. (2009)
Canes Venatici II	1	1	0.5	Greco et al. (2008)
Ursa Major II	1	0	0.0	Dall'Ora et al. (2012)
Segue 2	1	0	0.0	Boettcher et al. (2013)
Bootes II	1	0	0.0	Sesar et al. (2014)
Segue 1	1	0	0.0	Simon et al. (2011)

Table 2 from Baker & Willman 2015

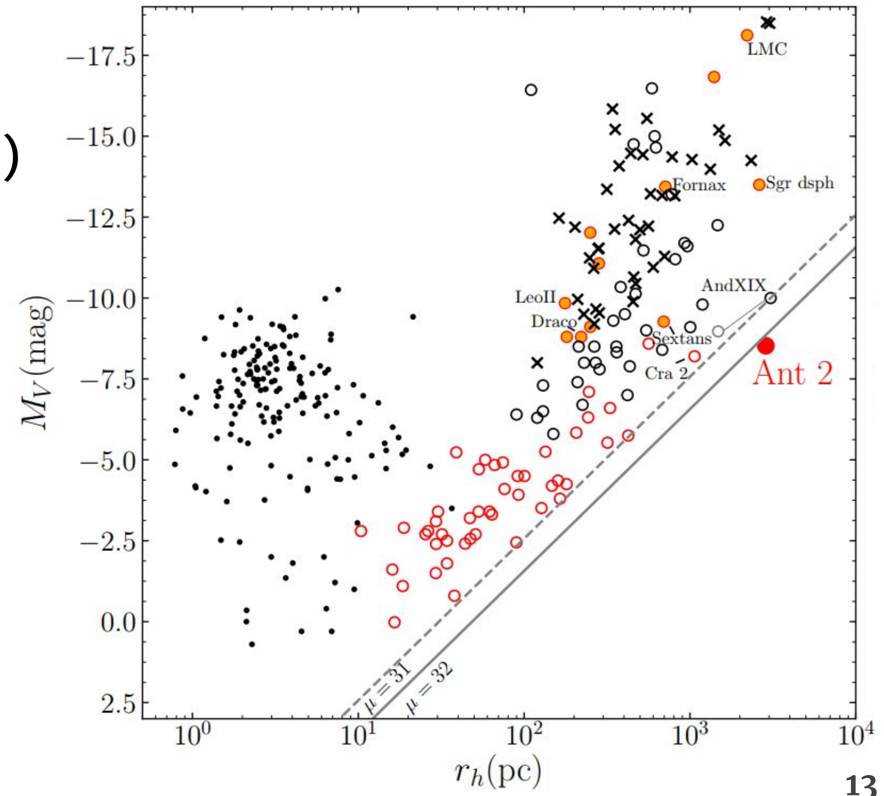
Antlia 2

Found via overdensity of Gaia DR2 RRL filtered with proper motions (RRL from Holl+ 2018 & Clementini+ 2018)

Portion of Fig. 3 from Torrealba et al. 2018



Portion of Fig. 11 from same

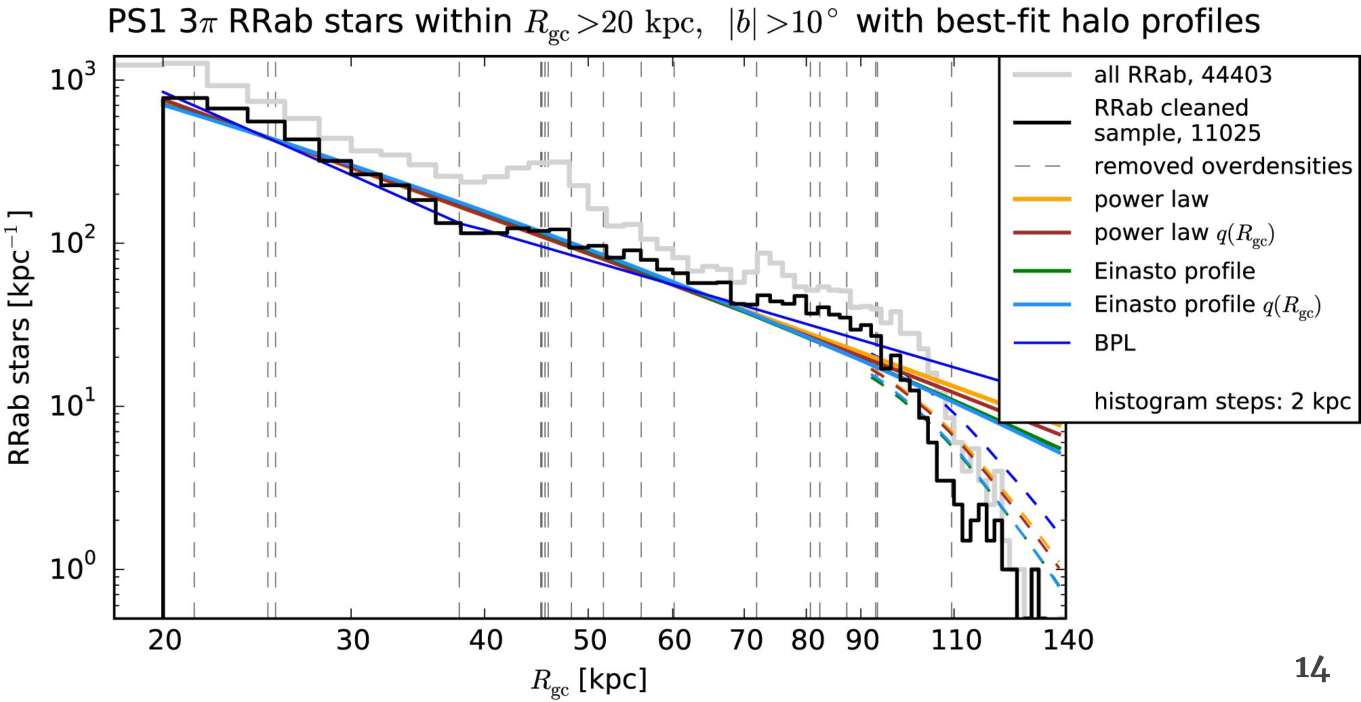


Shape of MW Profile

Simulations predict 1000's of RRL at d_{GC} > 100 kpc (Sanderson+ 2017)

These outer reaches still need exploring

Figure: Hernitschek et al. 2018 using RRL from Sesar et al. 2017



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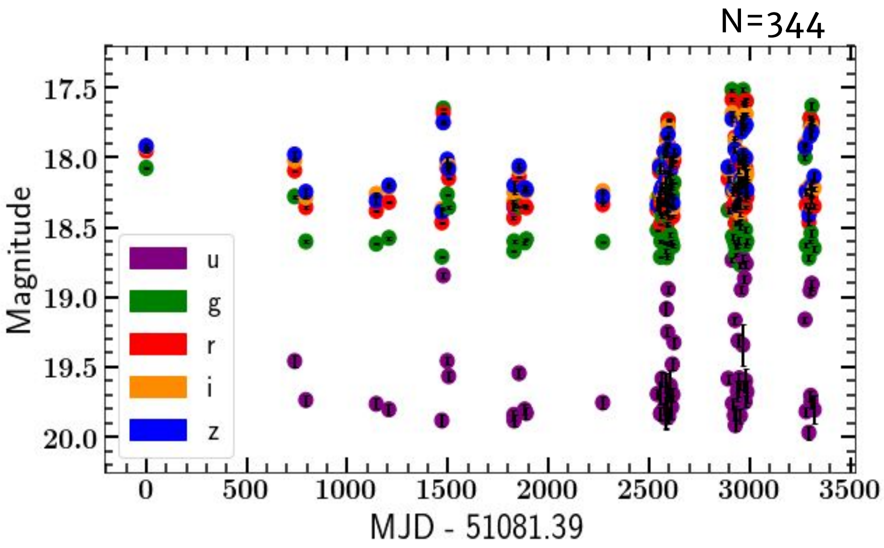
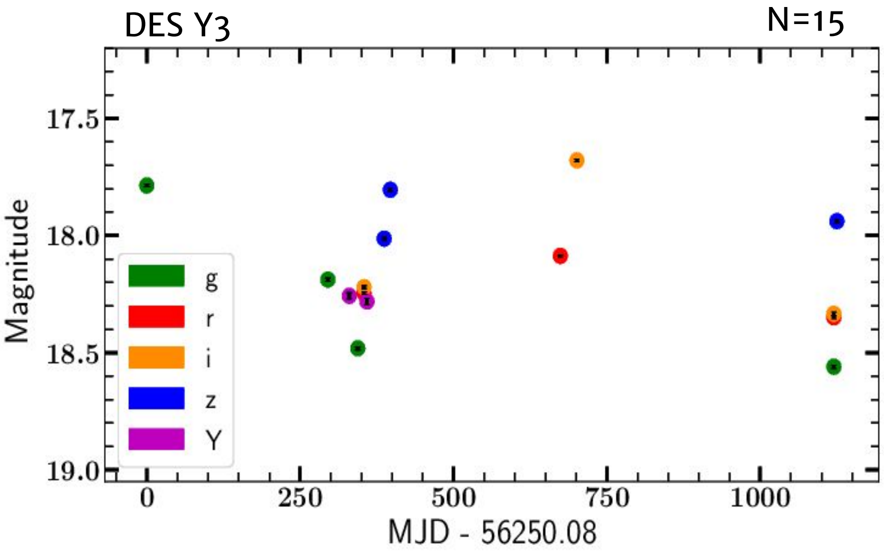
- Motivation: Why Search for RR Lyrae?
- **DES Data Set & Analysis**
- Results & Continuing Work

DES Y3 Light Curves

- Deep (g~23.5 in single exposure) and wide (~5000 deg^2) coverage
- Sparsely sampled and multiband

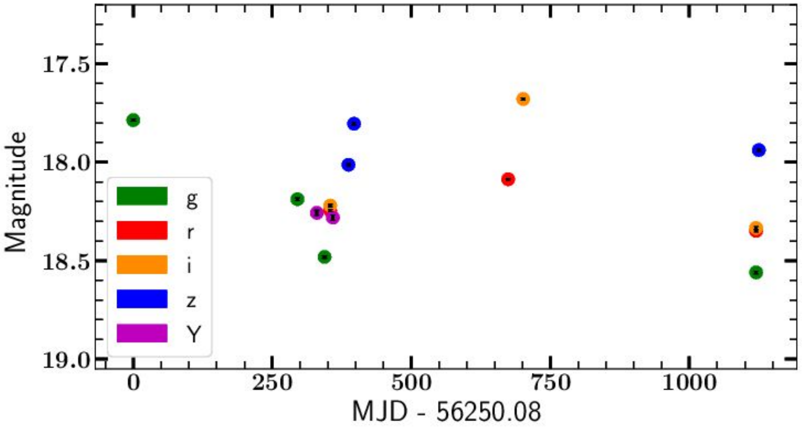




Data from Sesar et al. 2010 retrieved with gatspy (Vanderplas & Ivezic 2015)

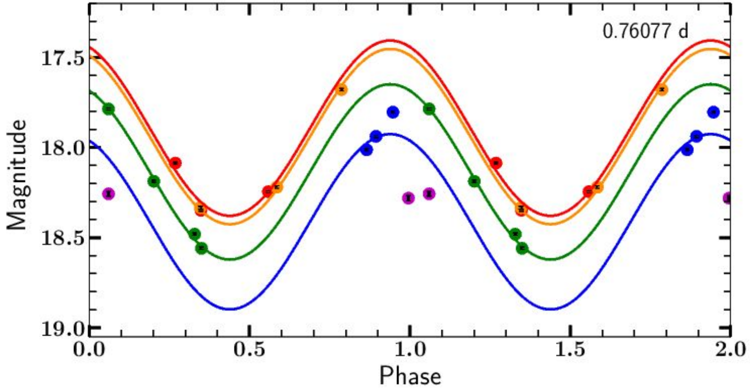
Light Curve Challenges

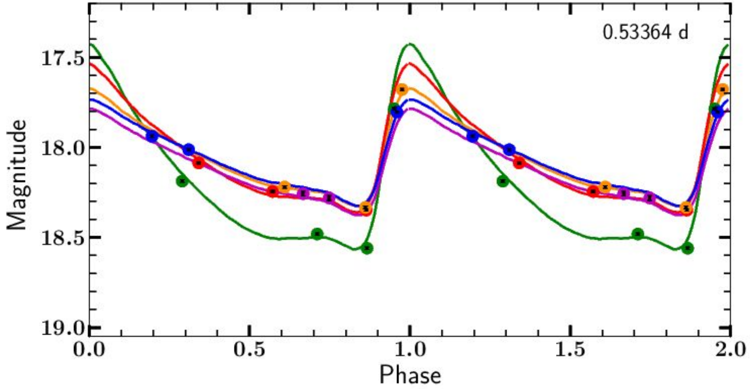
Time series data are sparsely sampled over several years and in multiple filters



Stringer et al. 2019

gatspy (Vanderplas & Ivezic 2015)





Initial Cuts to DES Data

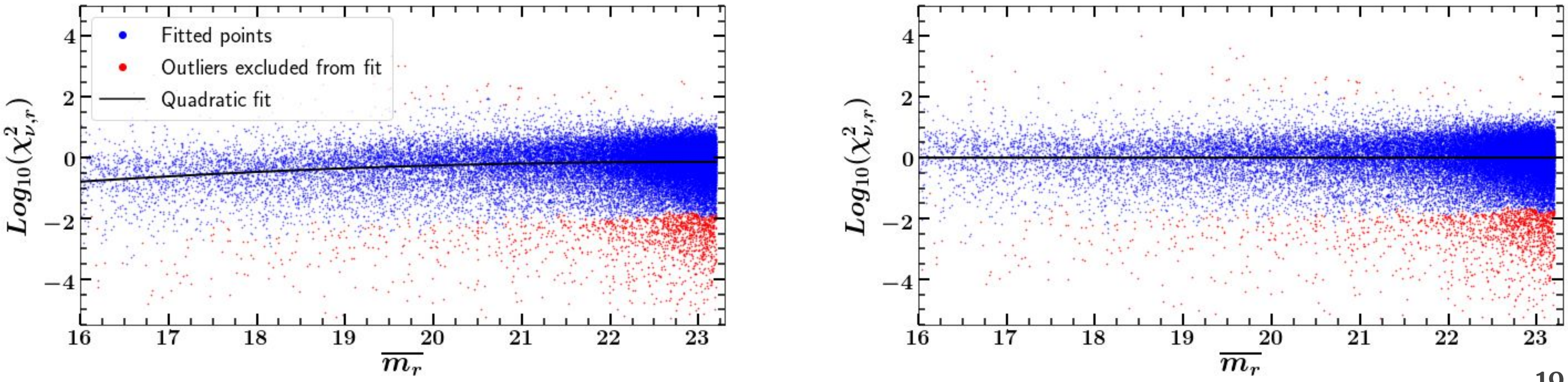
- ≥ 2 observations in a single band *griz*
- Star-Galaxy separation
- Coadd magnitudes within limiting magnitudes
- Errors < 0.3   (removes artefacts)

Reduces # of objects by a factor of ~10 (~2 billion → ~150 million)

Error Rescaling

- Most objects should be constant → trends are nonphysical
- Remove these by rescaling magnitude errors

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



Stringer et al. 2019

Training Set

Labeled RRL, variables and standard sources from SDSS stripe 82

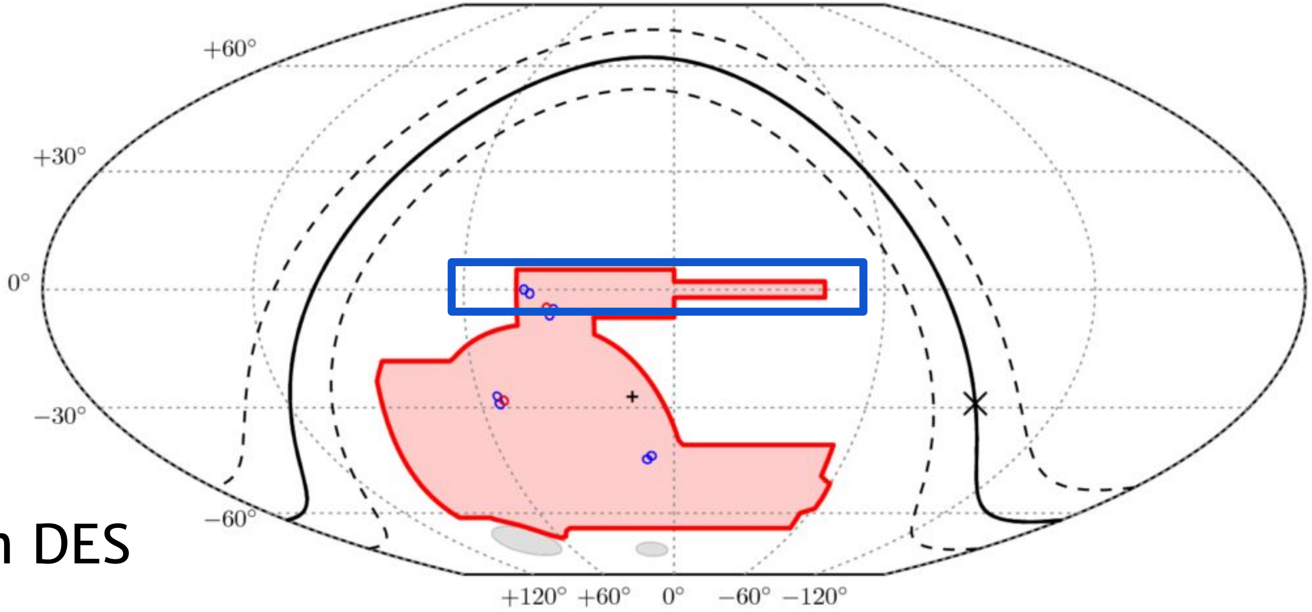
238 RRab[1]

58 RRc[1]

16752 variables[2]

641,710 constant[2]

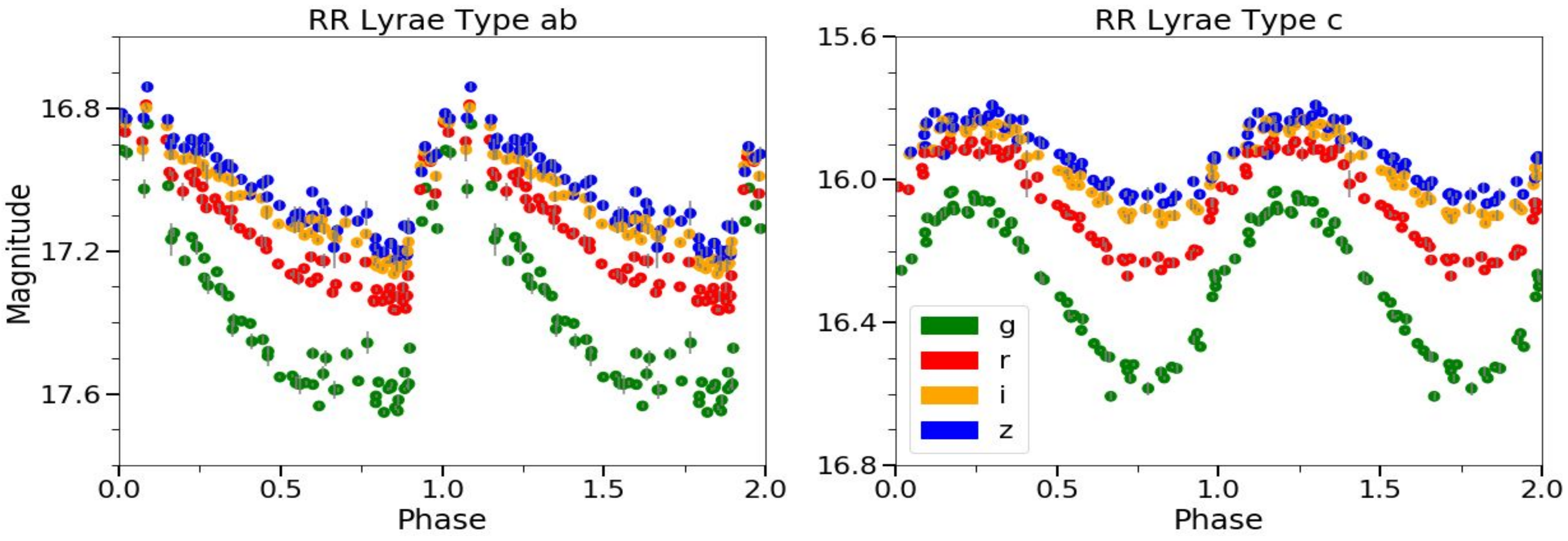
sources overlap with DES



1. Sesar et al. 2010 2. Ivezić et al. 2007

RRL Subtypes

RRab	0.4 < P < 1 d	$0.5 < A_g < 1.5$	Most common
RRc	0.2 < P < 0.5 d	$0.2 < A_g < 0.8$	Less numerous



Data from Sesar+ 2010

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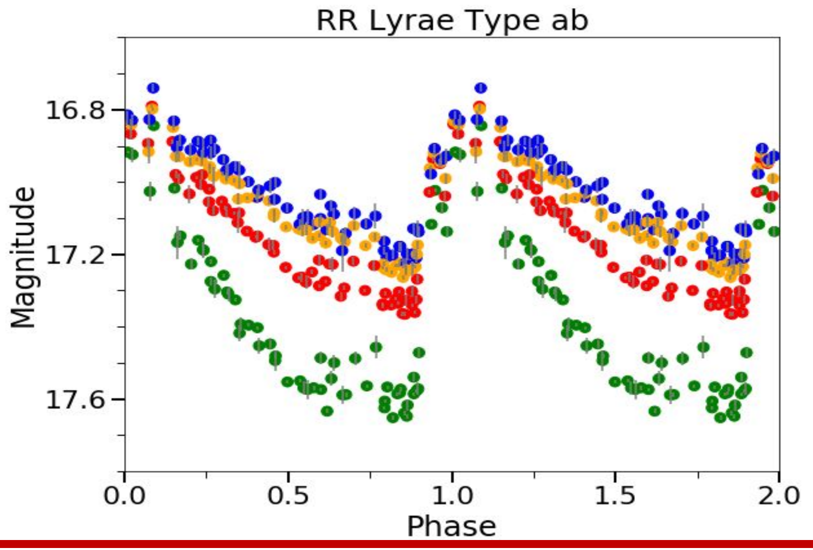
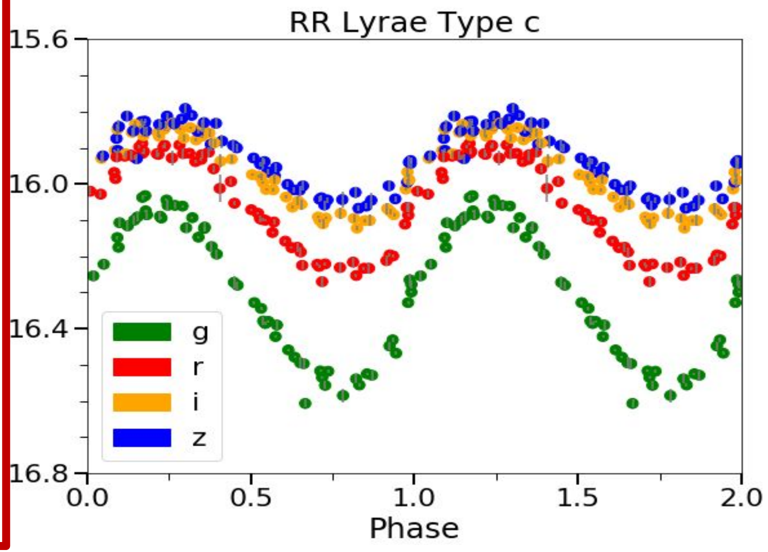


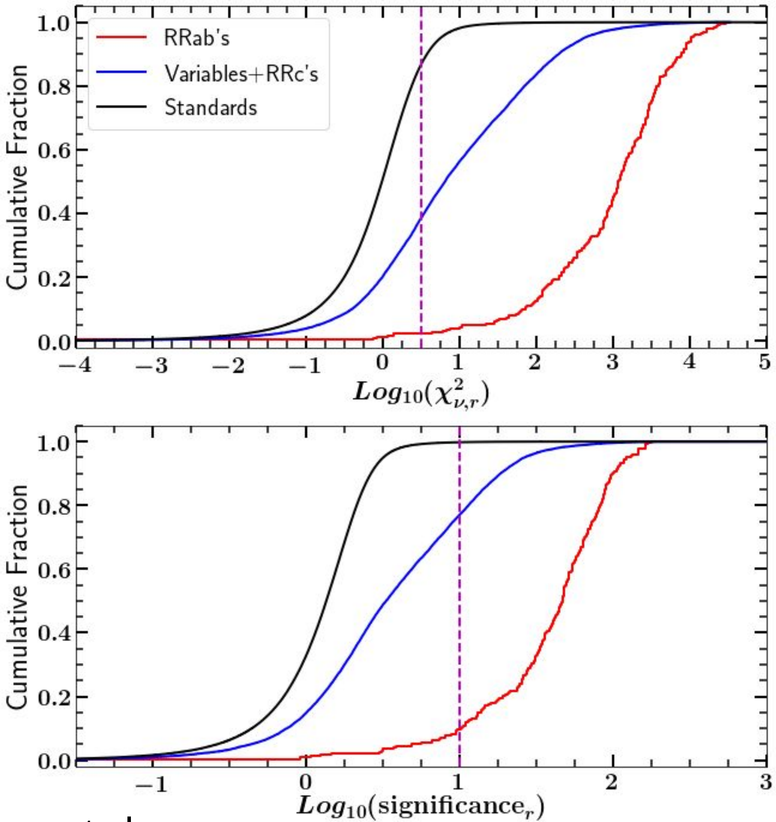


Data from Sesar+ 2010

Initial Variability Cuts

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

$$\text{significance}_b = \frac{m_{max,b} - m_{min,b}}{\sqrt{(\sigma^2_{max,b} + \sigma^2_{min,b})}}$$

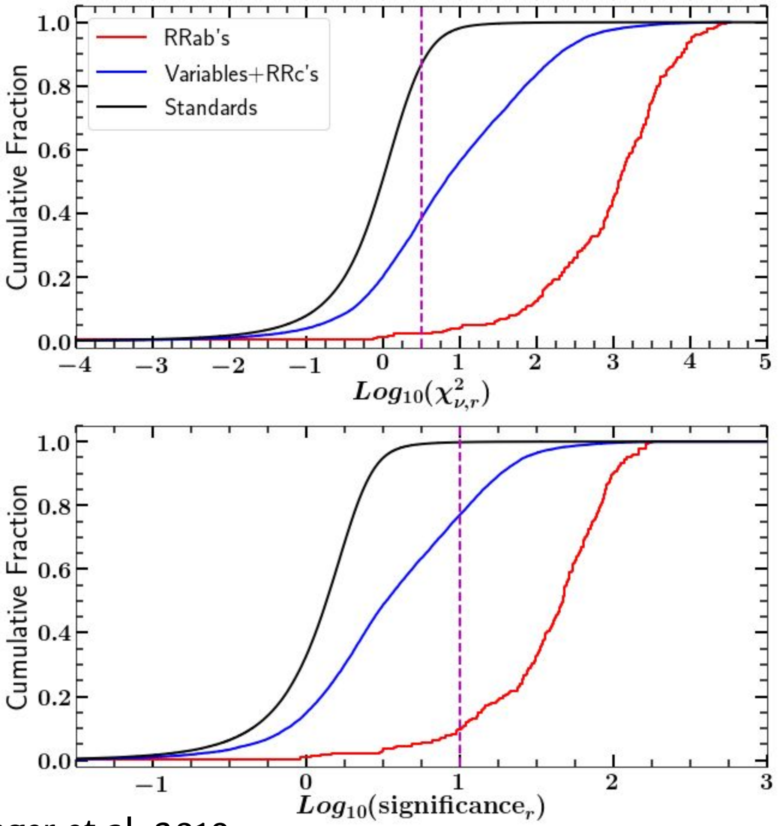


Stringer et al. 2019

Initial Variability Cuts

Training set that passed cuts:

RRab	~98%
Variables + RRc	~31%
Standards	< 0.5%



Stringer et al. 2019

Template Free Parameters

$$m_b = \mu + M_b(P) + A\gamma(t/P - \phi)$$

P : Period [days] (restricted to 0.44- 0.89 d)

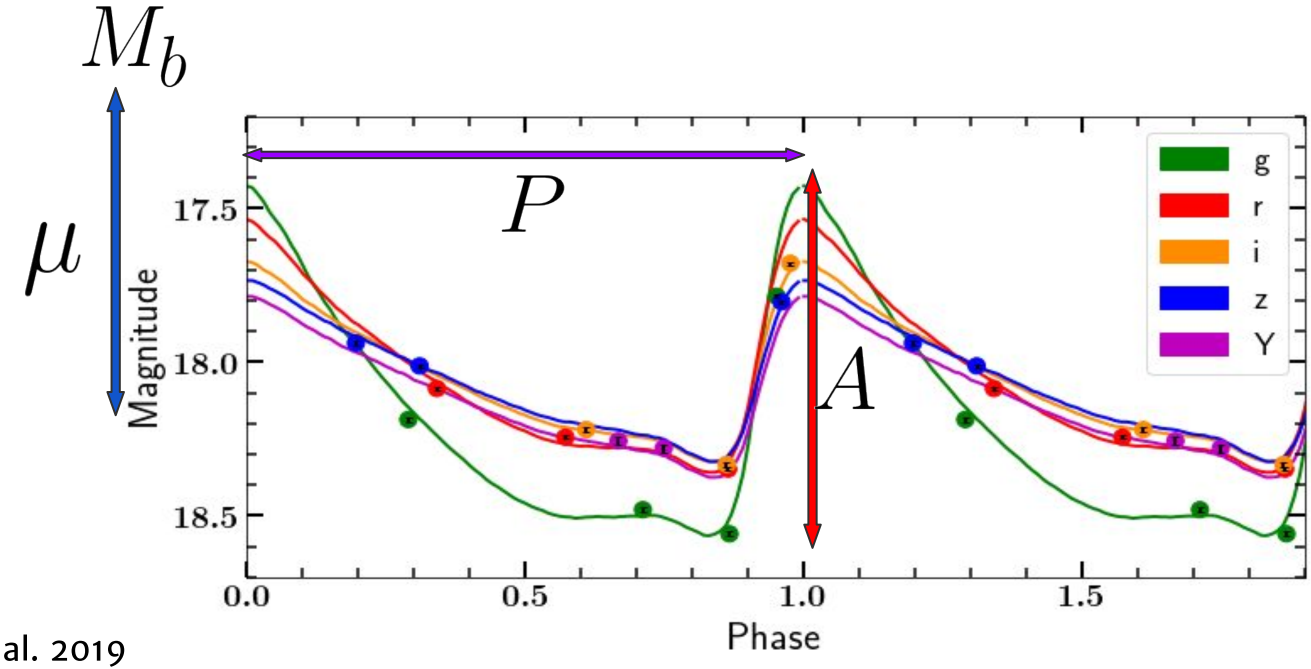
ϕ : Phase offset of maximum light [phase = (t/P)%1]

A : Amplitude in *g* [mag]

μ : Distance modulus [mag]

The RRab Template

$$m_b = \mu + M_b(P) + A\gamma(t/P - \phi)$$



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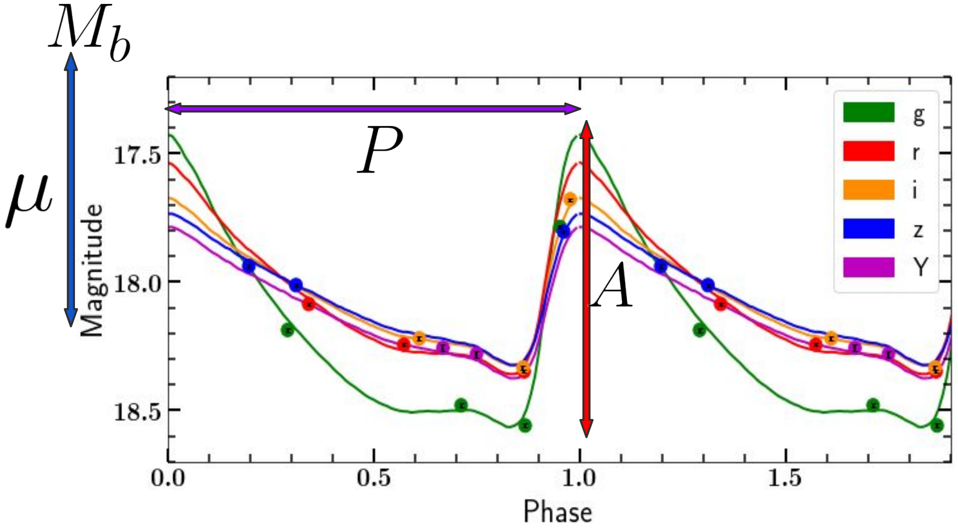
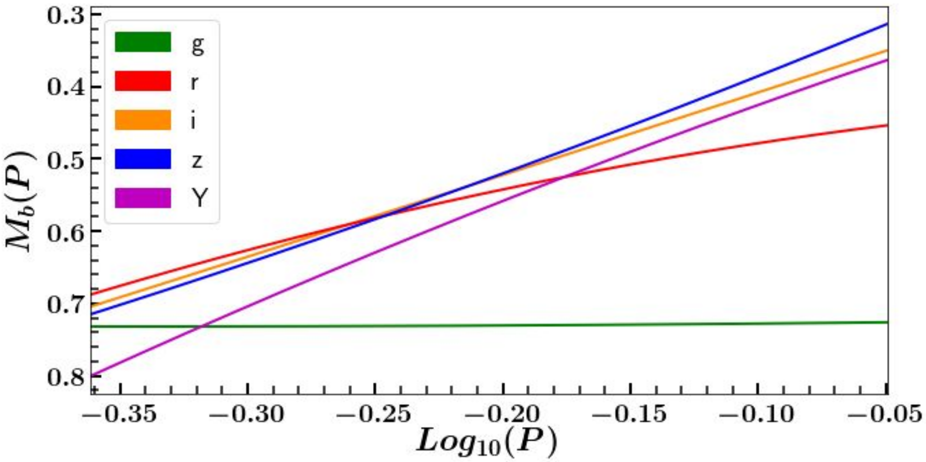
P–L Relation

$$M_b = \beta_{0,b} + \beta_{1,b}(log_{10}(P) + 0.2) + \beta_{2,b}(log_{10}(P) + 0.2)^2$$

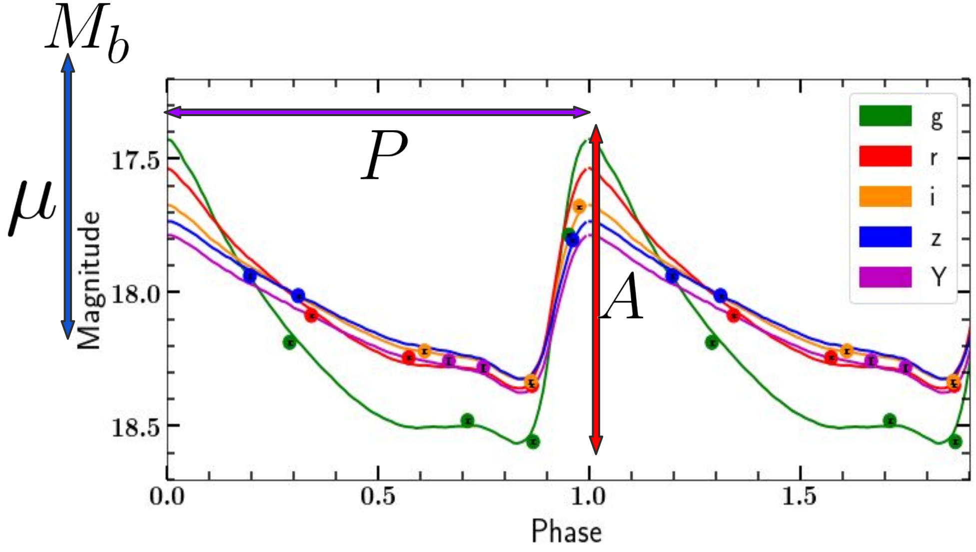


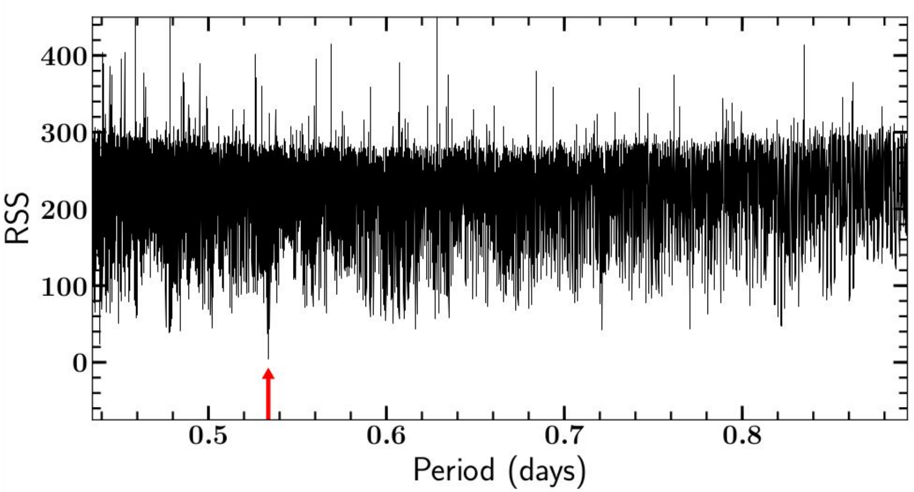


Stringer et al. 2019

Fitting the Template

$$m_b = \mu + M_b(P) + A\gamma(t/P - \phi)$$





Stringer et al. 2019

Classification

- Fit template to > 700,000 light curves– far too many to examine visually!
- Estimated template parameters are not enough to separate RRab from non-RRab
- Need an automated way to identify likely RRab candidates...

Random Forest Classifiers

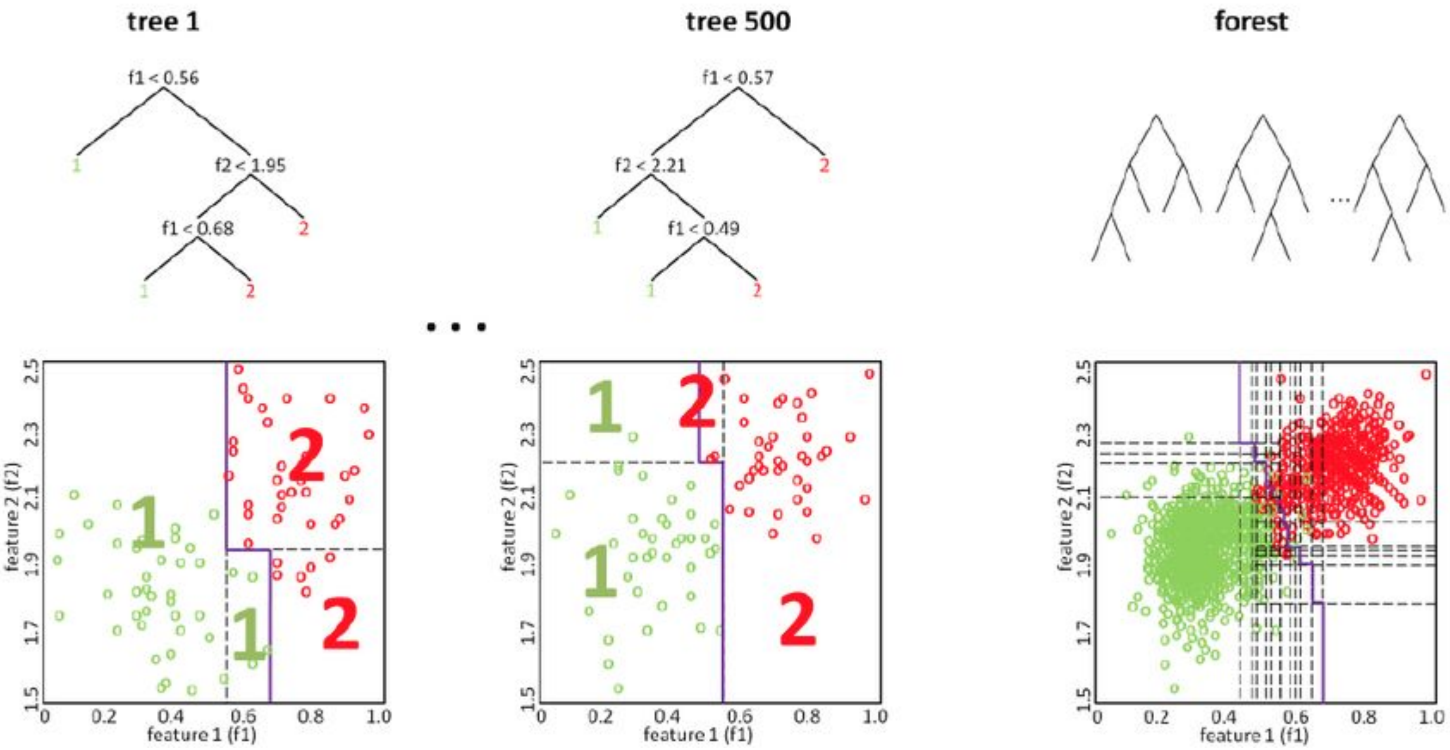


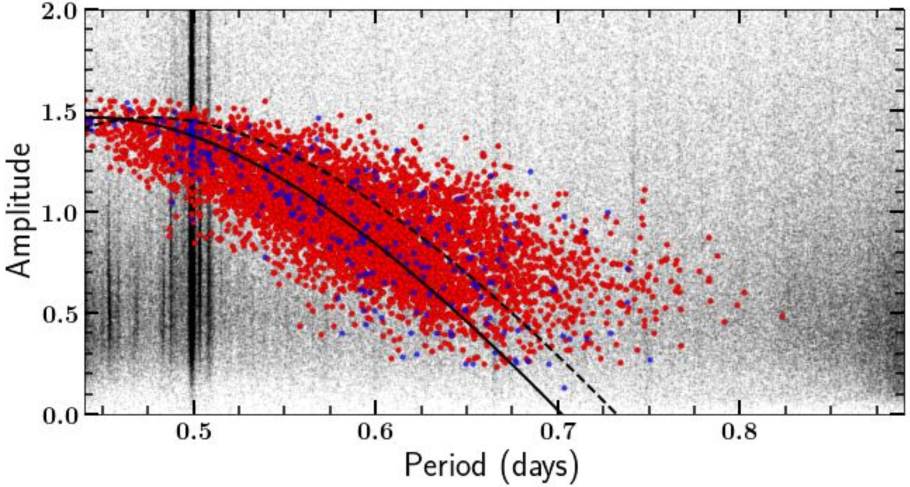
Figure from Hanselmann et al. 2009

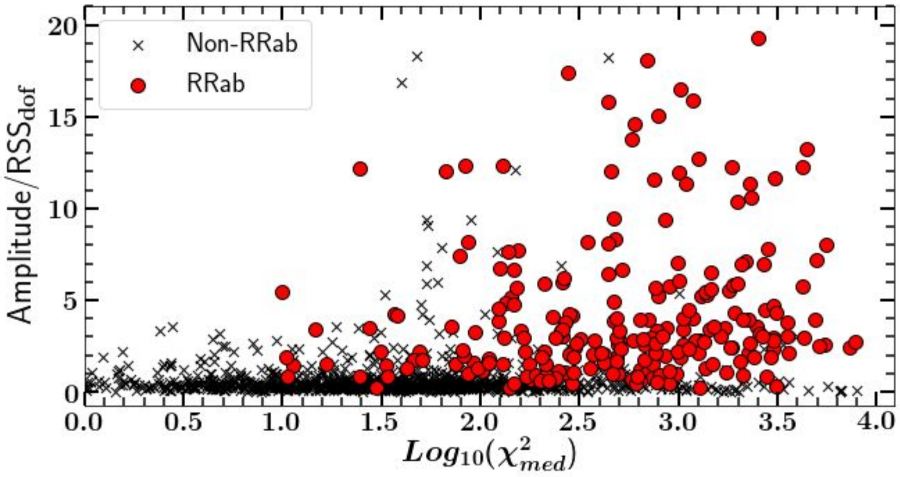
Features

Features based on:

- Quality of RRab template fits (RSS)
- Observational properties of RRab (amplitude, proximity to Oosterhoff relations)
- Light curve properties (concentration in phase, $\chi^2_{\nu,b}$)

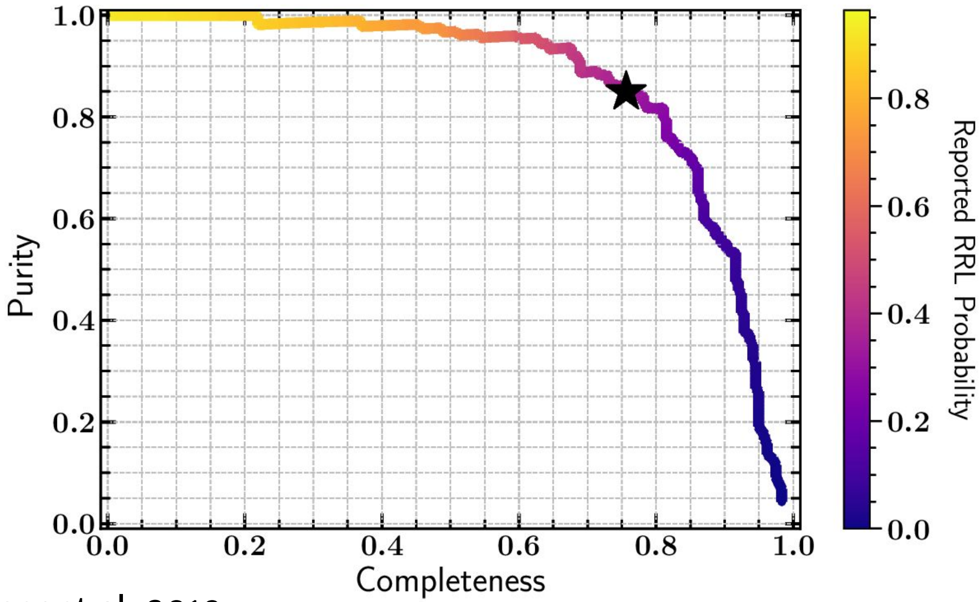
Stringer et al. 2019





Classifying RRab

- Train random forest classifier on labeled S82 objects
- Choose cutoff score to maximize purity & completeness



At a score of 0.35:

Purity ~ 85%

Completeness ~ 76%

Stringer et al. 2019

Visual Validation

- ~8000 objects passed the Random Forest score cut
- A visual check provides further validation and a clean set for Galactic studies

* Used LIneA SkyViewer extensively

Compelling Candidates

10570600134089

P = 0.577 d

$p = 0.928$

A = 0.925

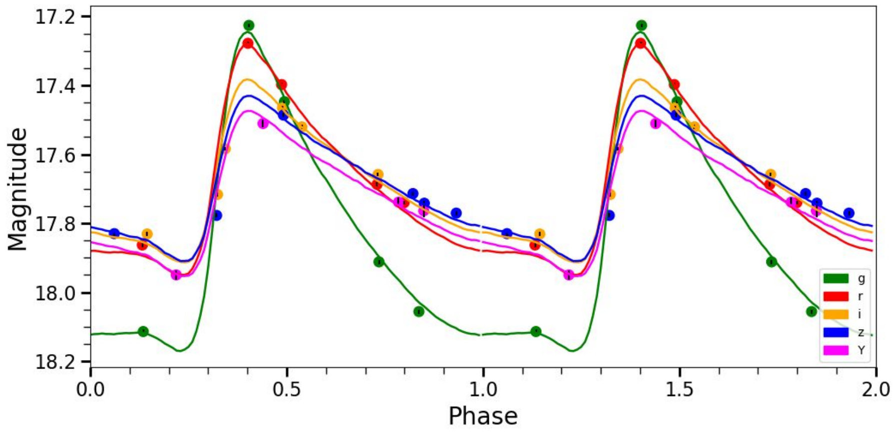
$\kappa = 0.218$

$\mu = 17.12$

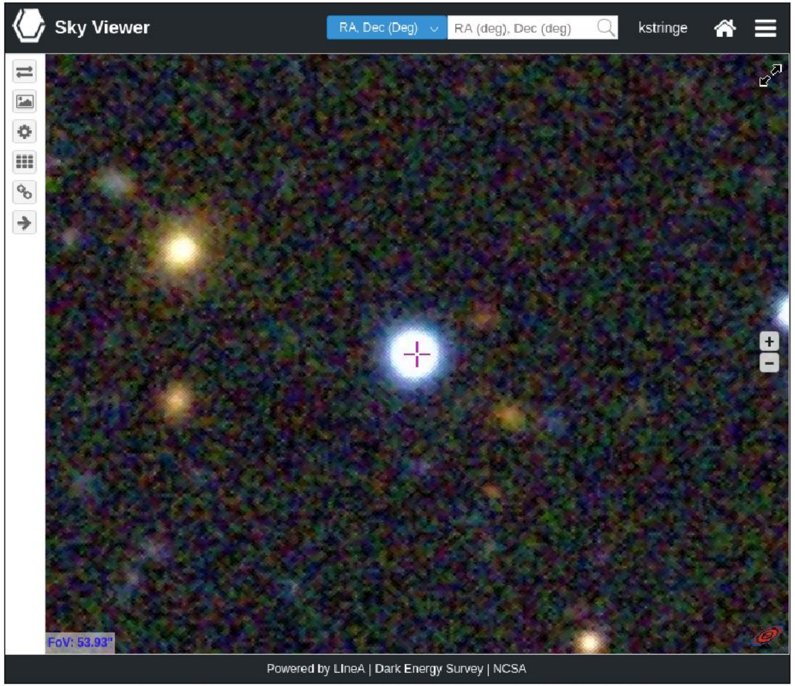
$E(B-V) = 0.030$

$rss_\nu = 0.118$

N = 26



$(\alpha, \delta)_{hms}$= 1:47:41.82 +3:28:12.04



$(\alpha, \delta)_{deg}$= 26.92426 +3.470010

Ambiguous Candidates

11175600292521

P = 0.571 d

$p = 0.402$

A = 1.148

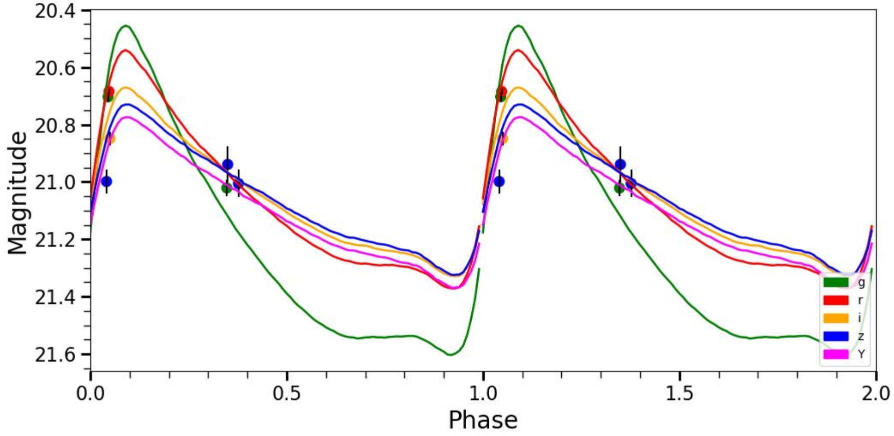
$\kappa = 1.406$

$\mu = 20.48$

$E(B-V) = 0.047$

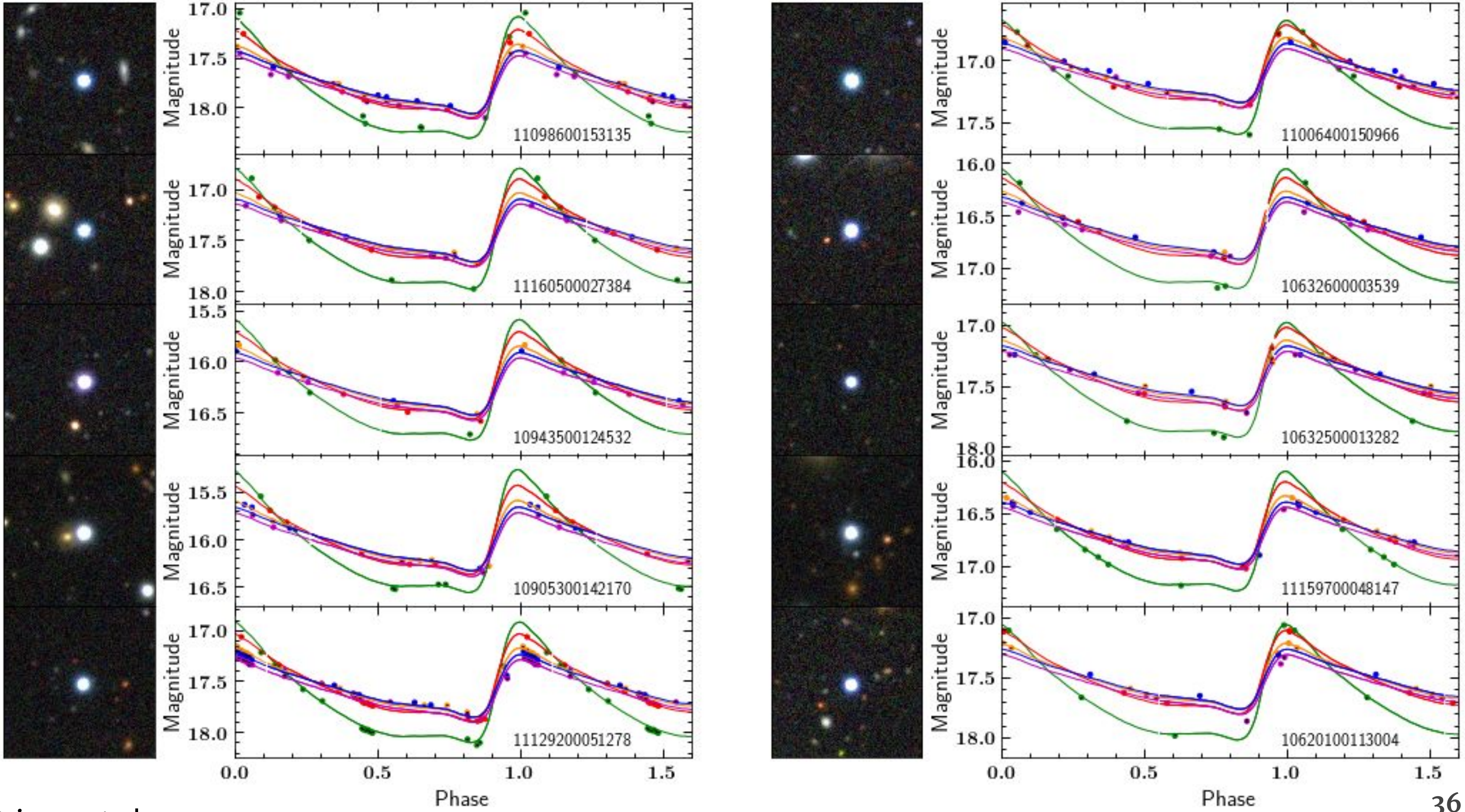
$rss_\nu = 0.232$

N = 7



$(\alpha, \delta)_{hms}$= 4:37:14.67 -65:51:41.58

$(\alpha, \delta)_{deg}$= 69.31114 -65.86155



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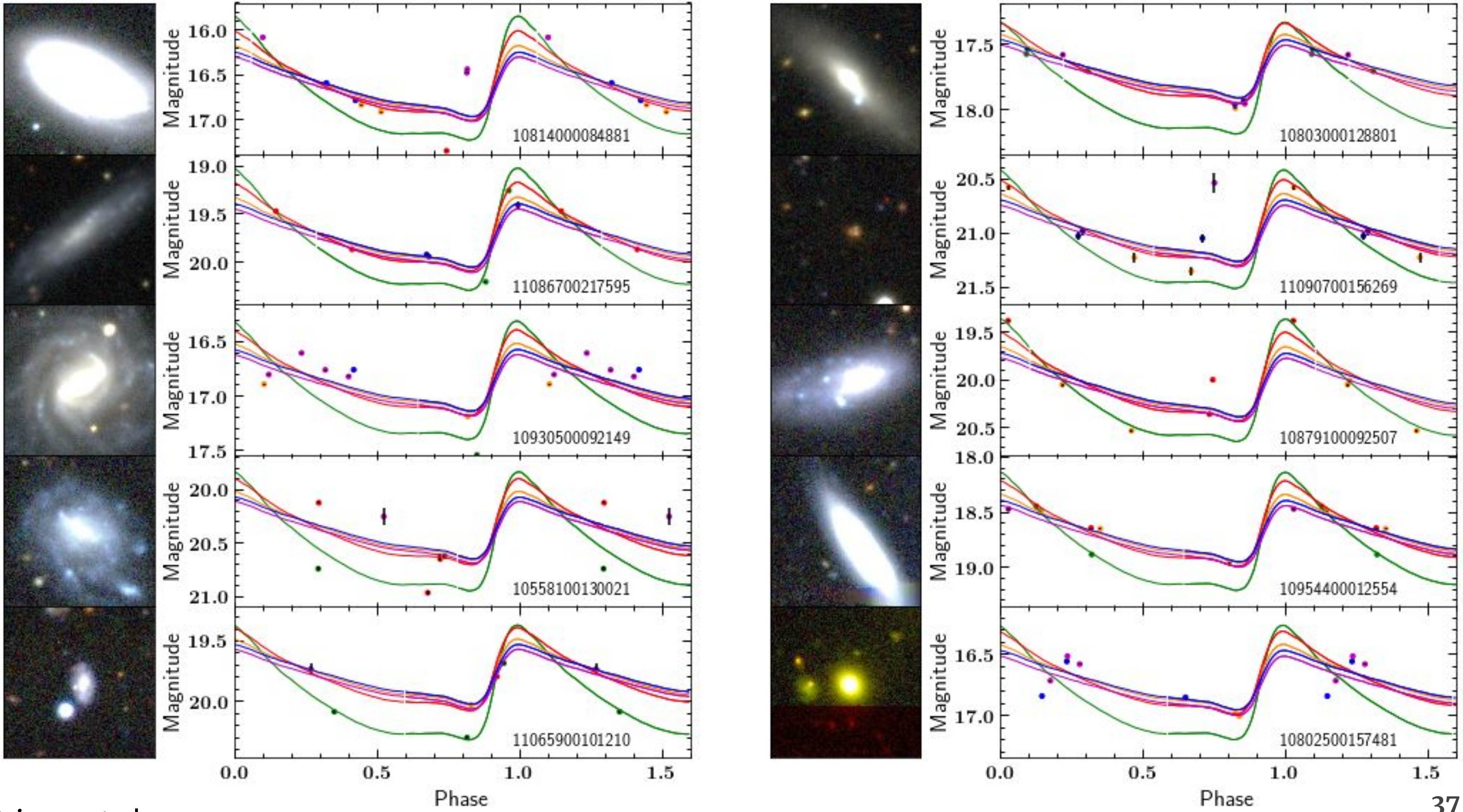
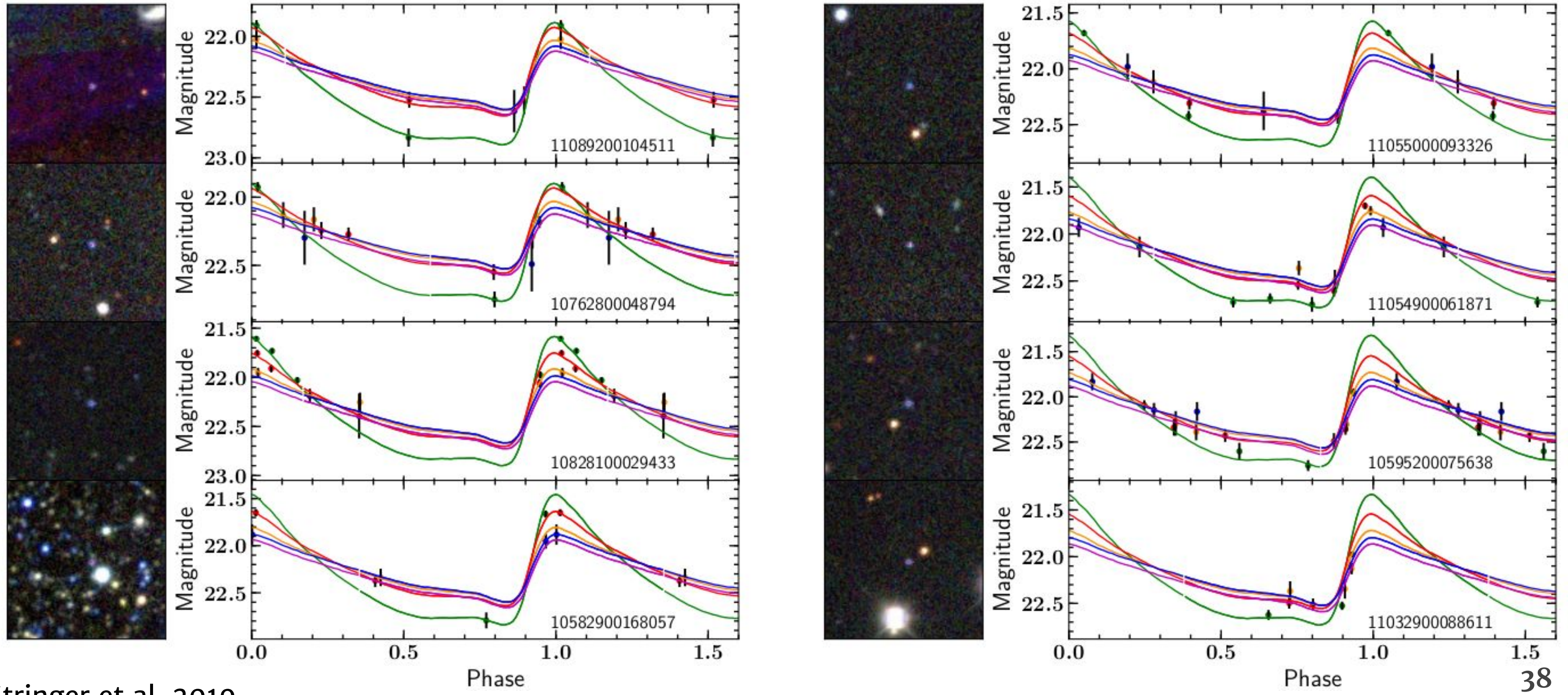


Stringer et al. 2019

Distant Candidates



Stringer et al. 2019

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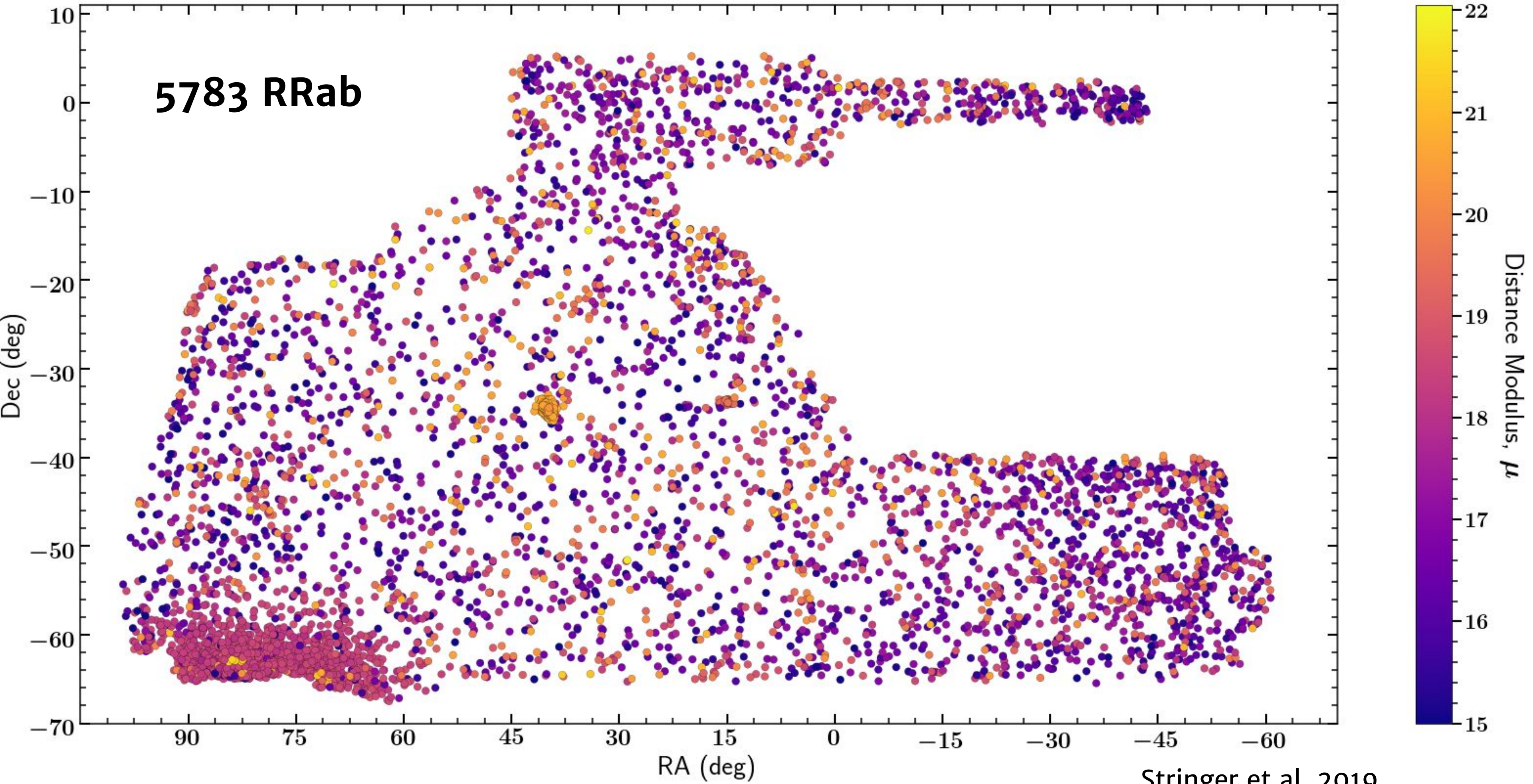
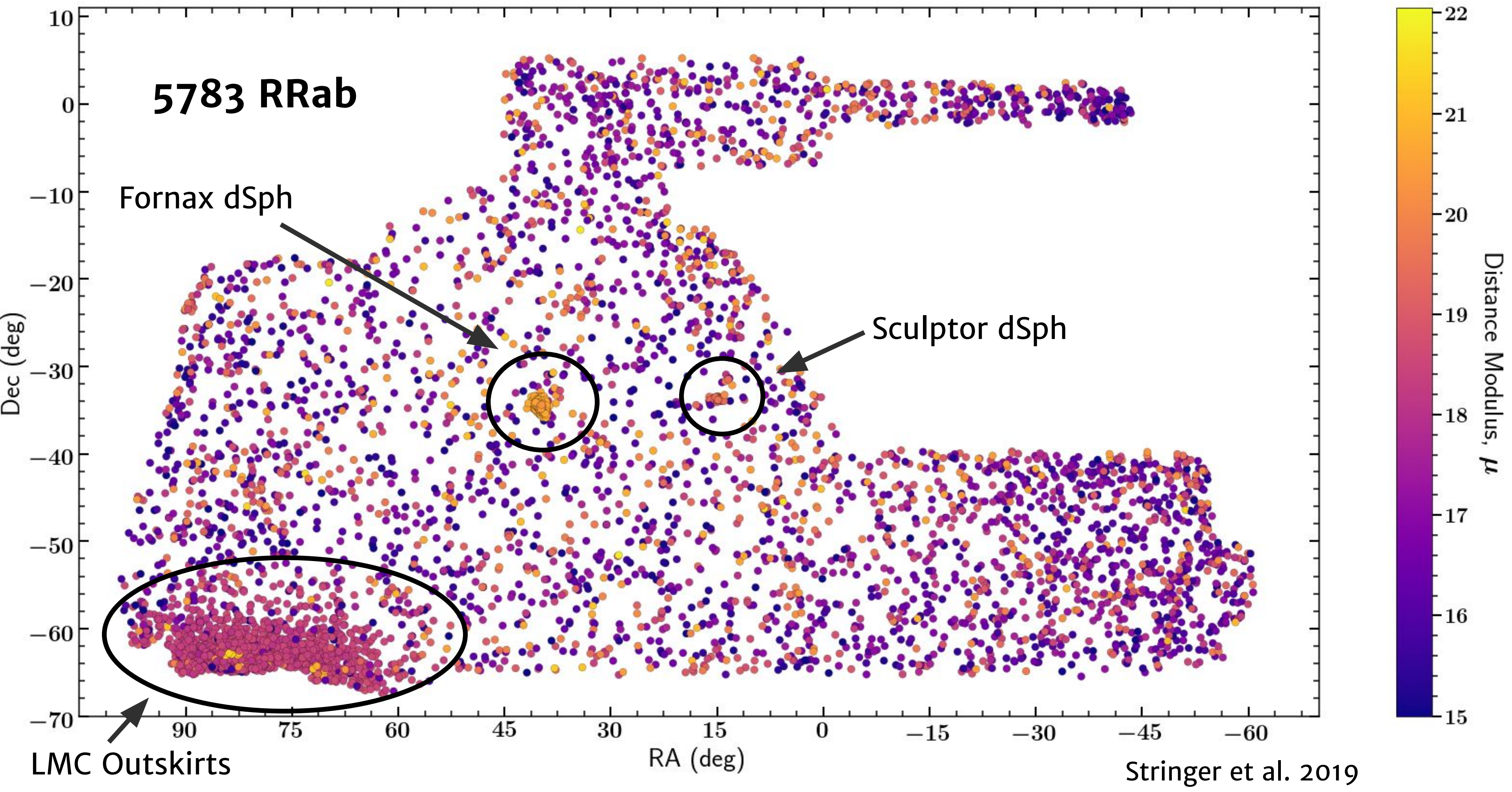
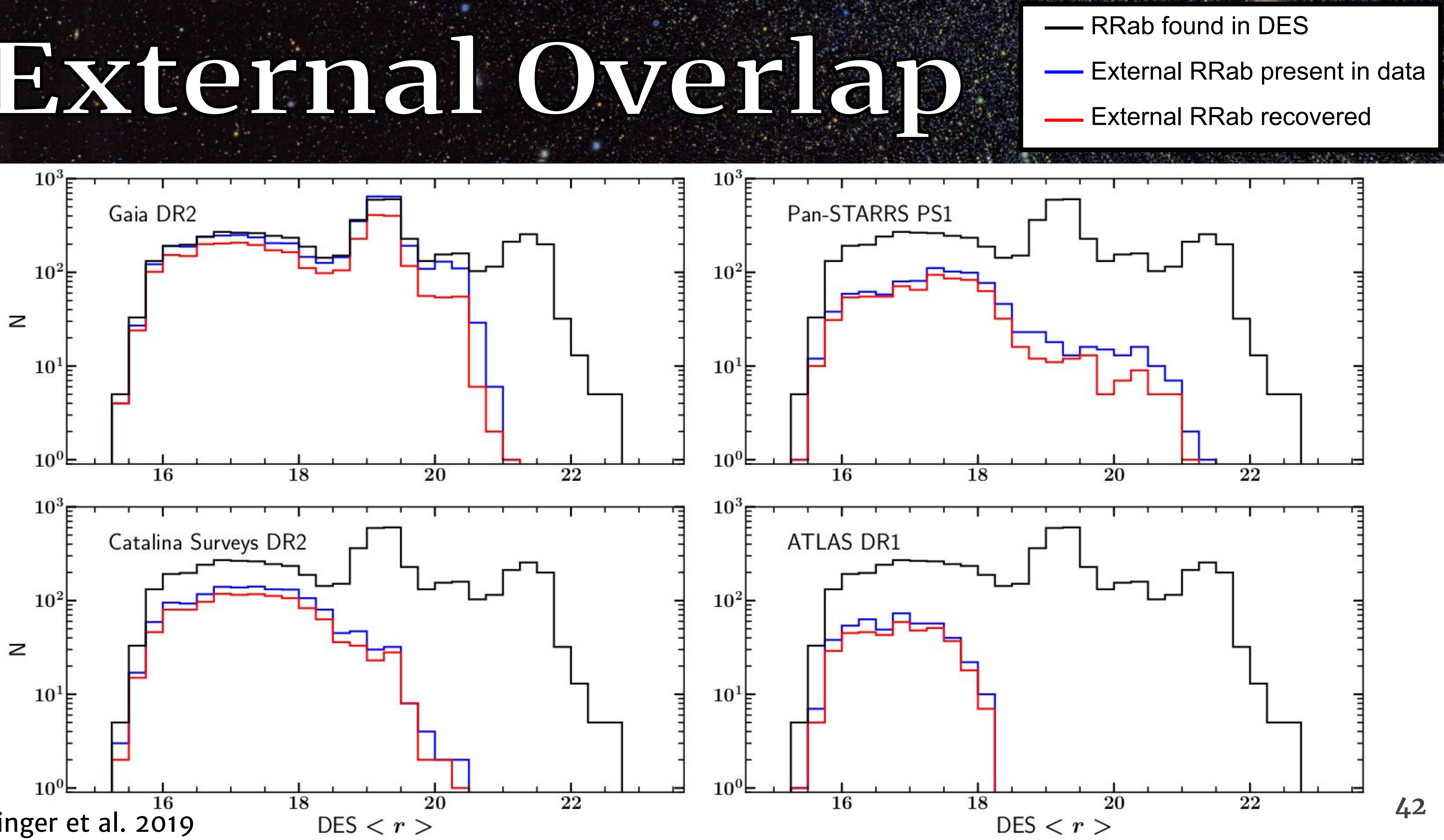


Stringer et al. 2019



5783 RRab
Fornax dSph
Sculptor dSph
LMC Outskirts
Dec (deg)
RA (deg)
Distance Modulus, μ
10
0
−10
−20
−30
−40
−50
−60
−70
90
75
60
45
30
15
0
−15
−30
−45
−60
22
21
20
19
18
17
16
15
Stringer et al. 2019

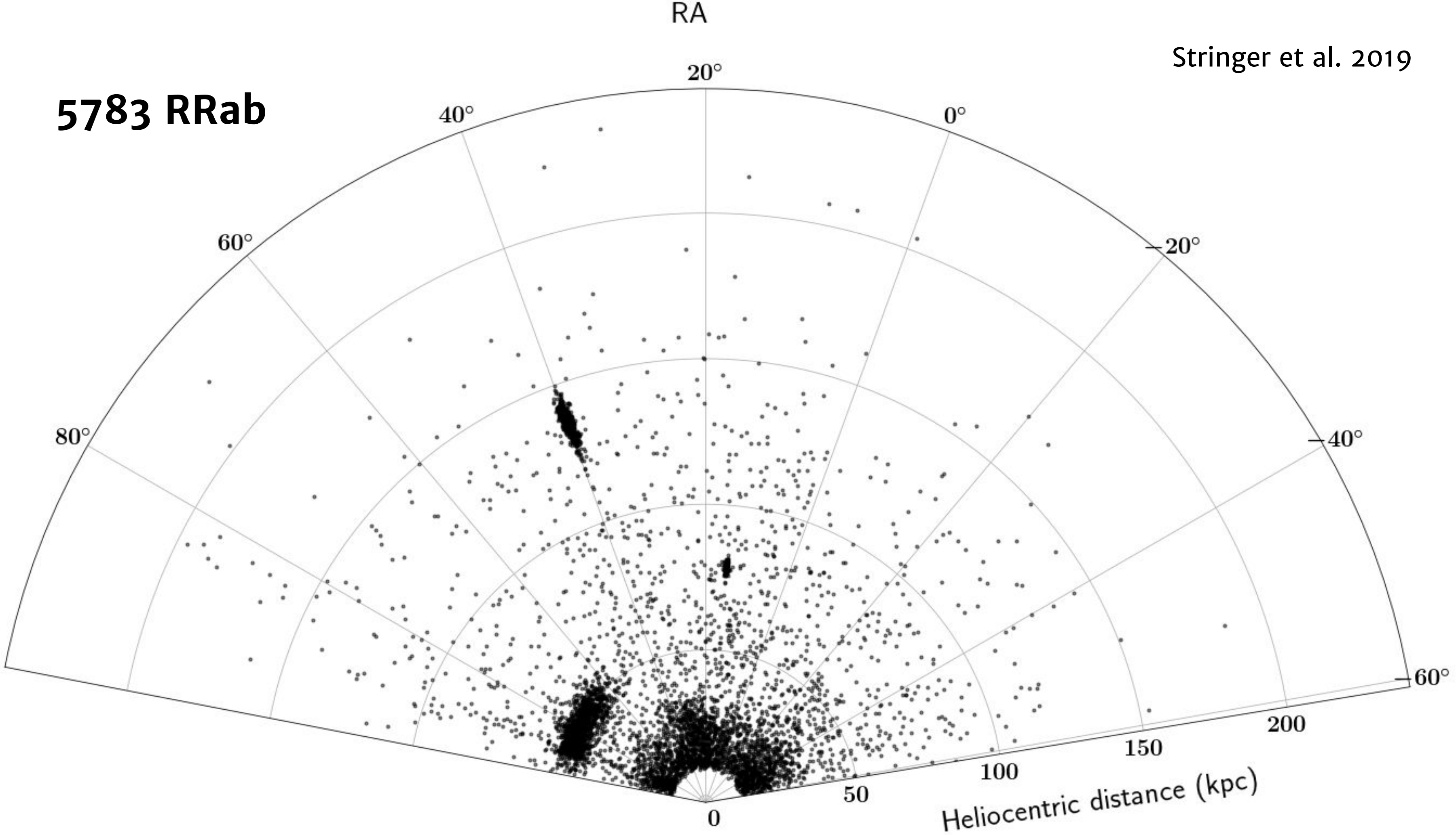
External Overlap



Stringer et al. 2019

5783 RRab

Stringer et al. 2019

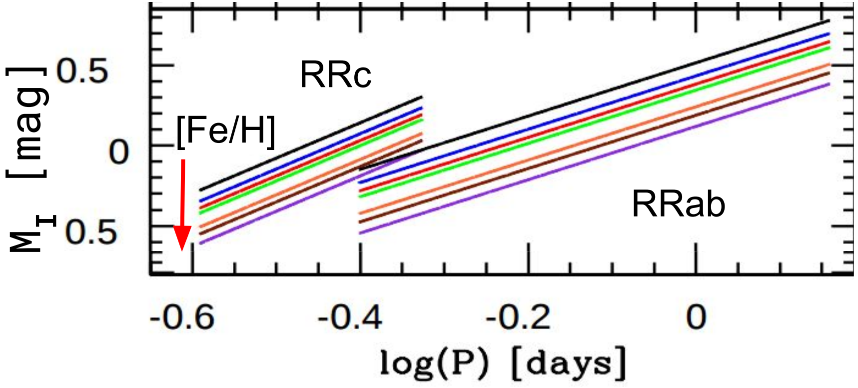


Distance Uncertainties

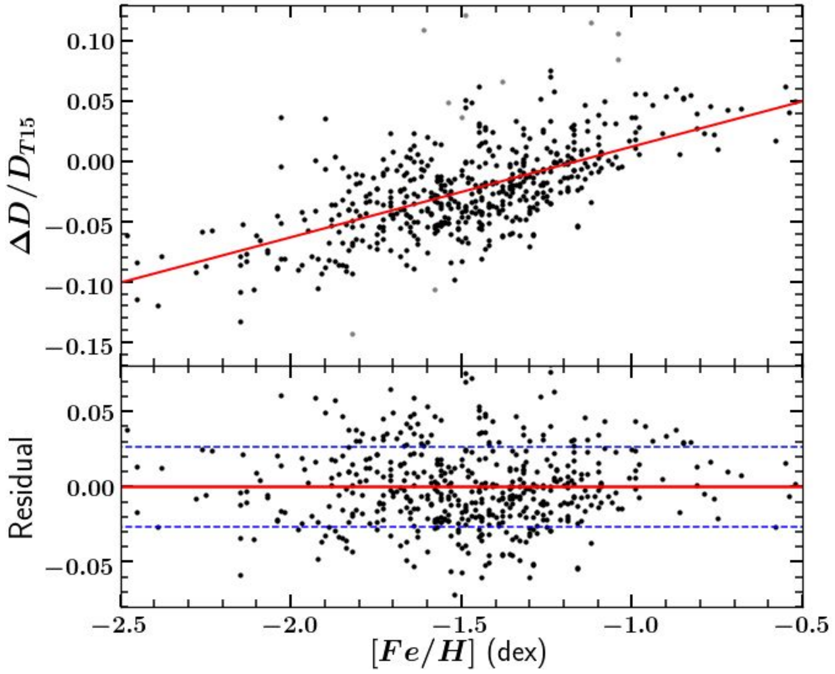
Estimated distance accuracy depends on metallicity

Sys ~ 4.2%

Stat ~ 2.8%



Marconi et al. 2015



Stringer et al. 2019 using data from Torrealba et al., 2015

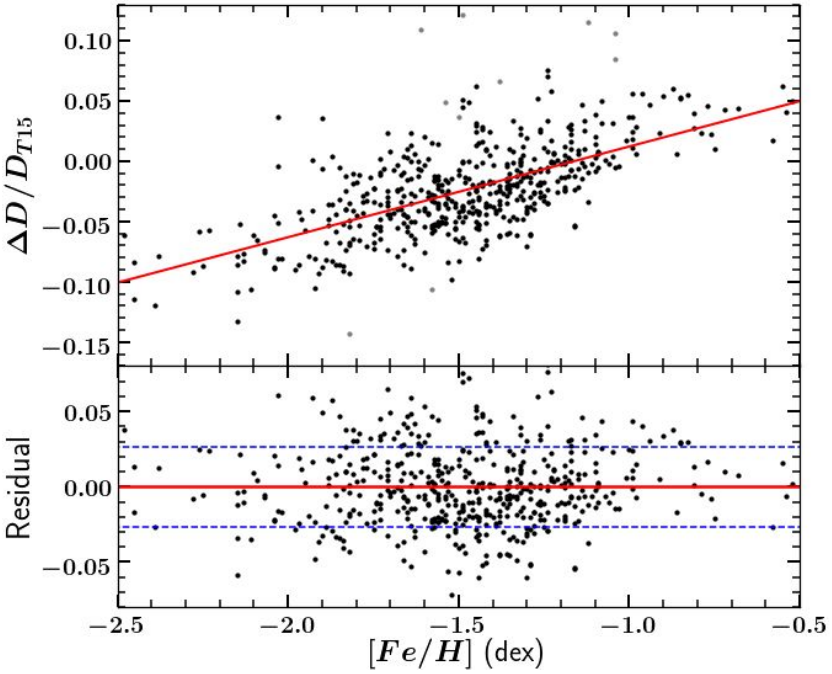
Distance Uncertainties

Estimated distance accuracy depends on metallicity

Sys ~ 4.2%

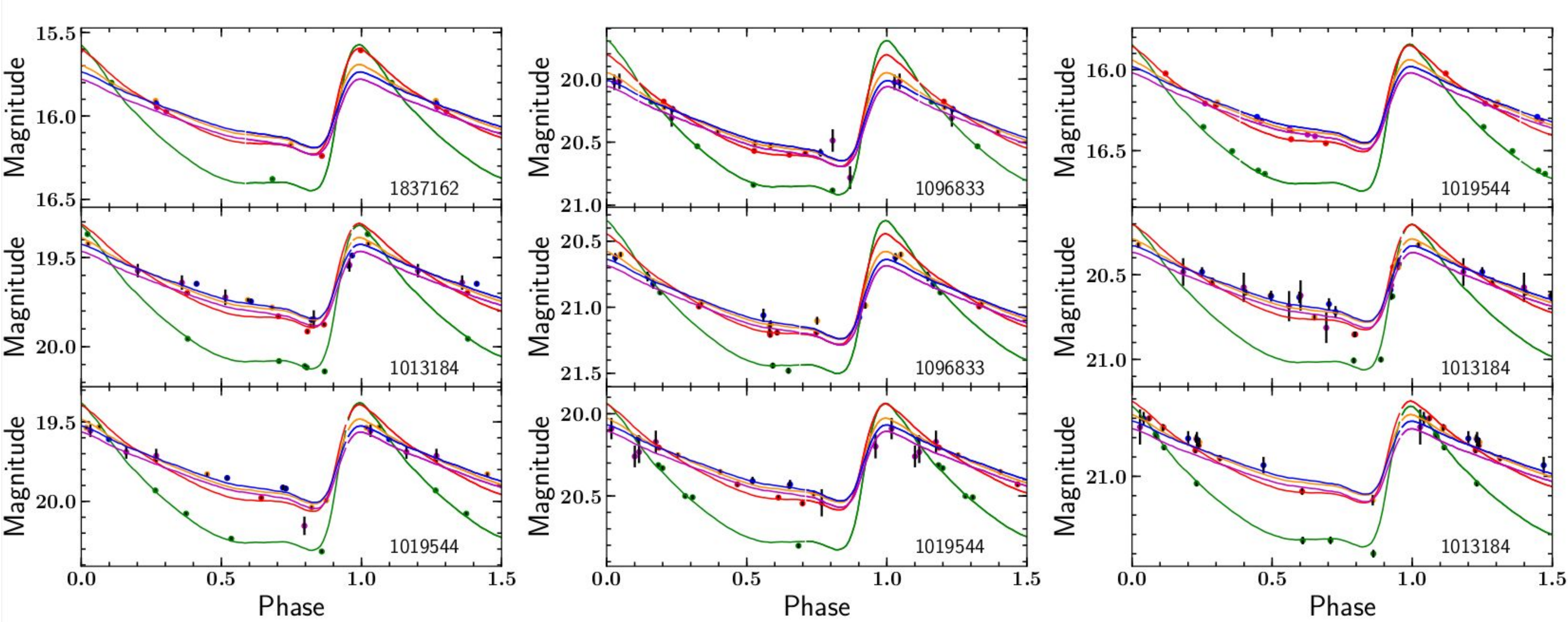
Stat ~ 2.8%

What about the other uncertainties?



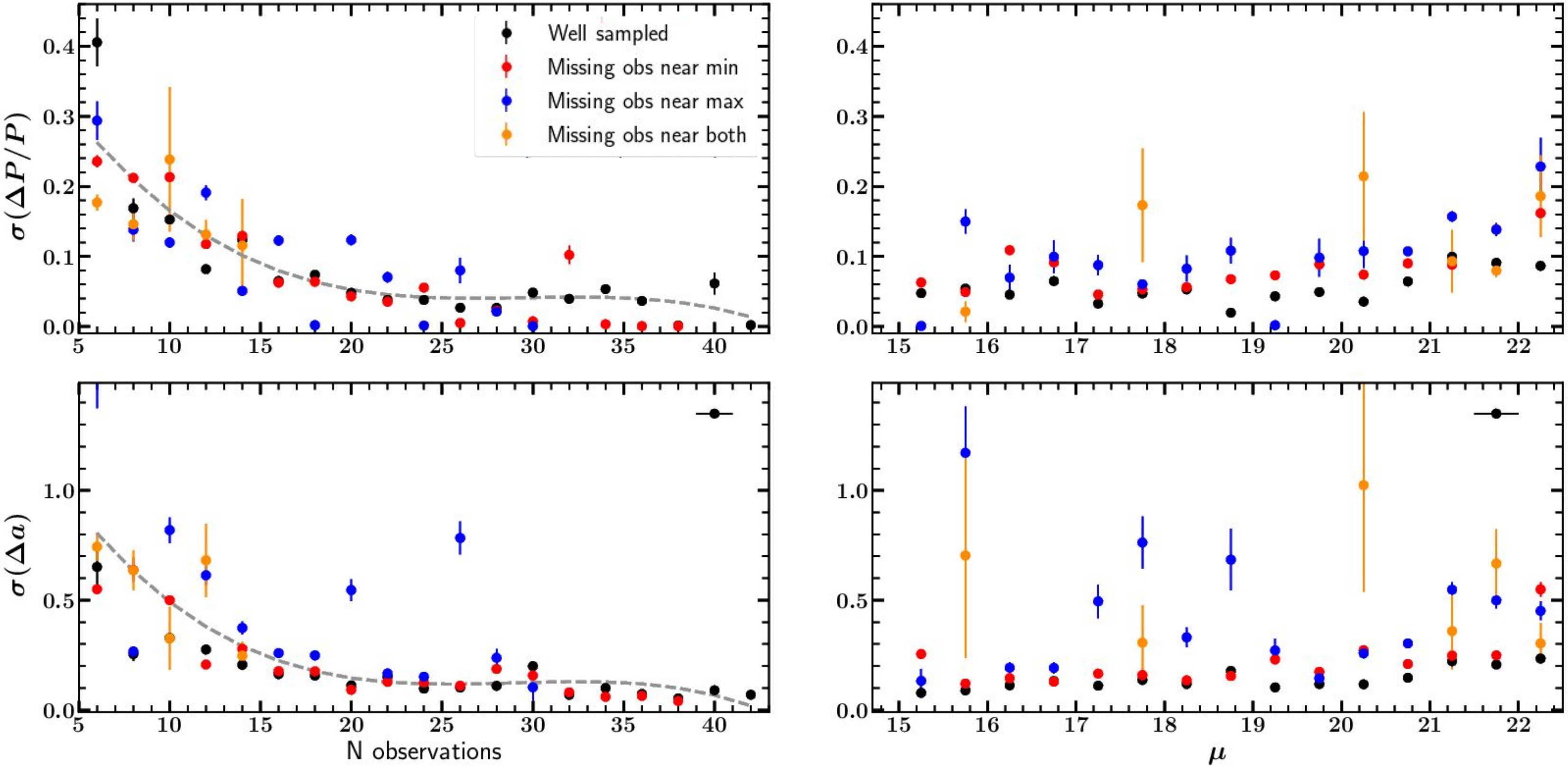
Stringer et al. 2019 using data from Torrealba et al., 2015

Simulating Light Curves



Stringer et al. 2019 using data from Sesar et al. 2010 in the gatspy package (Vanderplas & Ivezic 2015)

Template Performance

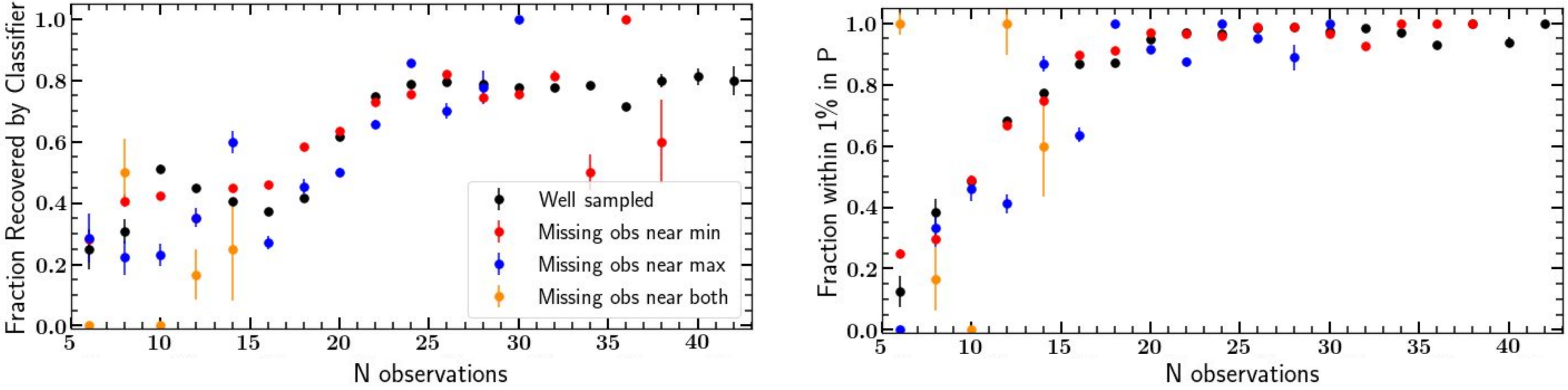


Stringer et al. 2019

Classifier Performance

Classifier doesn’t always recover RRab even when the period is correct → Future work

Stringer et al. 2019



Data Products Available

RRab Template & Fitting Algorithm available at

https://github.com/longjp/rr-templates

Data and documentation located at

https://des.ncsa.illinois.edu/releases/other/y3-rrl

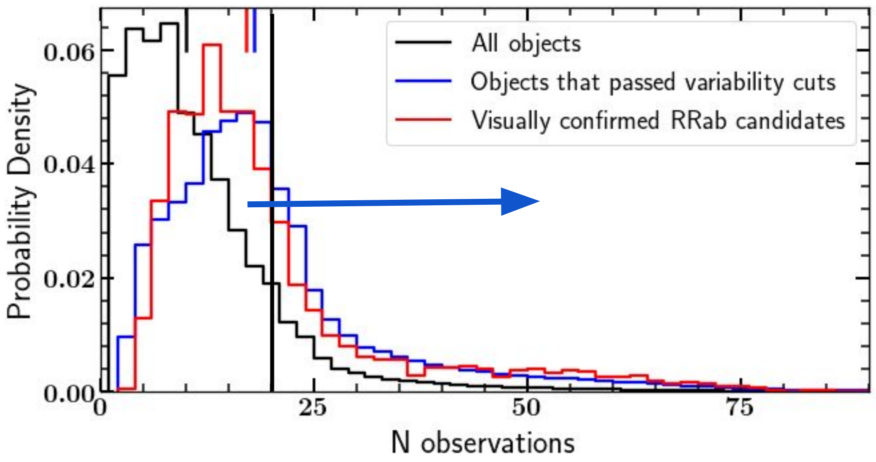
Thank you Science Release Team!

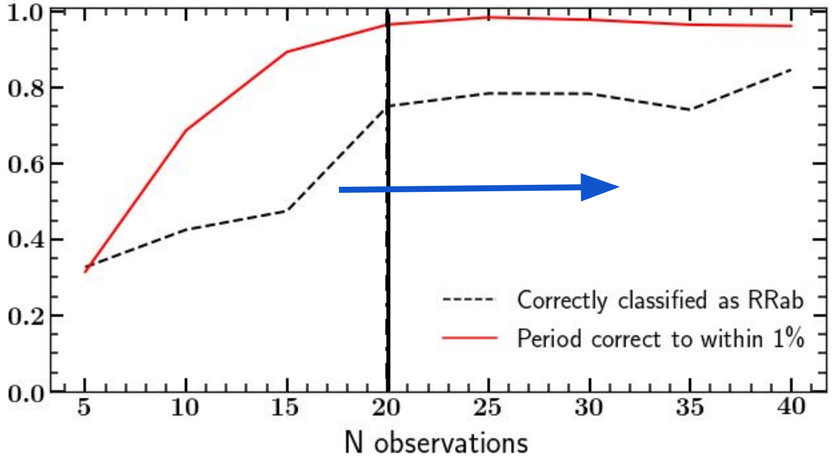
(Matias Carrasco Kind, Aurelio Carnero Rosell & Keith Bechtol)

More DES Data Incoming

Year 6 observations have concluded

Additional observations → improved performance





Stringer et al. 2019

Application to LSST

- Set to begin full science ops late 2022/early 2023
- Expected ~80 observations in *ugrizY* combined/ year
- This method useful within first year
- Other excellent methods available (e.g. Vanderplas & Ivezić 2015, Hernitschek+ 2016, Sesar+ 2017, Huijse+ 2017)

Credit: LSST Project/NSF/AURA

Summary

- RRL are useful for locating and understanding the Milky Way's satellites and structure
- Our approach can recover RRL even in sparse and multiband time series data
- Incoming DES Y6 data will enable improved RRL detection

Thank you!