The Detailed Substructure of the Milky Way Stellar Streams:
DECam Imaging of the Eastern Banded Structure

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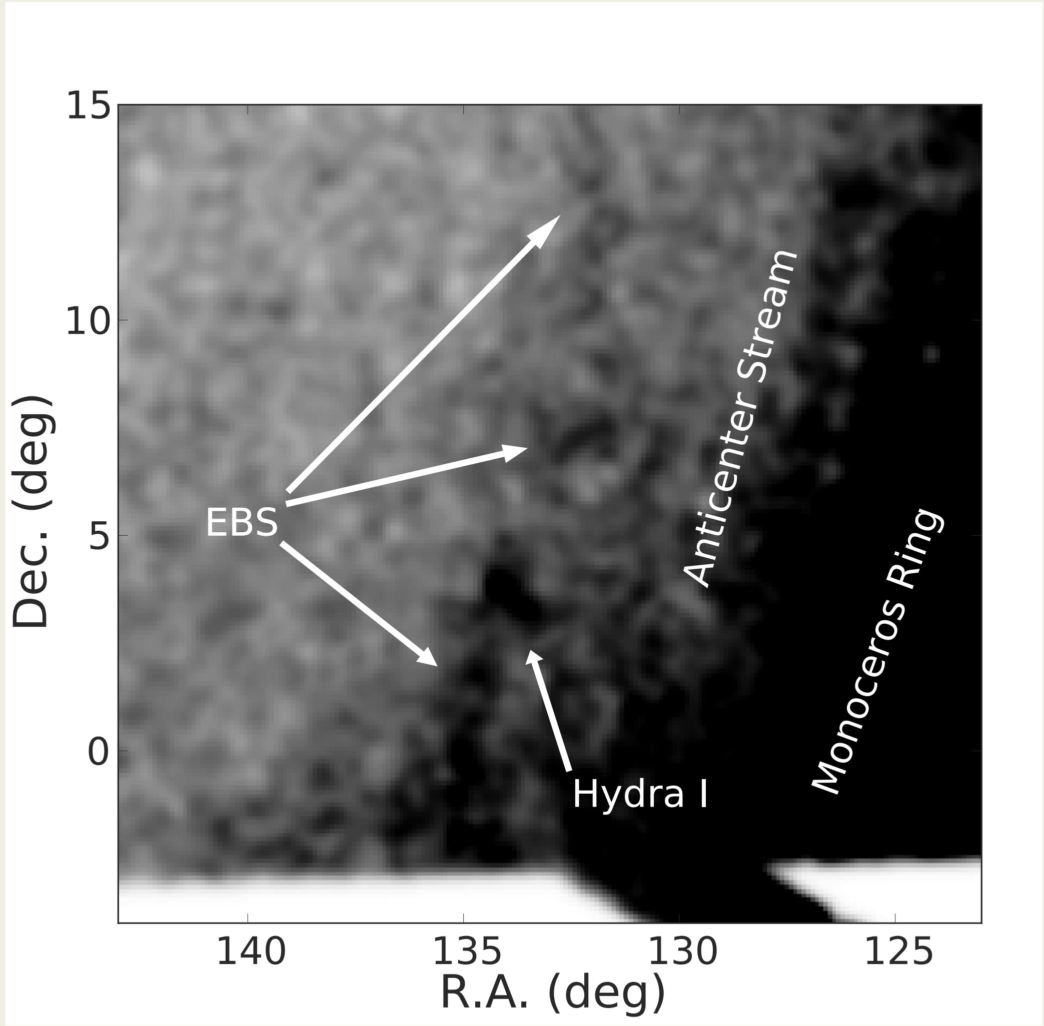
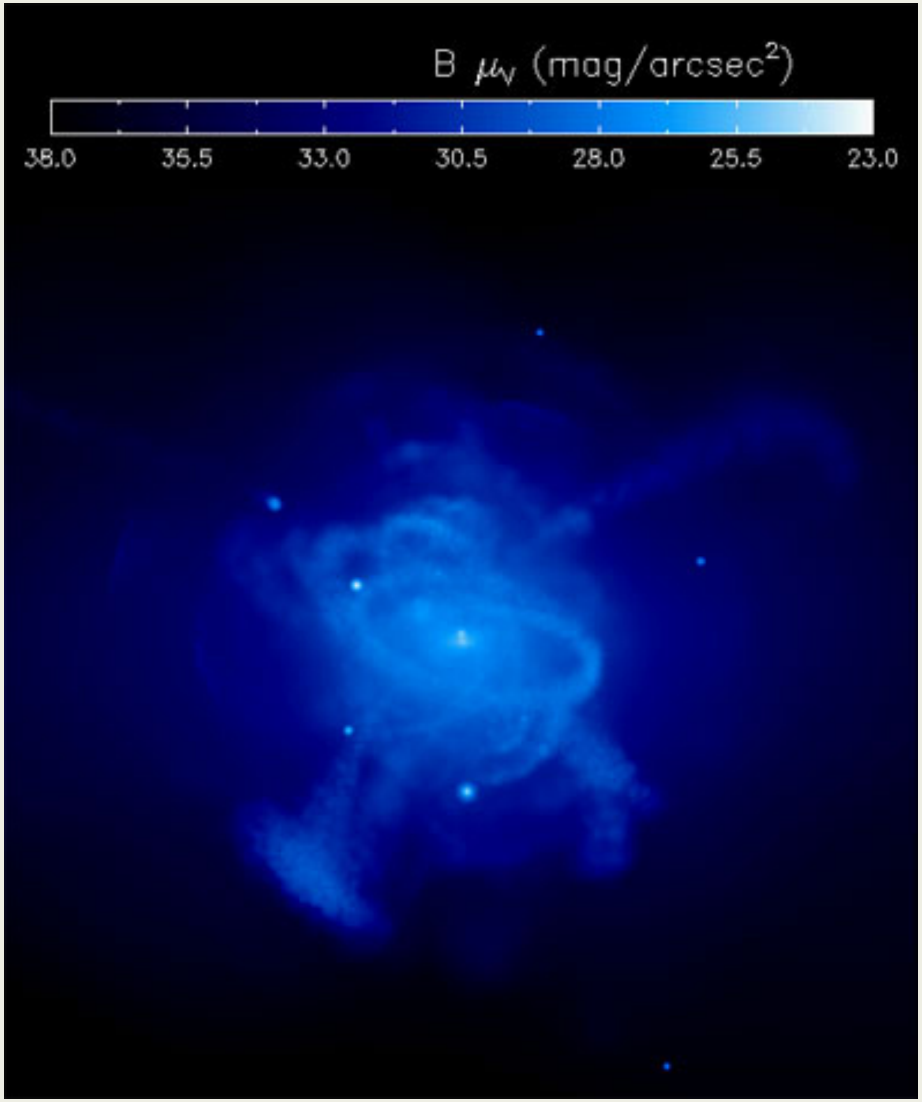


CMD filtered and smoothed surface density map of the EBS region (data from Grillmair 2011)

What can stellar streams tell us about the Milky Way in a cosmological context?

Streams trace the hierarchical nature of galaxy formation and the assembly of the Galactic halo

- Stream orbits probe the Galactic potential out to large galactocentric radii
- Identifying stream progenitors informs our understanding of the relative contribution of various objects to the halo's formation
- Spatial morphology of streams may contain signatures of the numerous dark subhalos predicted by LCDM



LCDM simulation of a Milky Way-like galaxy showing the stellar streams created from tidal destruction of accreted dwarf galaxies (Bullock & Johnston 2005)

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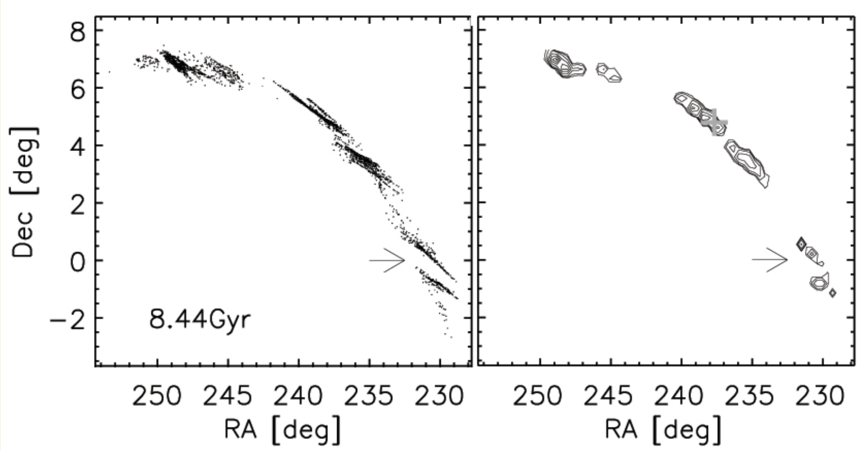
- **Spatial morphology of streams** may contain signatures of the numerous dark subhalos predicted by LCDM

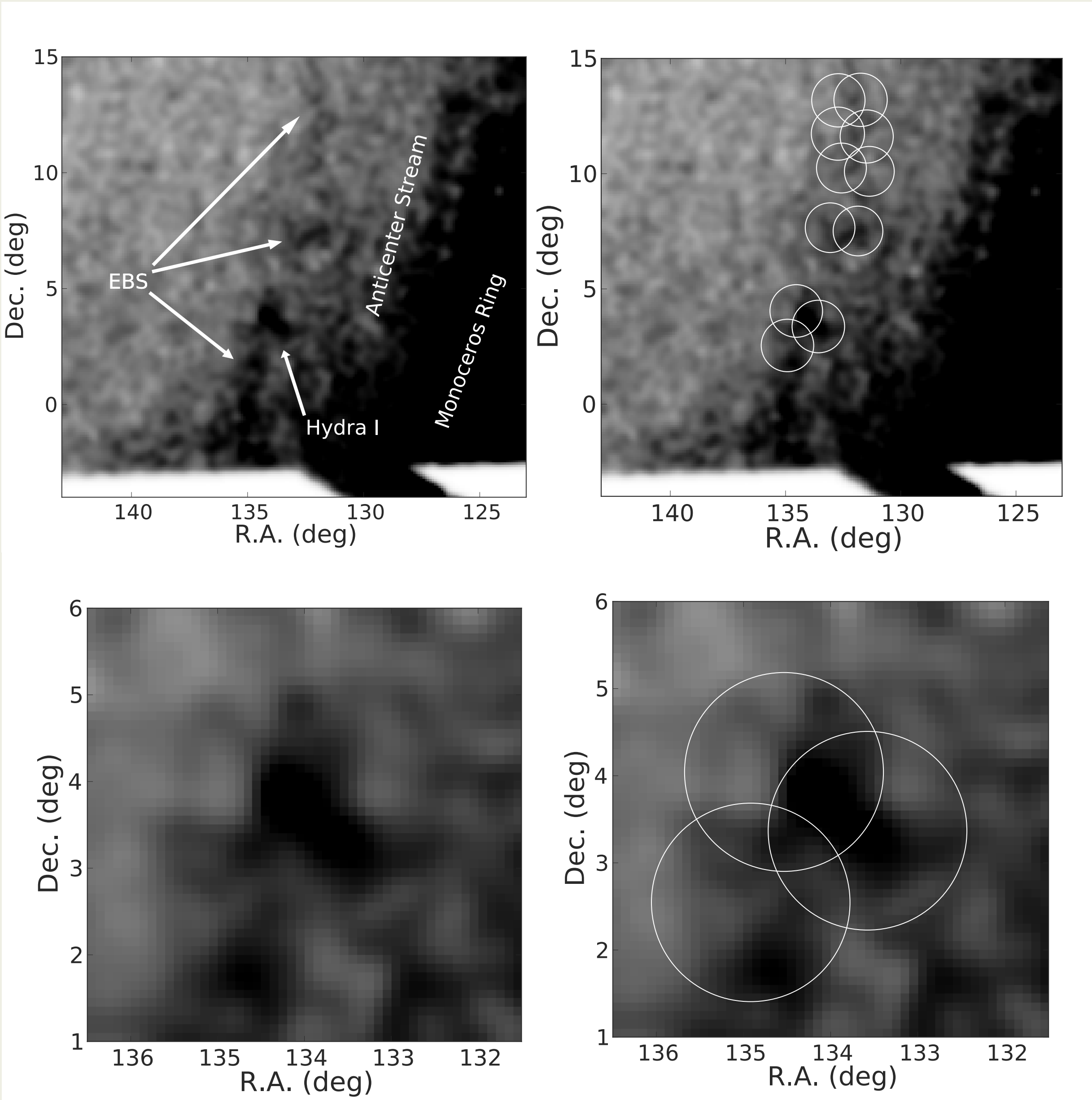
What are the progenitors of the known stellar streams? How do dwarfs and globular clusters contribute to halo assembly?

At present: Only ~3 stellar streams have known progenitors. Most streams have no identifiable progenitor.



Numerical simulations of subhalo + stream encounters in Pal 5 by Yoon et al. (2011)

The Eastern Banded Structure (EBS)



Photometry:
DECam *gri*
1080 s per pointing

Spectroscopy of Hydra I:
MMT + Hectochelle
700 MSTO stars
[selected from SDSS!]
RV errors < 5 km/s

Filtered and smoothed surface density maps from Grillmair (2011)

DECam Data Analysis and Photometric Calibration

NOAO CP Image Reduction

+

Python/DAOPHOT photometry pipeline

↓

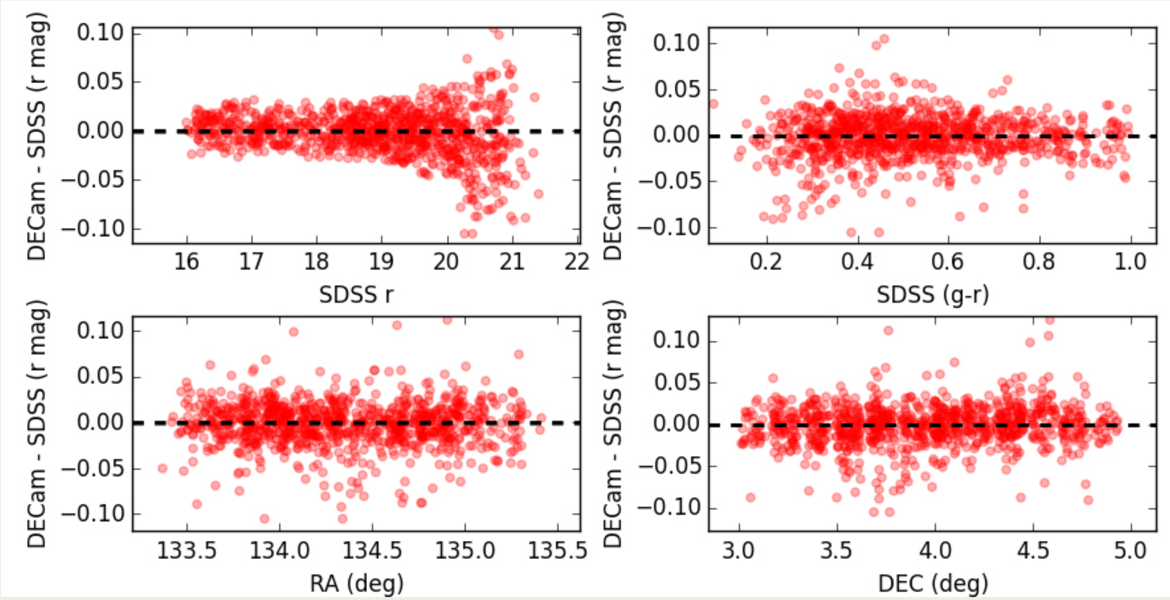
Calibrate each image directly to SDSS using ML analysis:

→ Color terms + ZPs for each image

→ Only (g-r) < 1

↓

Examine residuals as a function of **magnitude, color, focal plane position, chip**



Residuals as a function of magnitude, color, and spatial position (r band)

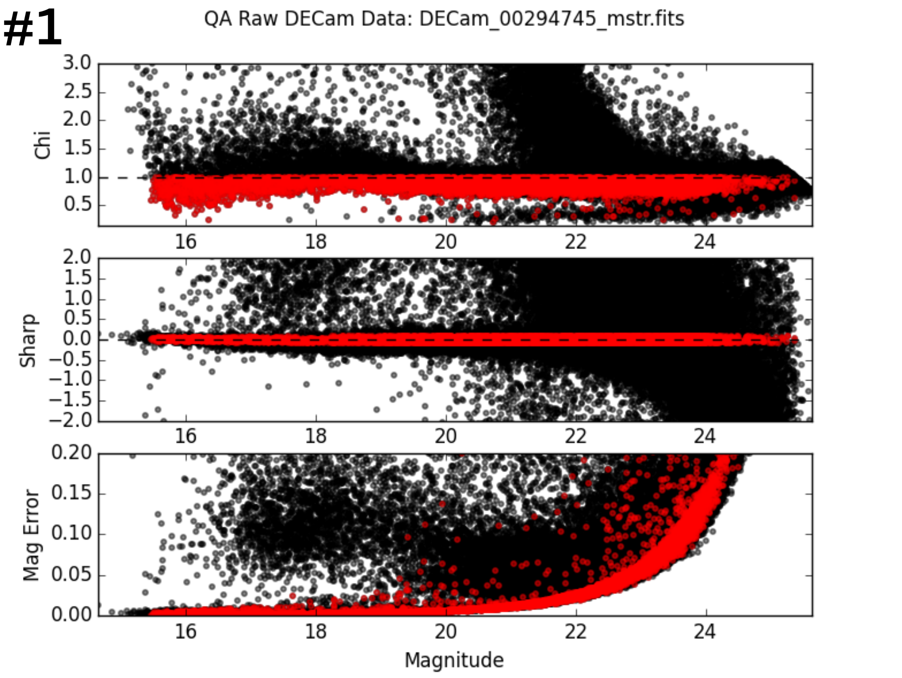
What We Learned:

- **Reject low S/N SDSS stars**
- **Use well-measured DECam point sources → Should mitigate brighter/fatter in the calibration…?**

DECam Photometric Calibration

1) Quality cut the raw photometry
2) Match these to SDSS
3) Reject outliers to increase robustness of calibration

#1



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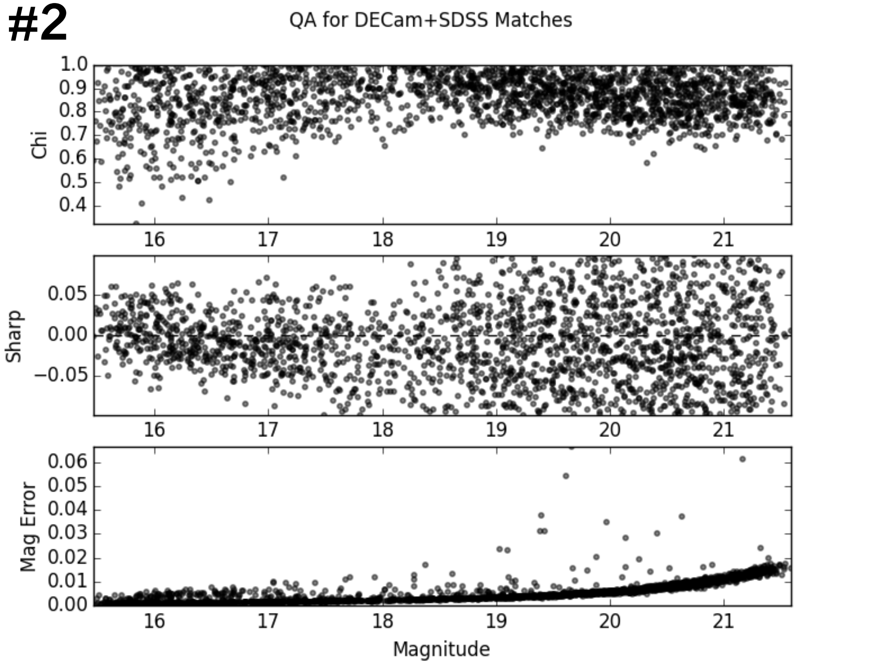

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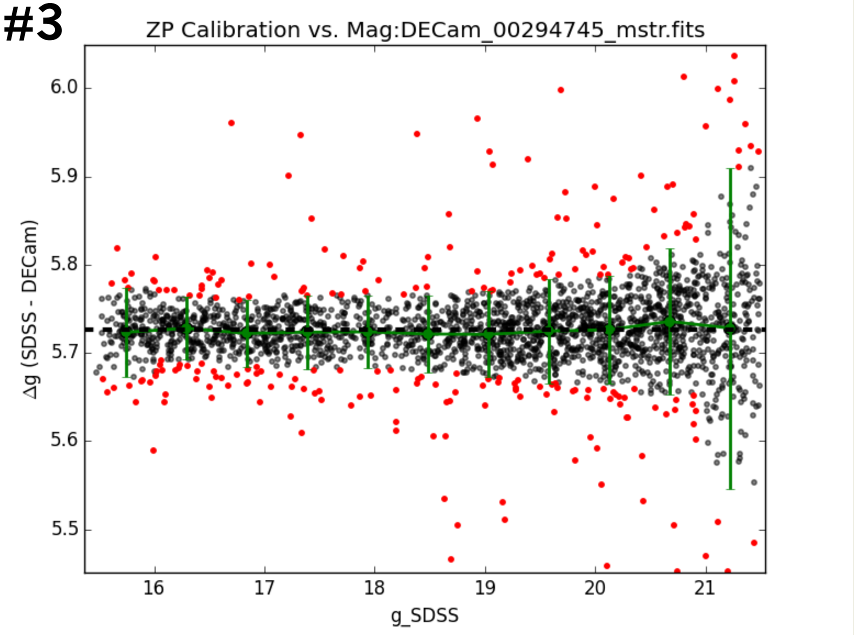
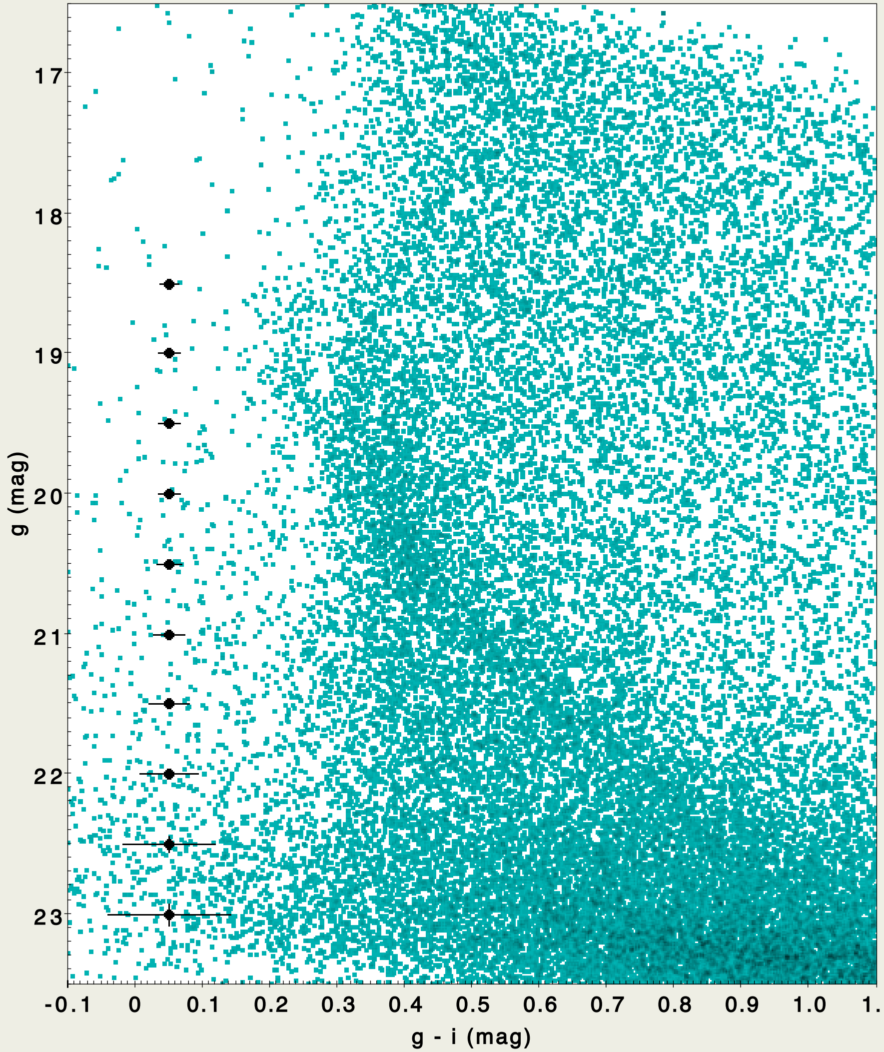
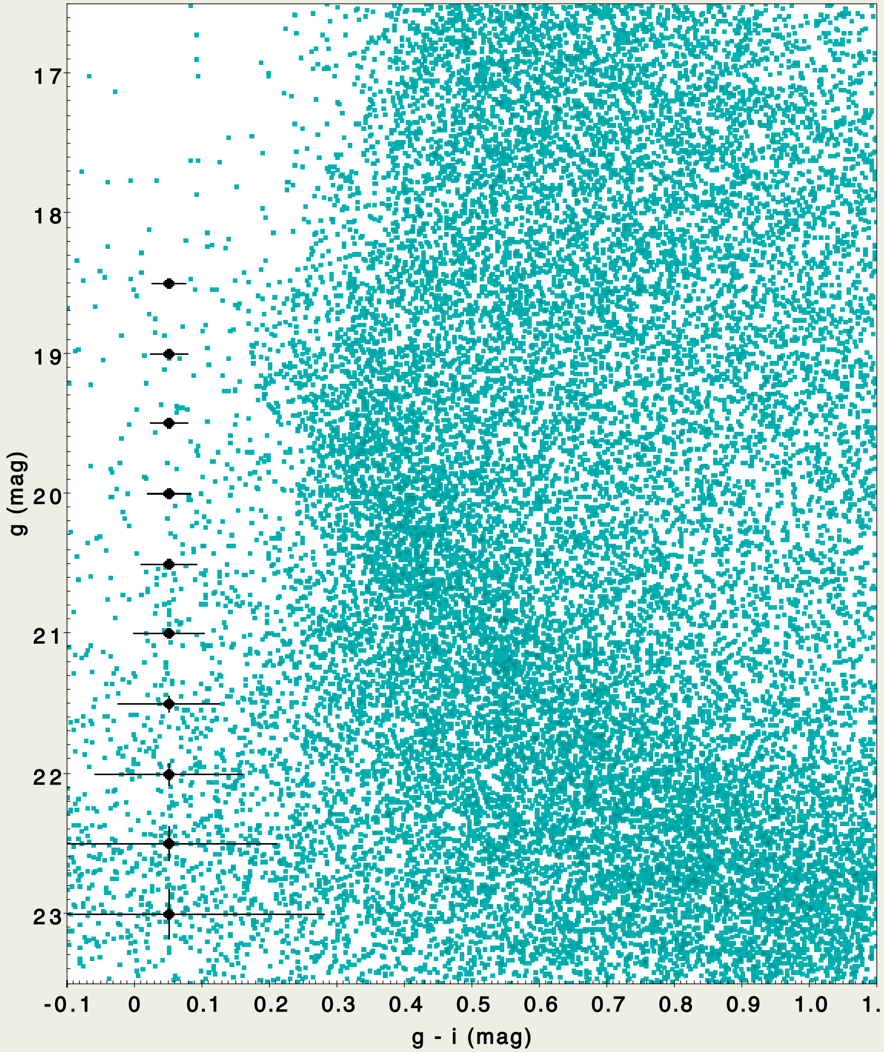


Color-Magnitude Diagram: **Hydra I region**

DECam (180 s exposure)



SDSS



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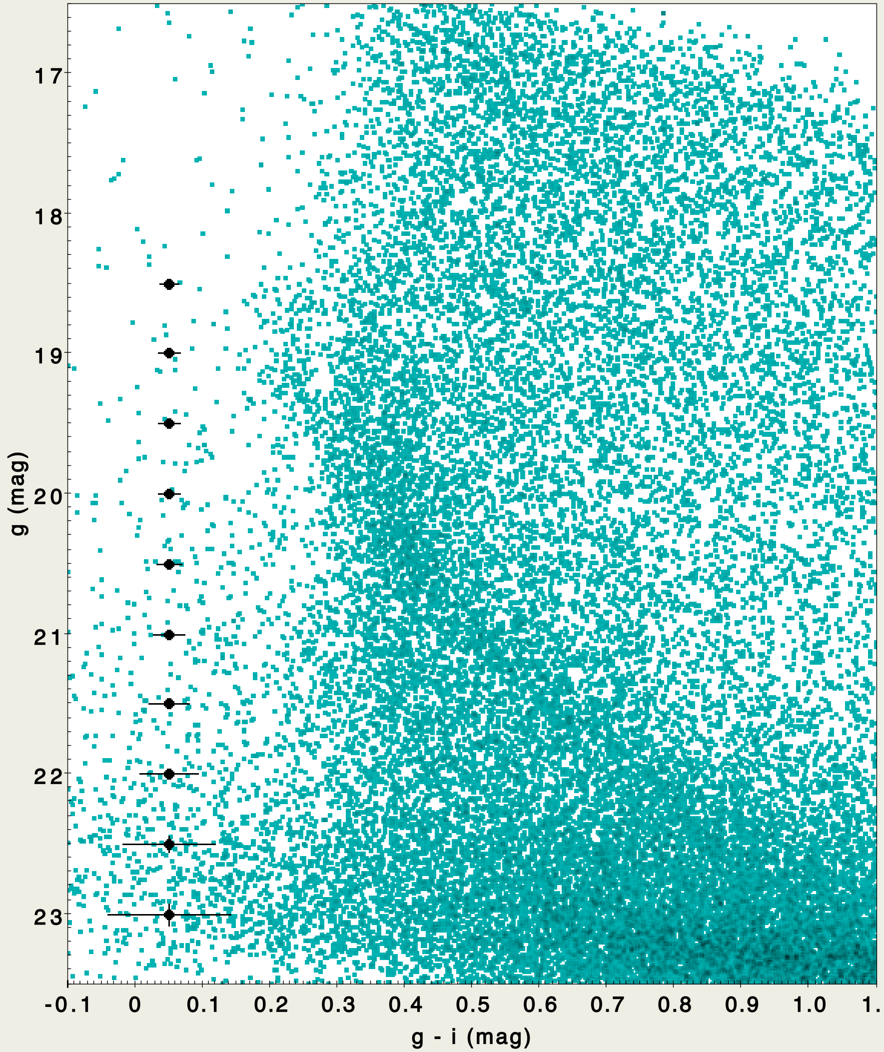

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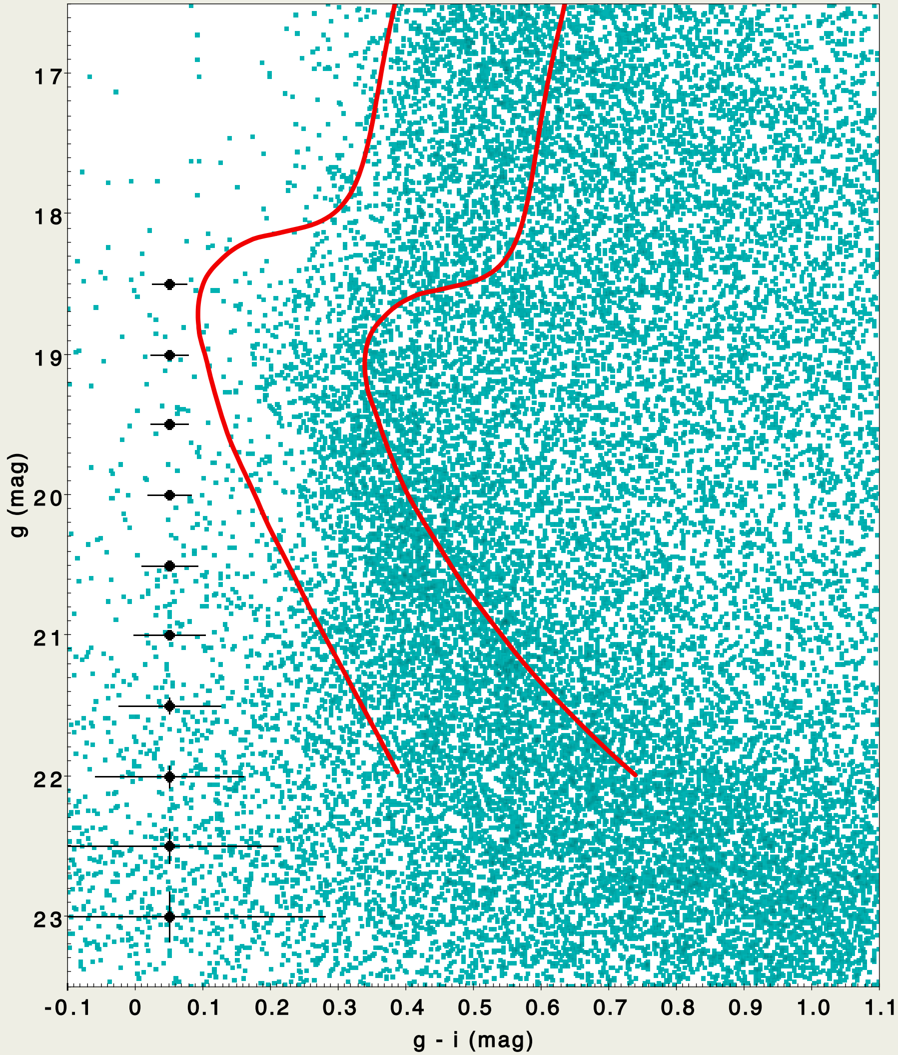
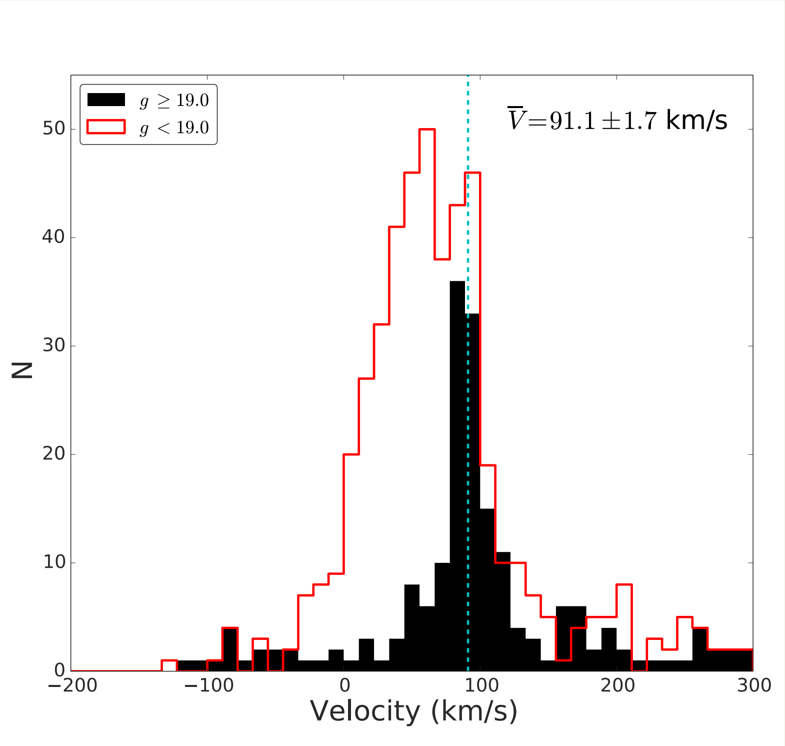
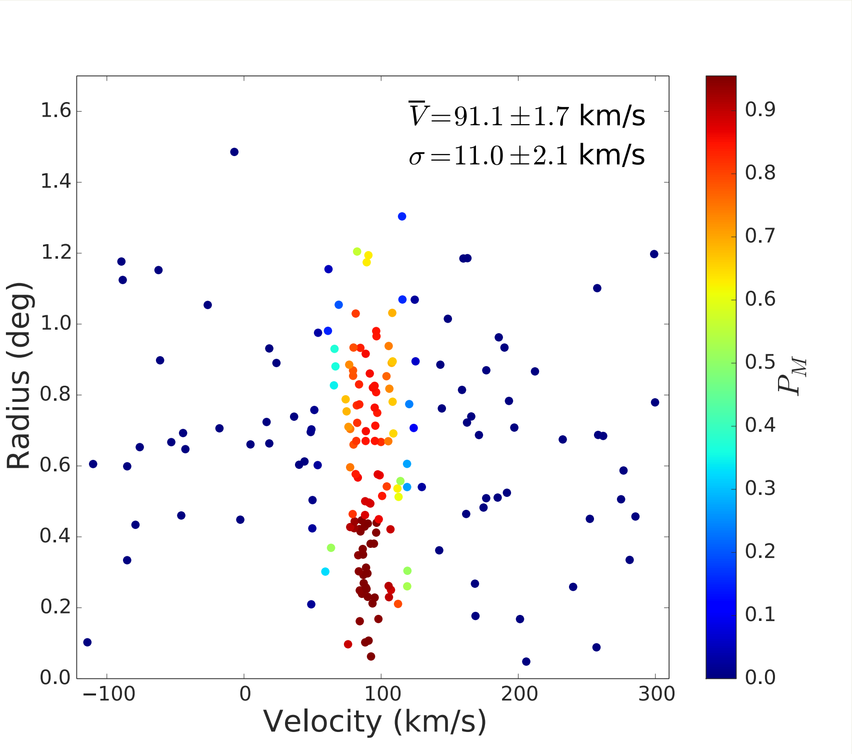


Results: **Chemo-Dynamic Properties**



Histogram of Hectochelle velocities



Velocity versus radius from Hydra I center

→ **Minimize thick disk contamination** by removing g < 19

→ N = 187 stars in faint sample

→ **Membership probabilities** determined using EM algorithm (Walker et al. 2009)

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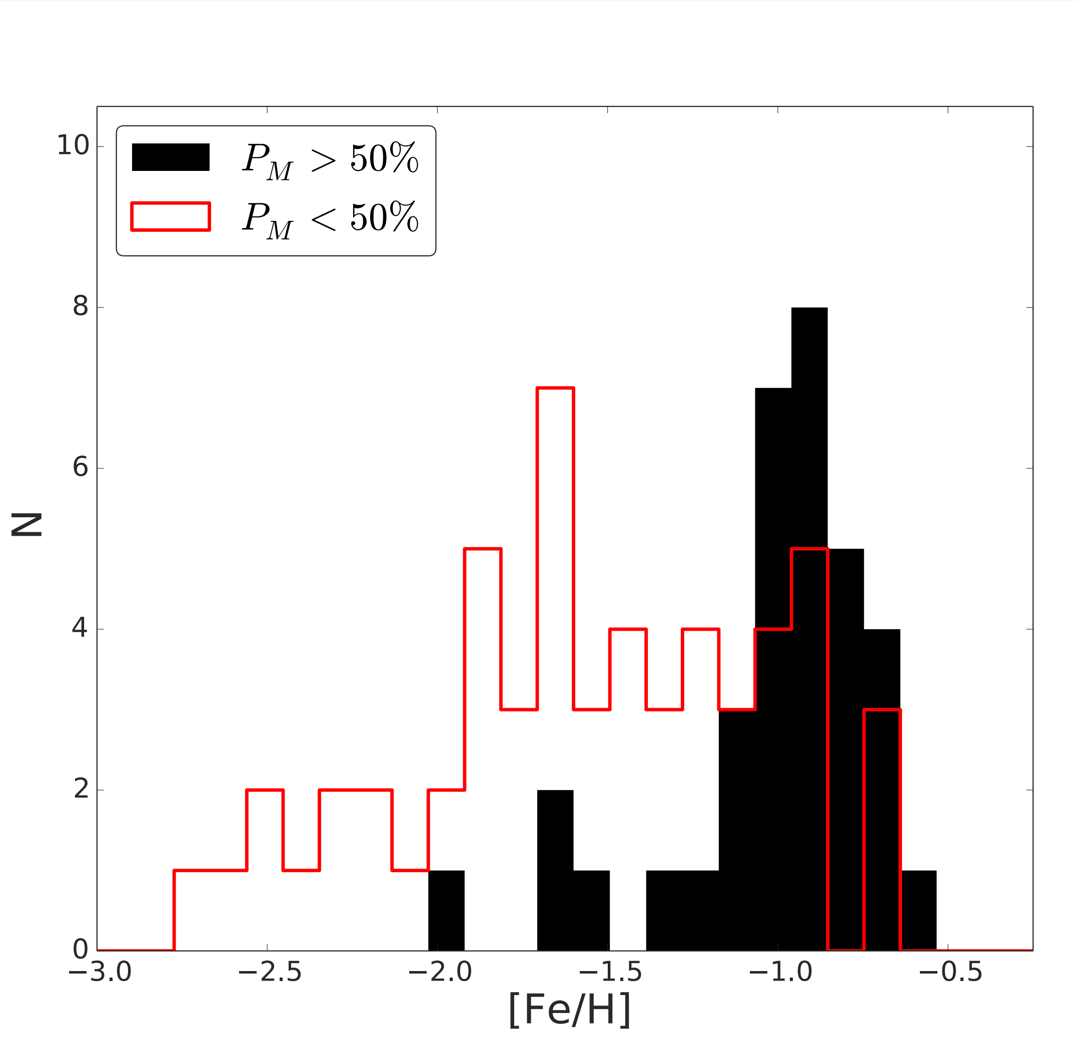
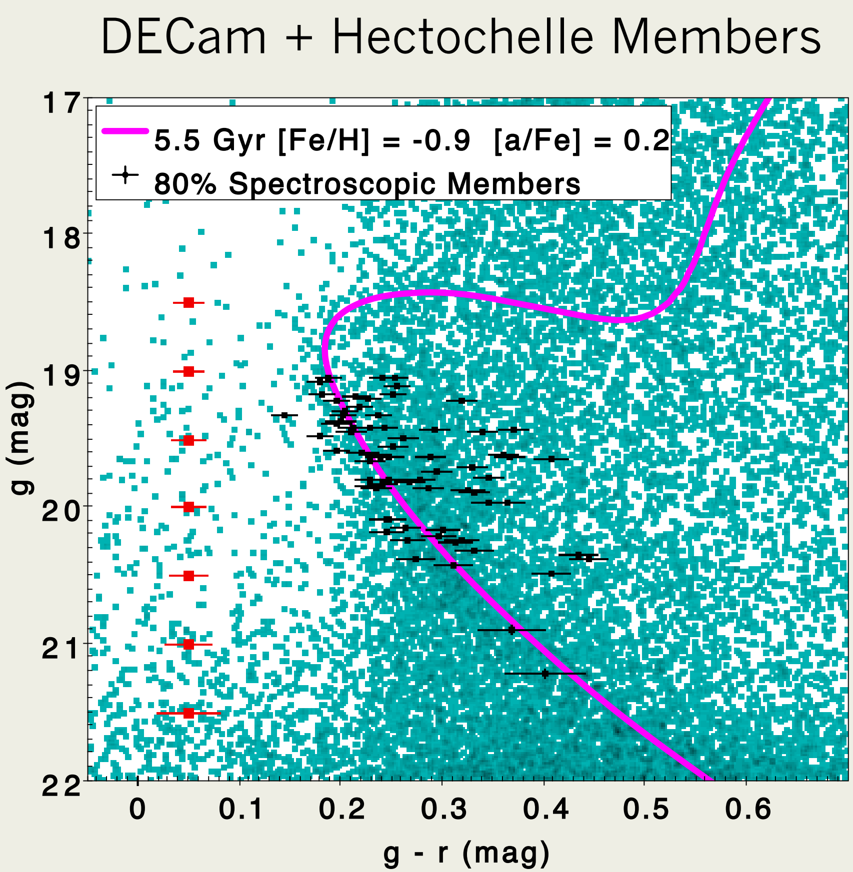
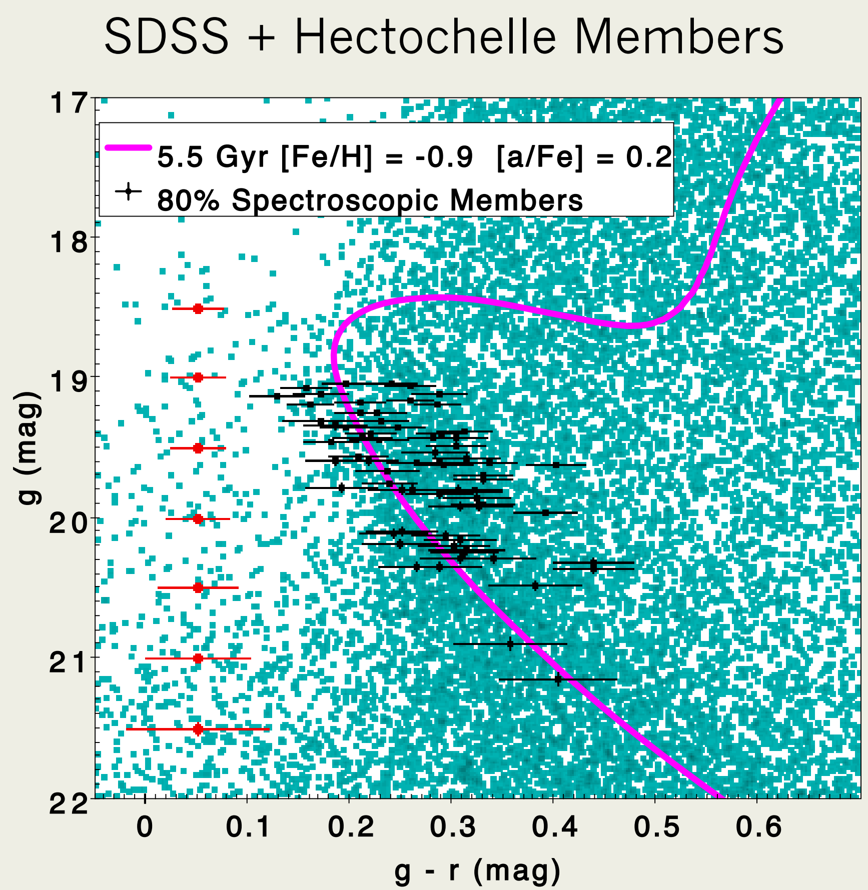


Histogram of [Fe/H] values from SDSS/SEGUE spectra

→ [Fe/H] = -0.93 +/- 0.03
→ Four stars with [Fe/H] < -1.5 are likely contaminates

Results: **Stellar Populations**





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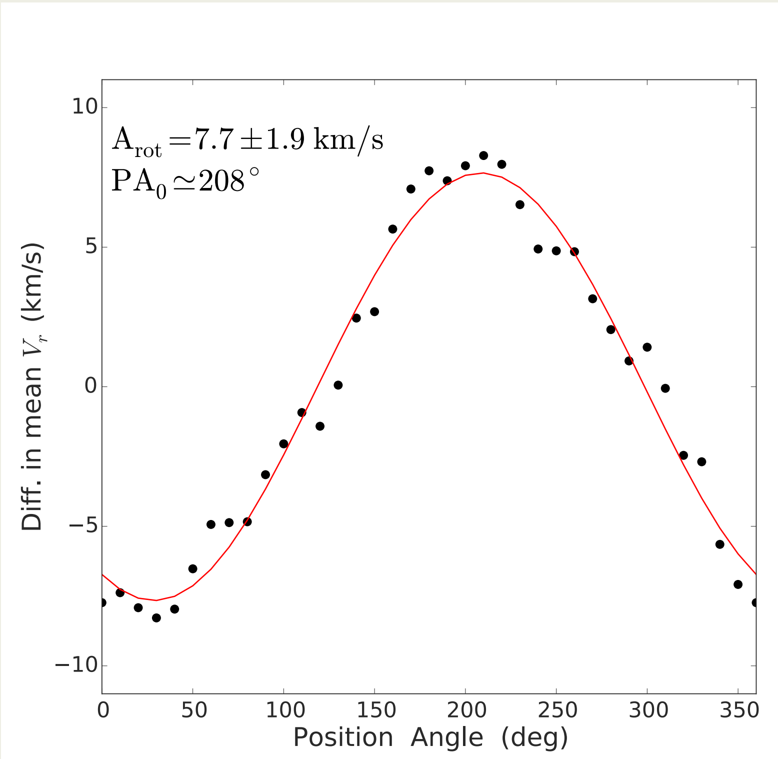
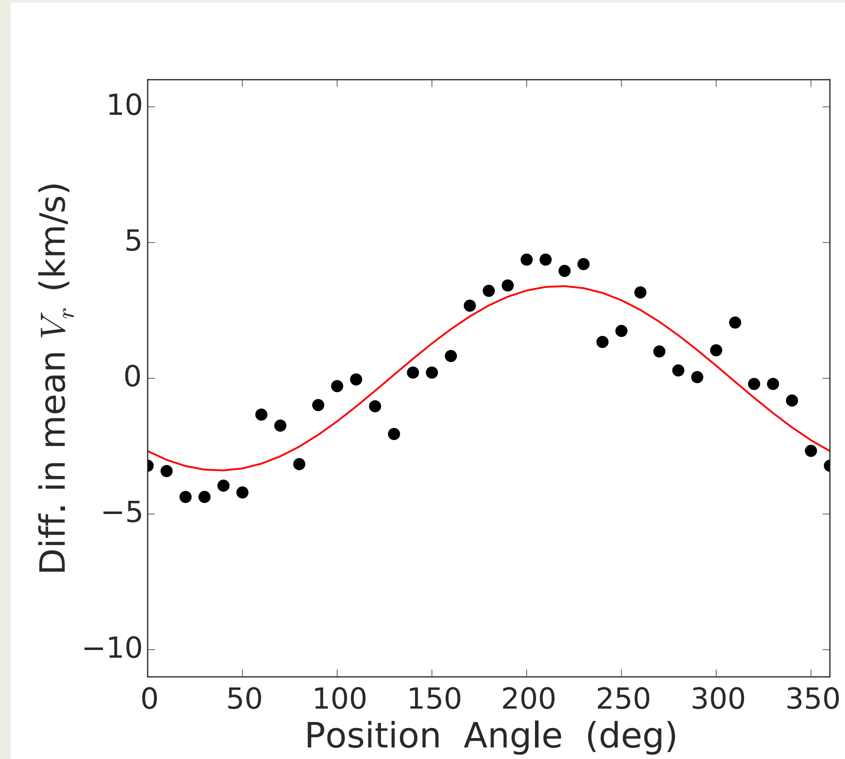


Observed rotation in Hectochelle sample of stars with $P_m > 50\%$.

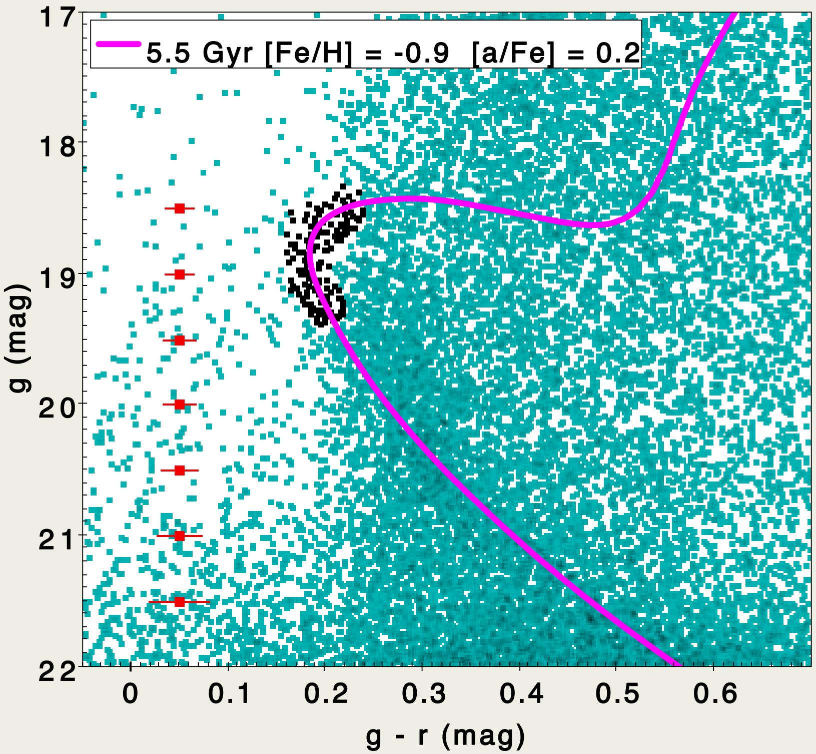
→ **Before** removing photometric contaminates: **8 +/- 2 km/s**



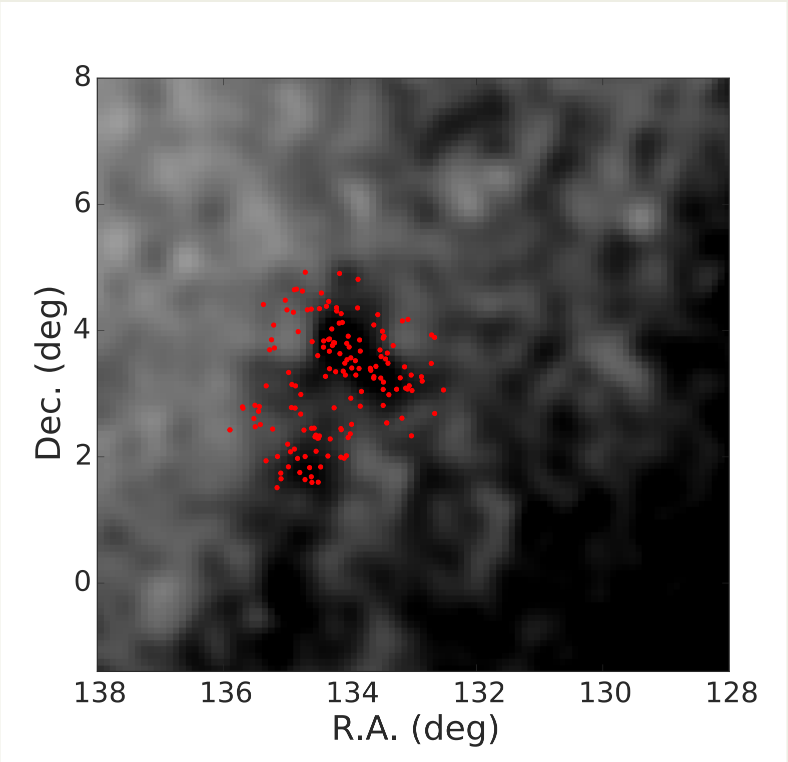
Observed rotation in Hectochelle sample of stars with $P_m > 50\%$.

→ **After** removing photometric contaminates**: 3 +/- 2 km/s**

Results: **Spatial Distribution of MSTO Stars**



Selection of MSTO stars with g-r errors consistent with isochrone



Spatial position of MSTO stars (red) compared to spatial distribution of all point-sources

What is Hydra I?
Three Hypotheses…

Star Cluster

If a globular cluster, we expect:

- Old age (10–13 Gyr)
- –2 < [Fe/H] < – 0.5

If an open cluster, we expect

- Young age (< ~2 Gyr)
- –0.5 < [Fe/H] < 0.2

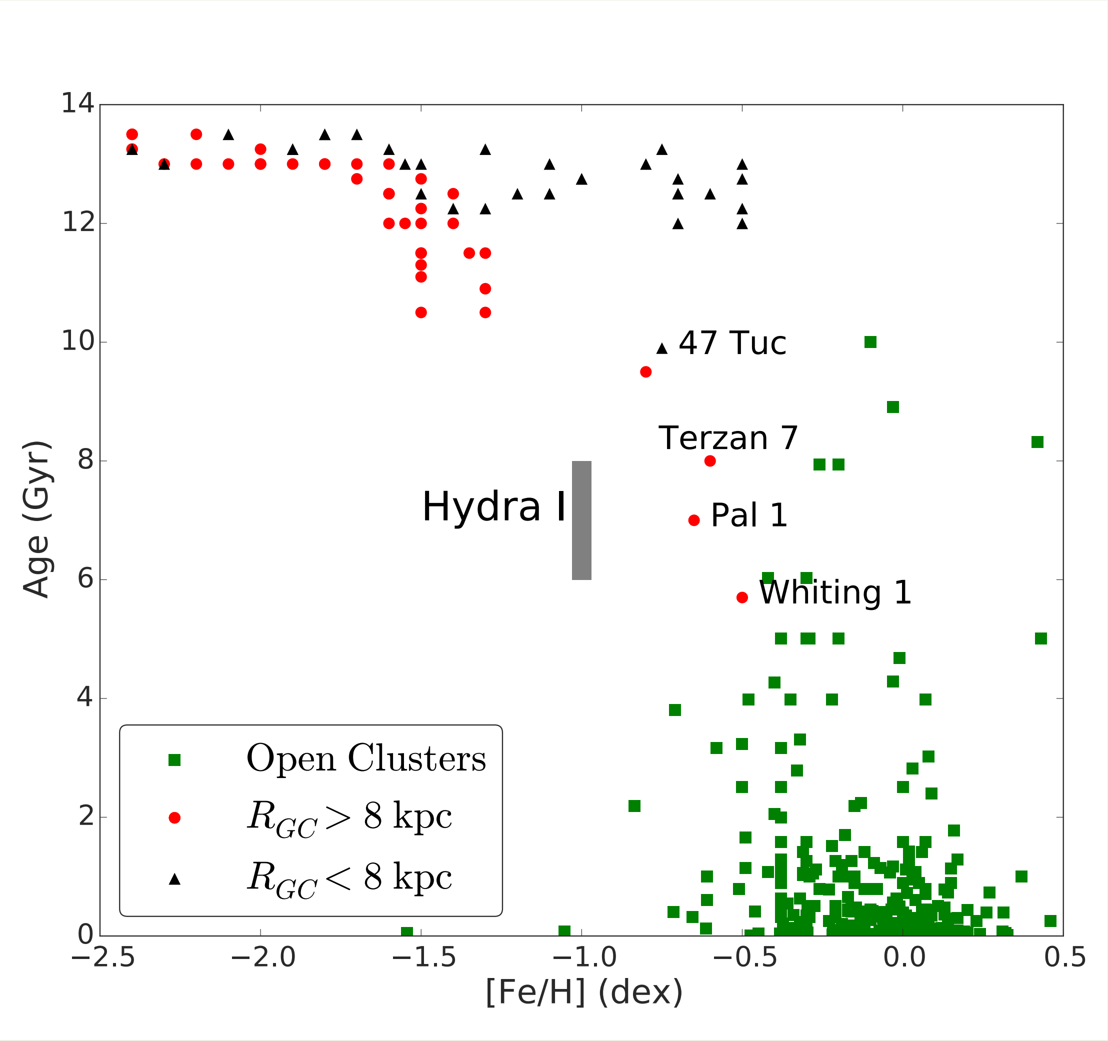
Dwarf Galaxy

From mass-metallicity relation: progenitor would have been a Fornax-like dwarf

- Implies significant (>99.99%) mass loss

Substructure in the Monoceros Ring

EBS/Hydra could simply be part of the large Monoceros Ring complex



Age-[Fe/H] diagram for Milky Way globular (red, black) and open (green) clusters. Data from Dotter et al. 2011, Dias et al. 2014.

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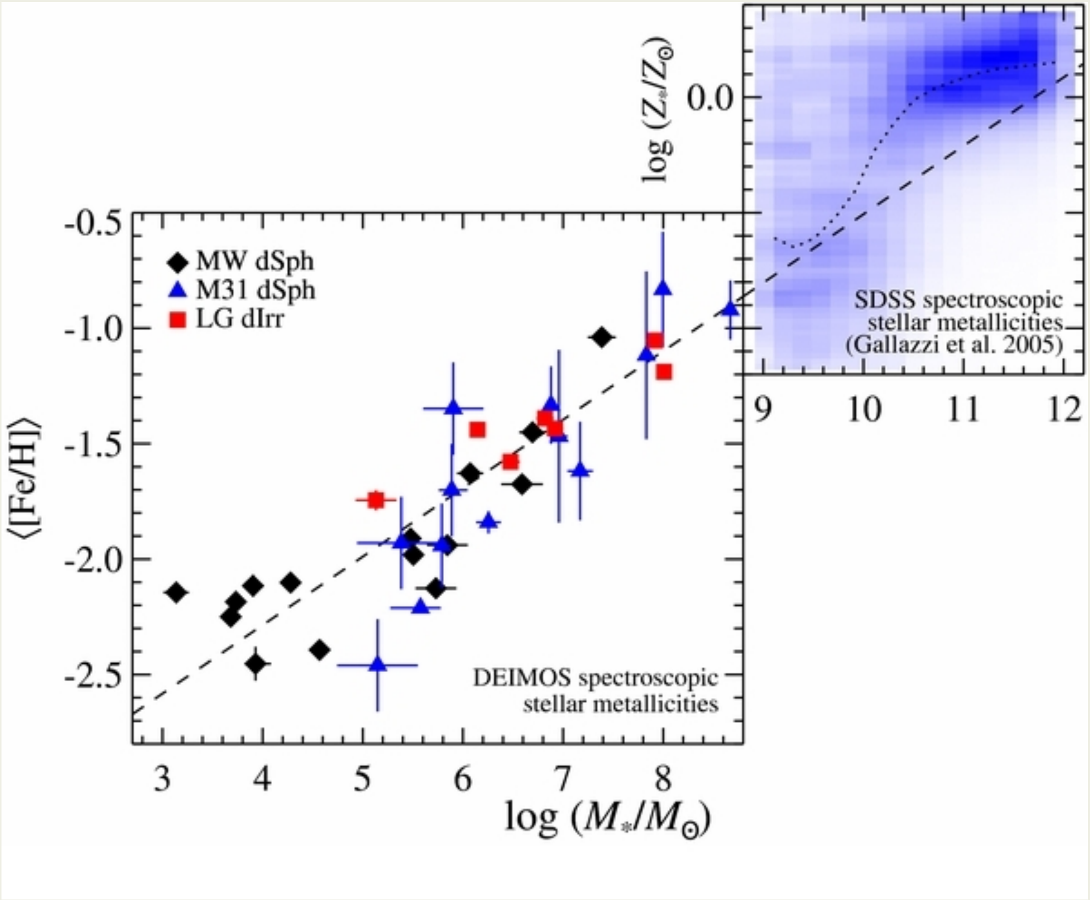

Stellar mass versus [Fe/H] for Local Group dwarf galaxies (Kirby et al. 2013)

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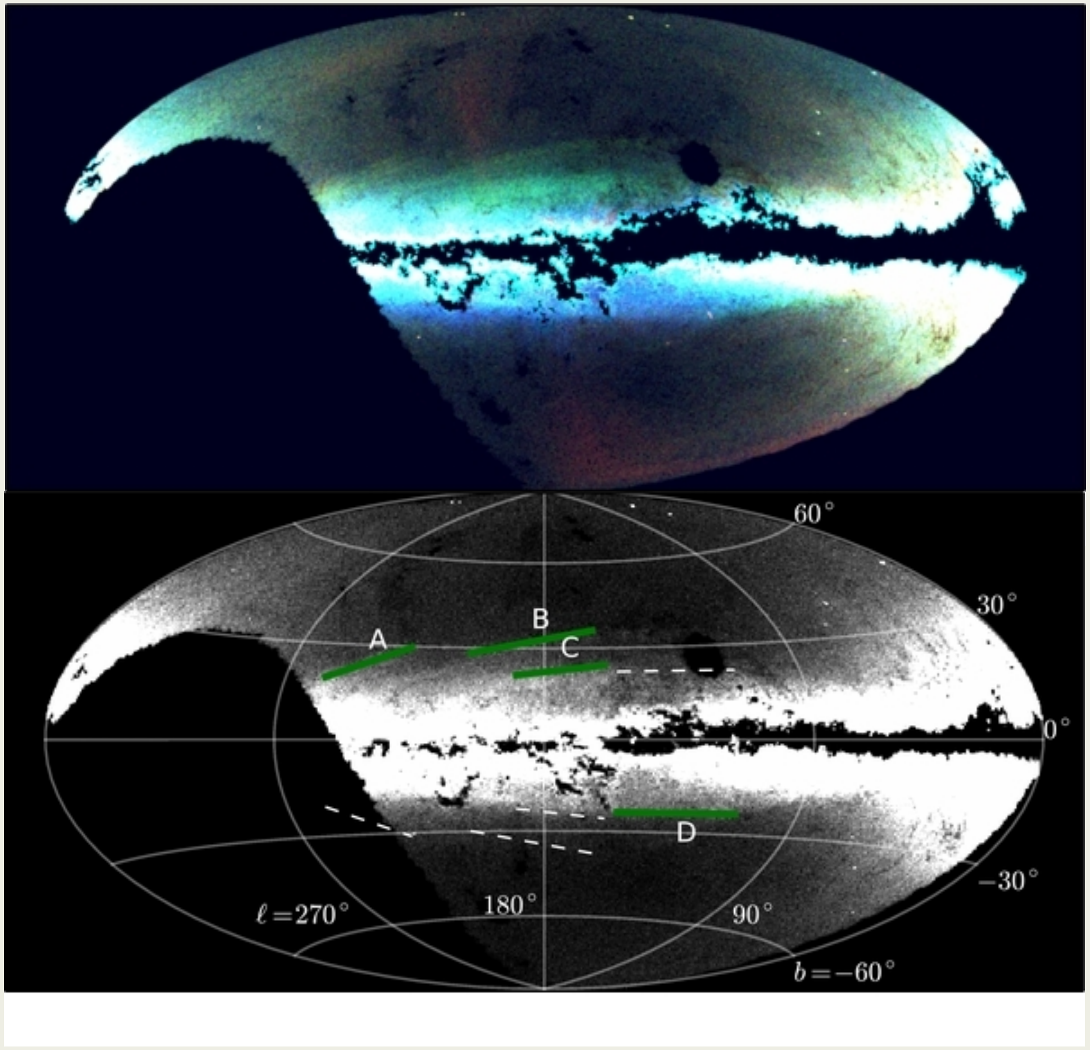


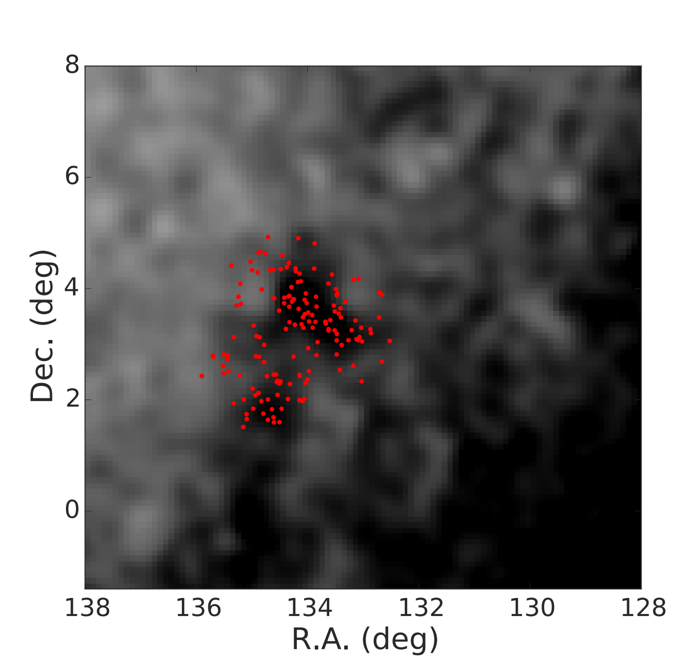
Star count map of MSTO stars from Pan-STARRS1 (Slater et al. 2014). In the top panel, color indicates distance. The EBS stream is labeled as feature B in the bottom panel.

What To Take Away:

The Milky Way affords us the chance study halo substructure in great detail. Much remains unknown about stream progenitors!

The properties of Hydra I:

- No rotation at the few km/s level
- Stellar pops as young as ~6 Gyr
- [Fe/H] = -0.93 +/- 0.03



Future Work:

- Attempt CMD foreground subtraction to disentangle Hydra I from MRi region
- Artificial star test to improve star-galaxy separation; quantify completeness
- Detailed analysis of stream substructure using spatial maps
- Simulate observations of stream gaps/ clumps to test for statistical significance