Picking Up the Pieces* of the Broken Halo

*halo substructures, such as halo streams and ultra-faint dSphs (bound or not)

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Motivation: Find the “missing” ultra-faint dSph galaxies

Predicted number of observable faint MW satellites → LSST should be able to observe ~300

Hundreds of satellites fainter than $M_V \sim -8$ are predicted to exist, only about a dozen have been found → where are the “missing” MW satellites?
CMD Filtering Technique

Age \sim 12.6 \text{ Gyr}

[Fe/H] \sim -1.6 \text{ dex}

Distance \sim 13 \text{ kpc}

MSTO

19.5 \text{ mag}
Isochrone at the right distance...

Greyscale: surface density of CMD-selected sources
CMD Filtering Successes

Faint dSph galaxies (e.g., Segue 1; Belokurov et al. 2006, UMa II; Zucker et al. 2006)

Tidal streams (e.g., GD-1 stream; Grillmair & Dionatos 2006, Belokurov et al. 2007)
Limitations of CMD Filtering

- What if a faint satellite galaxy is distant and spreads over a few degrees (is disrupted)?
- **Problems**: unknown distances, foreground stars, contamination by unresolved galaxies (star-galaxy separation)
- **Solution**: use variable sources and standard candles → RR Lyrae stars

![CMD diagram with MSTO ~ 24.5 mag, 45 deg² region, ~450,000 sources, Distance ~ 85 kpc, Unresolved galaxies, MSTO ~ 24.5 mag]
RR Lyrae Stars

- **Old**, evolved stars (> 9 Gyr)
- **Standard candles** → identify them → know their distance (with ~5% uncertainty)
- **Bright** ($M_V = 0.6$) → LSST will be able to detect them to ~400 kpc (Oluseyi et al. 2012)
- **Variable stars** ($P \sim 0.6$ day) with distinct light curves (~1 mag amplitude) → cannot be confused with galaxies!

Light curve of an RR Lyrae type $ab$
RR Lyrae stars in SDSS Stripe 82 (Sesar et al. 2010)

Detection of substructures using RR Lyrae stars works best beyond 30 kpc from the Sun.
Strategy for Current and Future Surveys

1. **Trace halo substructures** by finding clumps of RR Lyrae stars located beyond 30 kpc from the Sun
2. **Measure their [Fe/H] and RV** from spectra of RR Lyrae stars in clumps
3. **Identify K giants associated with detected substructures** using narrow-band imaging centered on Mg features
4. **Obtain [α/Fe], better RVs and [Fe/H]** from spectra of K giants in clumps
5. **Study** the dynamics, star formation history, etc. of detected remnants
Step 1: Look for clumps of distant RR Lyrae stars

White: Regions with >30 epochs in the Palomar Transient Factory survey

Blue dots: RR Lyrae stars detected in PTF (70 – 100 kpc)

8 RR Lyrae stars at ~85 kpc in 45 deg^2
Step 1: Look for clumps of distant RR Lyrae stars

2 streams?
Step 2: Spectroscopy of RR Lyrae stars (RV, [Fe/H])

2 moving groups of RR Lyrae stars → 2 streams!
Cancer Moving Groups (Sesar et al. 2012)

- Blue circles:
  - $v_{\text{GSR}} \sim 80 \text{ km/s}$, $\sigma_v \sim 12 \text{ km/s}$
  - $[\text{Fe/H}] \sim -1.6 \text{ dex}$, $\sigma_{[\text{Fe/H}]} \sim 0.4 \text{ dex}$

- Yellow squares:
  - $v_{\text{GSR}} \sim 20 \text{ km/s}$, $\sigma_v \sim 15 \text{ km/s}$
  - $[\text{Fe/H}] \sim -2.1 \text{ dex}$, $\sigma_{[\text{Fe/H}]} \sim 0.4 \text{ dex}$

- Most likely remnants of a disrupted dSph(s) (Sgr?)

![Graph showing positions of blue and yellow circles with labels.](image)
Dwarf-giant separation using the gravity-sensitive Mg features (e.g., Morrison et al. 2001)

- A SEGUE K dwarf and a giant (similar [Fe/H] and $T_{\text{eff}}$) → giants have weaker Mg features
- Idea: Use narrow-band imaging to select candidate RGB stars
- 5200/70 filter + Palomar 200-inch Large Format Camera
For a fixed \((g-i)_0\) color, giants have bluer 5200/70-g color than dwarfs.

Candidate giants

\[\approx\text{Giant/dwarf discriminator}\]

\[\approx\text{Effective temperature}\]
Narrow-band imaging (5200/70 filter) centered on positions of RR Lyrae stars in the Cancer region
Candidate giants in the Cnc region (based on their 5200/70-g color)
RR Lyrae stars: ~86 kpc, [Fe/H] ~ -1.6 dex, [Fe/H] ~ -2.1 dex

Candidate giants targeted for spectroscopy
Isochrones at ~86 kpc

RR Lyrae stars: ~86 kpc, [Fe/H] ~ -1.6 dex, [Fe/H] ~ -2.1 dex

Weak Na I doublet @ 8190 Å → likely not dwarfs

Isochrones at ~86 kpc
RR Lyrae stars: ~86 kpc
[Fe/H] ~ -1.6 dex & \(v_{gsr}\) ~ 80 km/s, [Fe/H] ~ -2.1 dex & \(v_{gsr}\) ~ 20 km/s

Isochrones at ~86 kpc

42.9 km/s, 47.2 km/s, 75.8 km/s, 78.3 km/s, -16.7 km/s
SEGUE K giants

($v_{gsr} \sim 83$ km/s)

- $v_{gsr} \sim 80$ km/s
- $v_{gsr} \sim 20$ km/s
ΛCDM predicts hundreds of ultra-faint dSph galaxies orbiting the Milky Way. Can we use RR Lyrae stars to find them or their remnants?
\[ v_{gsr} \sim -80 \pm 15 \text{ km/s} \]

\[ [\text{Fe/H}] \sim -1.8 \text{ dex} \]

\[ d \sim 60 \text{ kpc} \]

0.3 kpc difference in distance between the two RR Lyrae stars.
RR Lyrae stars: ~60 kpc, $[\text{Fe/H}] \sim -1.8$ dex, $v_{\text{gsr}} \sim -80$ km/s

Isochrones at ~60 kpc
RR Lyrae stars: ~60 kpc, [Fe/H] ~ -1.8 dex, $v_{gsr}$ ~ -80 ± 15 km/s

 Isochrones at ~60 kpc

$<v_{gsr}> = -53 ± 10$ km/s

-60.5 km/s

-55.5 km/s

-41.2 km/s

[g-i]$_0$ vs. [Fe/H] diagram with different metallicities.
Conclusions

• Finding halo substructure with RR Lyrae stars works, finding K giants seems to work (5200/70 filter too narrow)

• For LSST:
  • Star-galaxy classification will be crucial for CMD filtering
  • Informed instead of a blind search for distant halo substructures: RR Lyrae stars → K giants + BHB stars → CMD filtering

• PTF: 900 RR Lyrae stars between 30 and 100 kpc → a premiere dataset of possible locations of ultra-faint dSphs

• Do ultra-faint dSphs have RR Lyrae stars?
Table 4 of Boettcher, Willman et al. (2013)

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\(a\) Table of multiplicity for RRab stars.
CMD Filtering: Signal vs. Background

Willman, B. et al. (in prep)

- field stars + galaxies
- stream, d = 150 kpc, $\mu_r = 32.0$

$\log_{10}(N_{g,r<1}/\text{mag/deg}^2)$

6x, 3x, 1.6x
Densities of stars and galaxies in the COSMOS field
Be Aware of the Contamination!
CRTS RR Lyrae Completeness vs. Magnitude

Fig. 13 of Drake et al. (2013)