Mapping the Milky Way Halo with the Dark Energy Survey

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Collaboration

Astronomers

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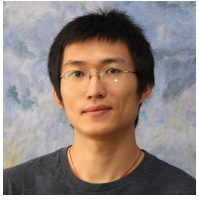


Zhenfeng Lin

Outline

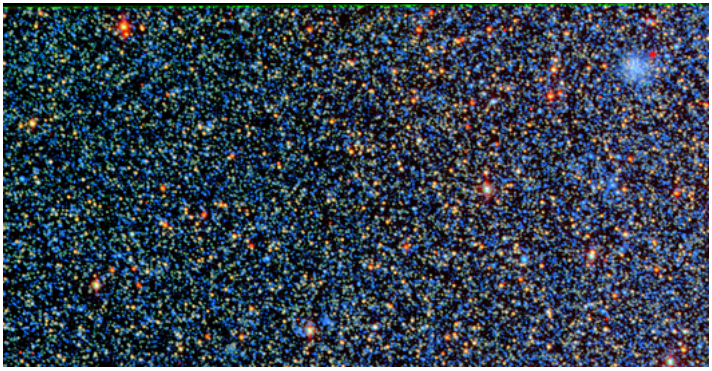
Distance Determination, Variable Stars, Milky Way Halo

Model for RR Lyrae Variable Stars

Results on SDSS Stripe 82 and DES
- SDSS Stripe 82: Simulation
- Dark Energy Survey: Preliminary Results

Outline

What are the distances to these objects?



Problem:

$$\text{brightness} \propto \frac{\text{luminosity}}{\text{distance}^2}$$

Only brightness can be directly measured.

Image Source: DES Collaboration

Use Standard Candles to Determine Distances

Standard Candle: Class of objects with same luminosity

- Know absolute luminosity of standard candle.
- Determine object is standard candle and estimate its brightness.
- Solve for distance.

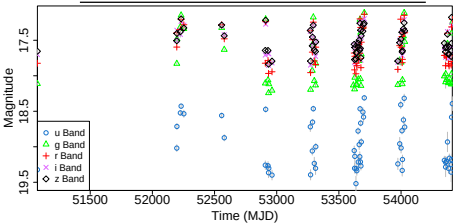
RR Lyrae (RRL): Standard candle star

- All RR Lyrae have (approximately) same luminosity

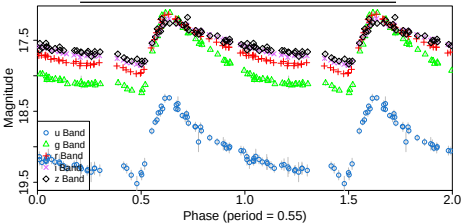
RR Lyrae are Standard Candle Periodic Variable Stars

Variable stars: Stars that vary in brightness across time.
Periodic variables: Repeat brightness variation over a fixed period.

RRL Unfolded Light Curve



RRL Folded Light Curve

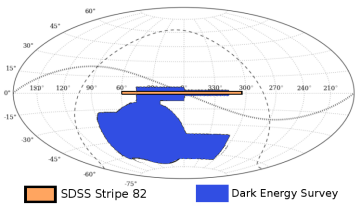


- phase = (time modulo period) / period
- period estimated from unfolded light curve
- star observed ≈ 250 times in 5 filters (u, g, r, i, z).

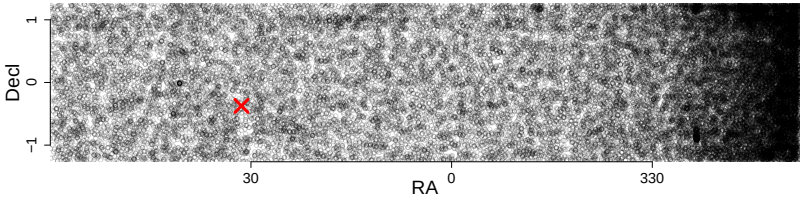
Distance to this star is proportional to mean magnitude.

Sloan Digital Sky Survey (SDSS) III – Stripe 82

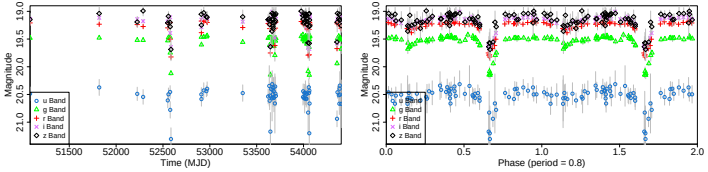
Celestial Sphere



Location of Variable Stars Discovered in Stripe 82



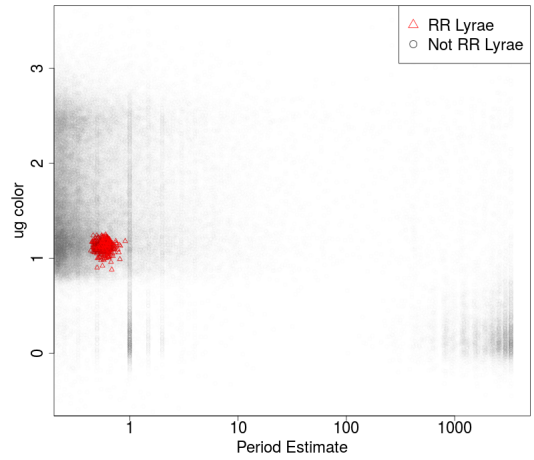
Star X Light Curve (Unfolded and Folded): Not an RR Lyrae

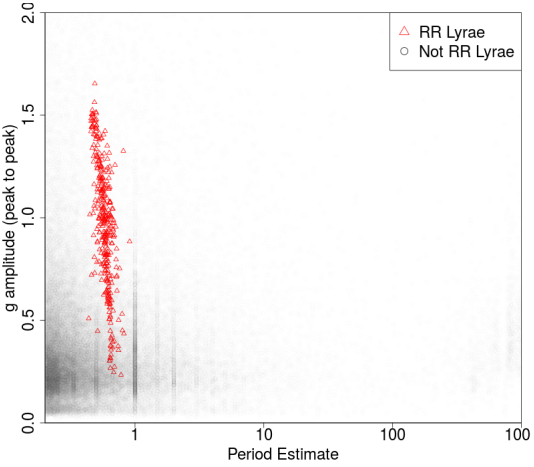


Source: See Ivezic [1]

Identifying RRL

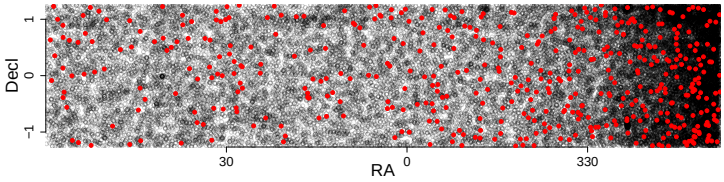
Features derived from light curves separate RR Lyrae from non-RRL.



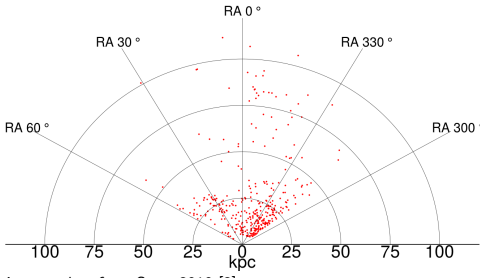


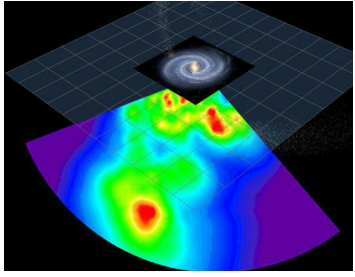
Stripe 82 Milky Way Halo Map

RR Lyrae Locations in Stripe 82



Map of the Milky Way Halo



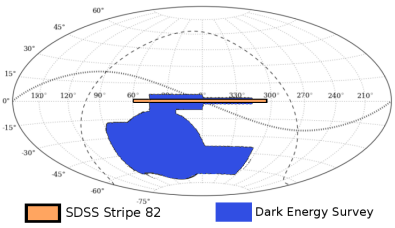


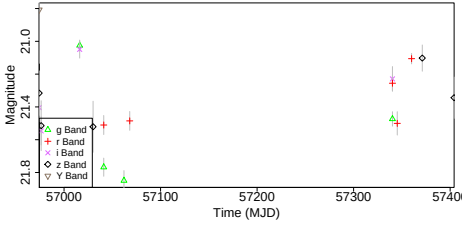
Source: Bottom right image taken from Sesar 2010 [2].

Project Goal: Extend Milky Way Halo Maps to DES Region

Dark Energy Survey (DES)

- ongoing survey (started 2013, 5 years of planned observing)
- 5000 square degrees ($\approx 1/9^{th}$ entire sky)
- depths to 24 mag in i
- $\approx$ 200 million stars
- $\approx$ 10 observations in each filter (g,r,i,z,Y) over five years





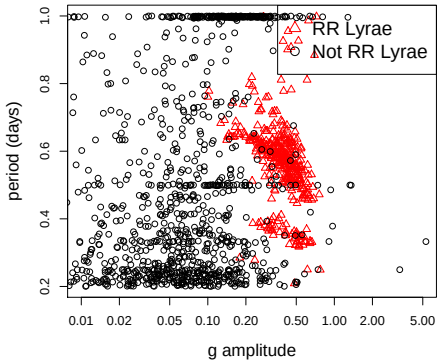
Challenge: DES stars are very sparsely observed.

Outline

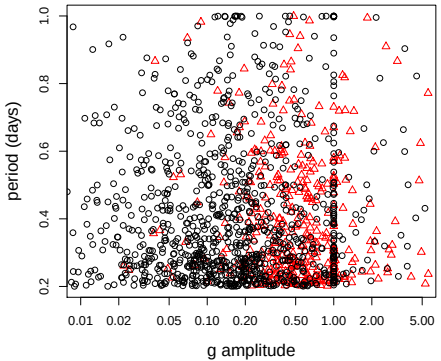
Traditional Features No Longer Separate RRL in DES Data

The features are very noisy due to the sparse temporal sampling.

SDSS Data



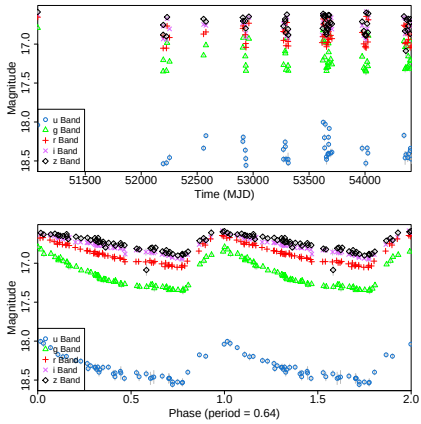
DES Simulation



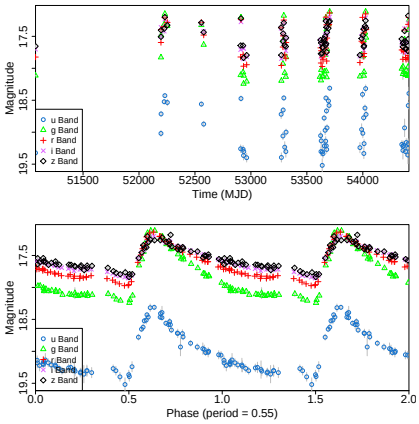
Parameters of best fitting sinusoid no longer separate RRL from non-RRL.

Building an RRL Model with SDSS Stripe 82 Data

RR Lyrae Example 1



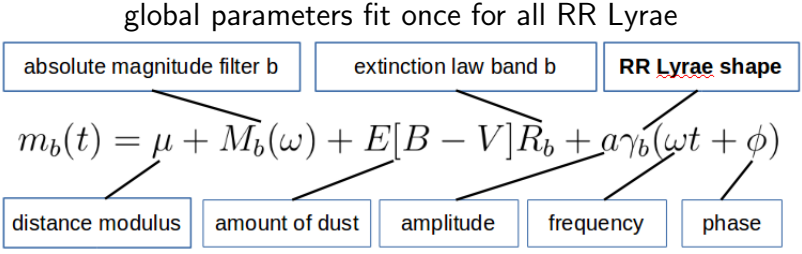
RR Lyrae Example 2



Common for all RR Lyrae? Shape, difference in filter means.

What varies? Distance, dust, amplitude, period, phase.

Parsimonious RR Lyrae Model: 5 Free Parameters

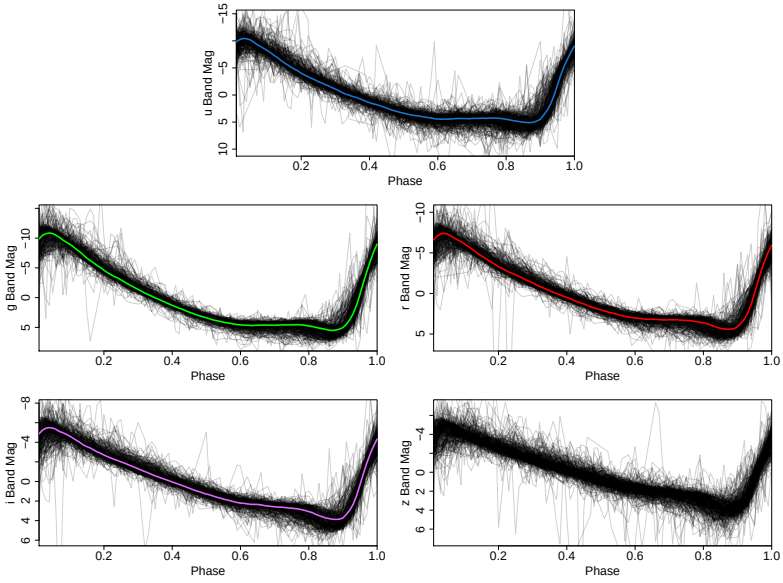


- $D = \{\{t_{jb}, m_{jb}, \sigma_{jb}\}_{j=1}^{n_b}\}_{b=1}^{B}$
- Model:

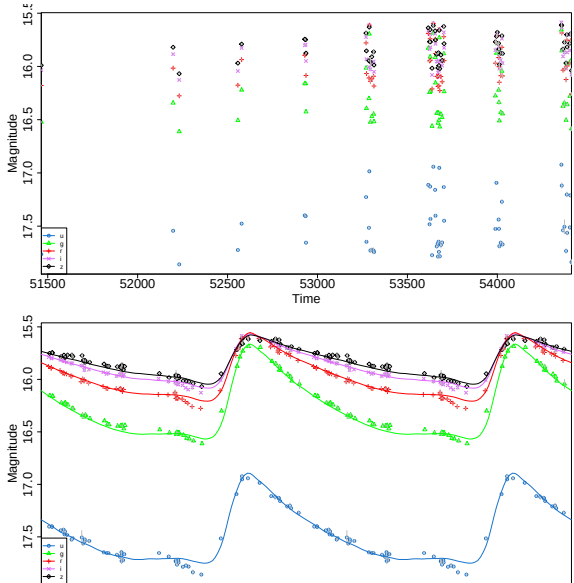
$$m_{jb} = m_b(t_{jb}) + \epsilon_{jb}\sigma_{jb}$$

where $\epsilon_{jb} \sim N(0,1)$ i.i.d.

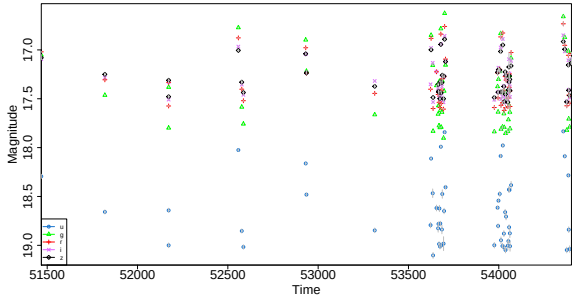
$\gamma_b(t) =$ median of functions at time t in filter b



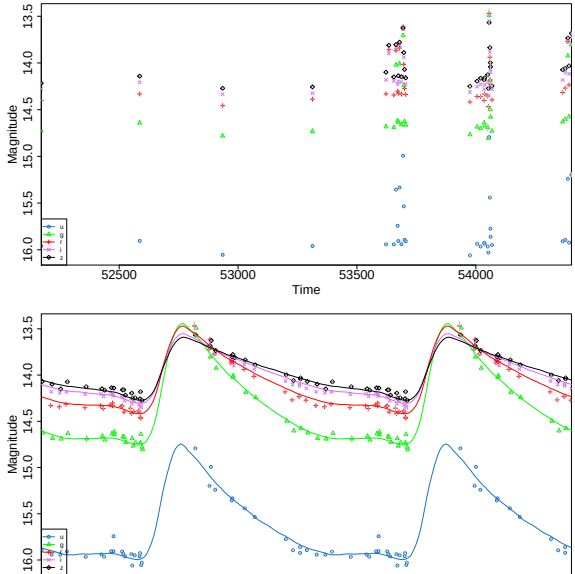
Example Fit to SDSS Light Curves



Example Fit to SDSS Light Curves



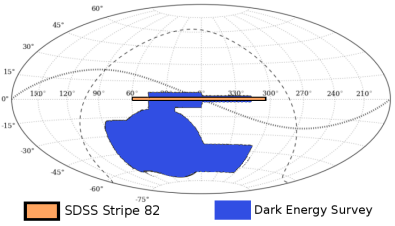
Example Fit to SDSS Light Curves



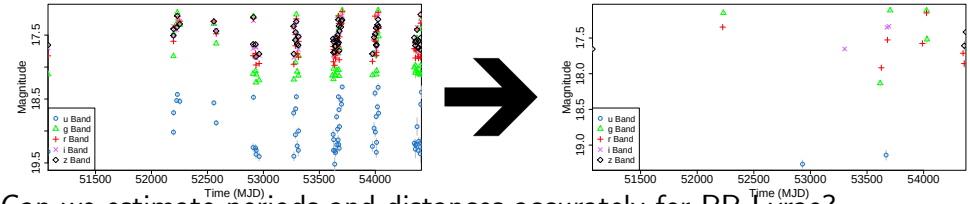
Outline

Outline

Simulate SDSS Stripe 82 to Resemble DES

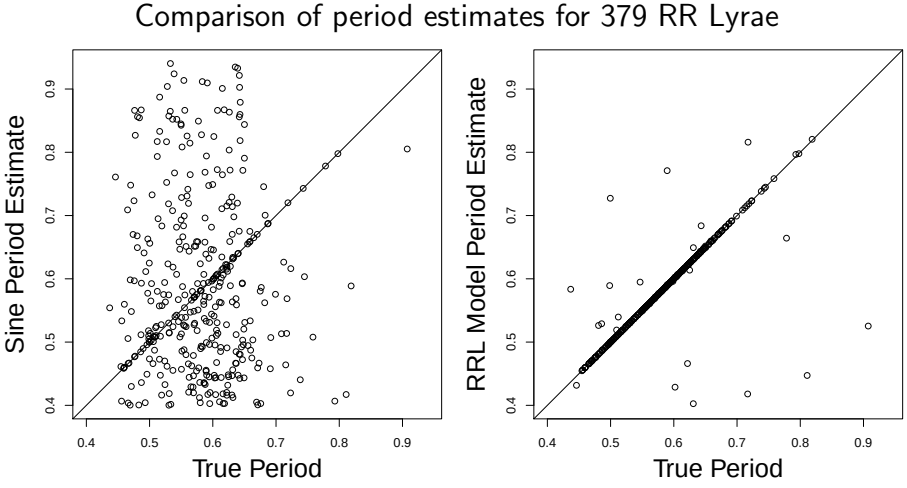


Downsample Stripe 82 variables to 20 observations:



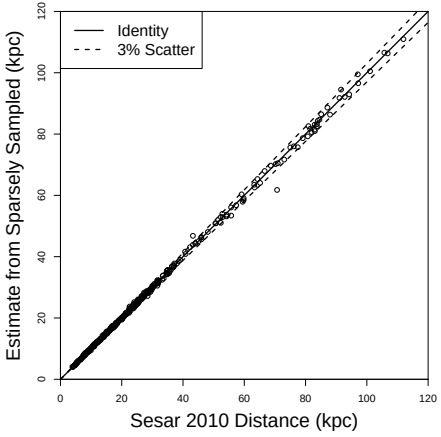
- Can we estimate periods and distances accurately for RR Lyrae?
- Can we classify RR Lyrae / reproduce halo maps?

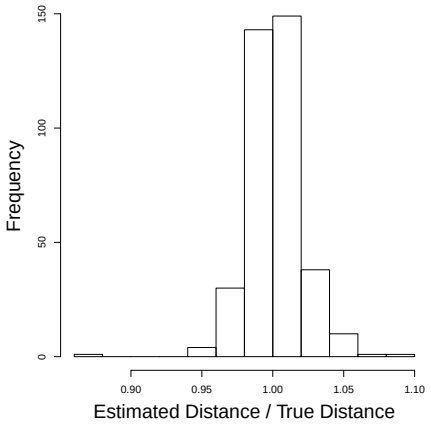
Results for Period Estimation



Simulation Results for Distance Estimation

- Use model to estimate distance modulus (μ) for RR Lyrae.
- Convert μ to distance (d) in parsecs: $d = 10^{\mu/5+1}$



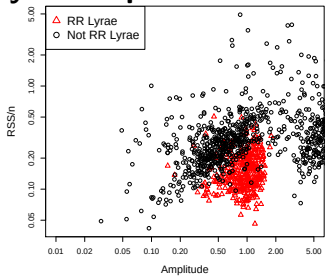


Reproducing Milky Way Halo Maps

Select 379 RR Lyrae and 1000 non–RR Lyrae from SDSS Stripe 82.

1. Fit RR Lyrae Model to light curves
2. Extract features: model parameters, goodness–of-fit, etc.
3. Build Random Forest Classifier
4. Classify RRL / not-RRL for out–of–bag data (cross–validation)
5. Estimate distances to stars classified as RRL
6. Construct MW Halo map

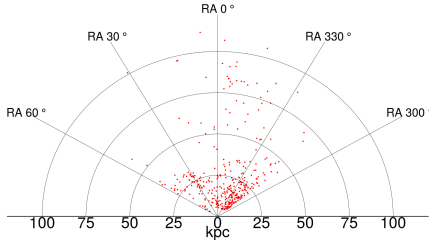
Summary of Steps 1–4:

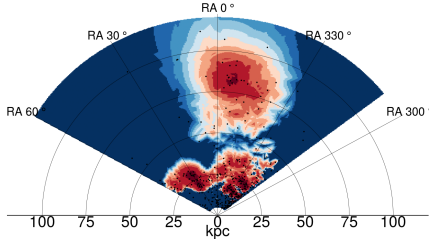


	Predicted	
Truth	Not RRL	RRL
Not RRL	978	22
RRL	40	339

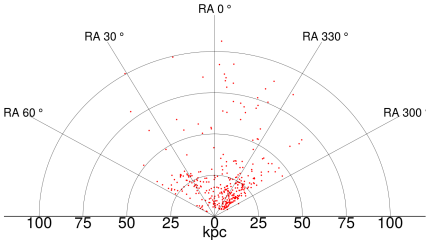
Results for Constructing Milky Way Halo Maps

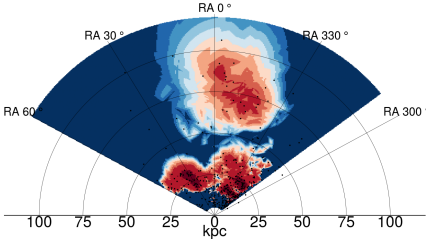
Ground Truth





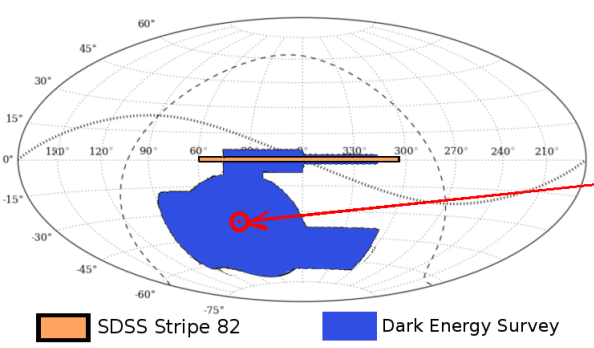
Estimates on Downsampled

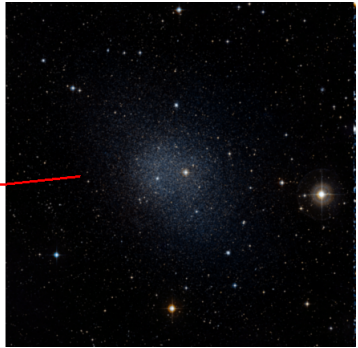




Outline

FORNAX Dwarf Spheroid Satellite Galaxy





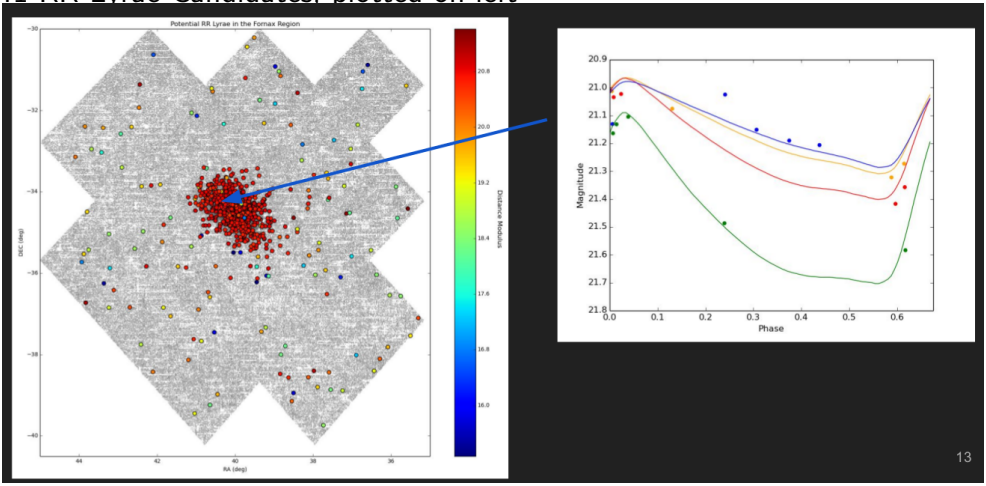
Fornax is a satellite galaxy of the Milky Way.

Challenge: Find structure (sets of gravitationally bound stars) around FORNAX.

Source: Wikipedia: https://upload.wikimedia.org/wikipedia/commons/4/45/Fornax_dwarf_galaxy.jpg

FORNAX RR Lyrae Candidates

- $\approx$ 1 million stars in FORNAX region
- 841 RR Lyrae Candidates, plotted on left



Courtesy Katelyn Stringer

Conclusions / Future Work

- Multi–stage inference problem: model fitting / classification followed by parameter estimation.
  - This is a common challenge with astronomy data.
- Current work:
  - Characterize uncertainty in MW Halo maps / probabilistic predictions.
  - Extend analysis to entire DES footprint.

Related Work: B. Sesar 2017. "Machine-learned Identification of RR Lyrae Stars from Sparse, Multi-band Data: The PS1 Sample" Astrophysical Journal.

Bibliography I

[1] Željko Ivezić, J Allyn Smith, Gajus Miknaitis, Huan Lin, Douglas Tucker, Robert H Lupton, James E Gunn, Gillian R Knapp, Michael A Strauss, Branimir Sesar, et al.
Sloan digital sky survey standard star catalog for stripe 82: The dawn of industrial 1% optical photometry.
The Astronomical Journal, 134(3):973, 2007.

[2] Branimir Sesar, Željko Ivezić, Skyler H Grammer, Dylan P Morgan, Andrew C Becker, Mario Jurić, Nathan De Lee, James Annis, Timothy C Beers, Xiaohui Fan, et al.
Light curve templates and galactic distribution of rr lyrae stars from sloan digital sky survey stripe 82.
The Astrophysical Journal, 708(1):717, 2010.