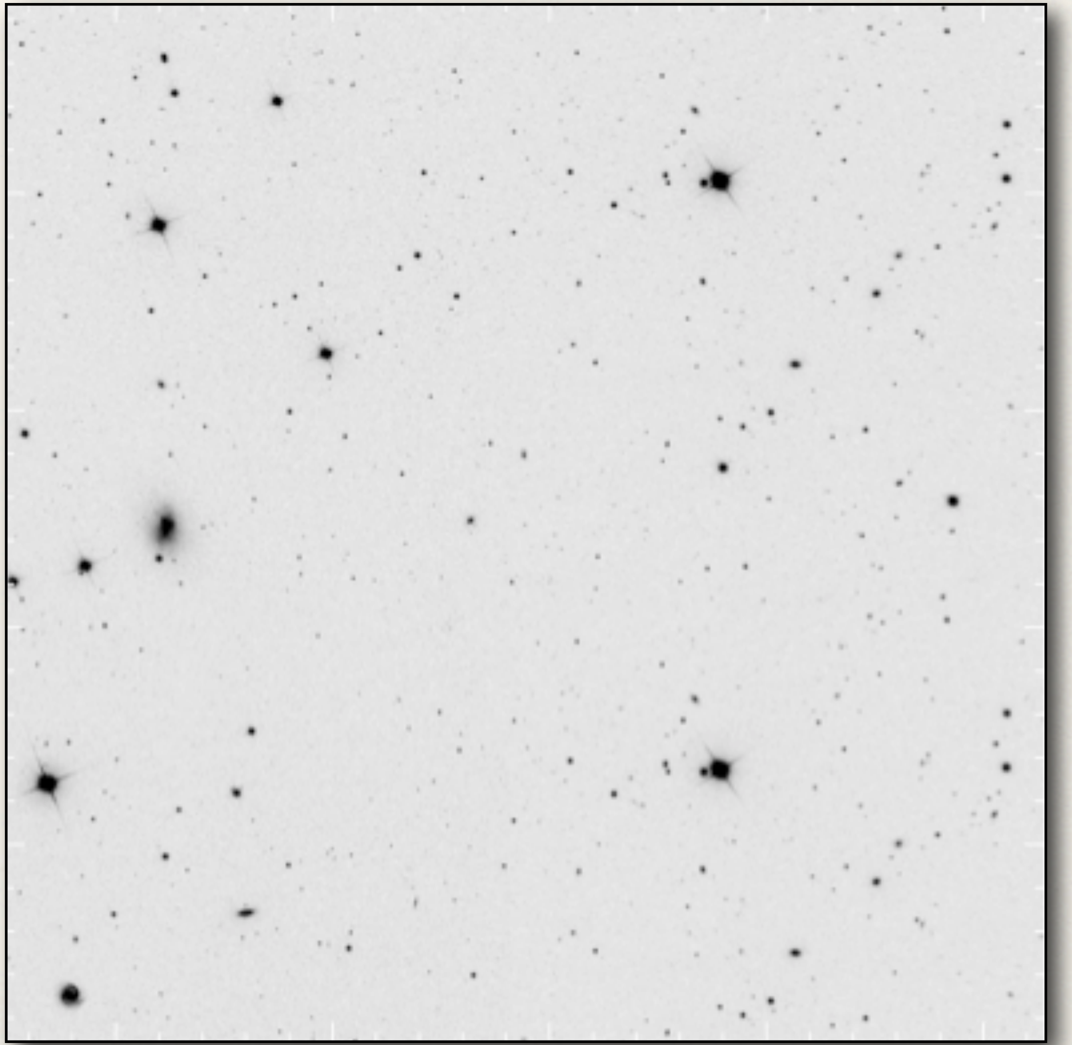
Kinematics of the Faintest Stellar Systems (around the Milky Way)

SDSS r-band Segue 1



Marla Geha
Yale University

Collaborators:

- Josh Simon (OCIW)
- Beth Willman (Haverford)
- Ross Fadley (Haverford)
- Ricardo Munoz (Yale)
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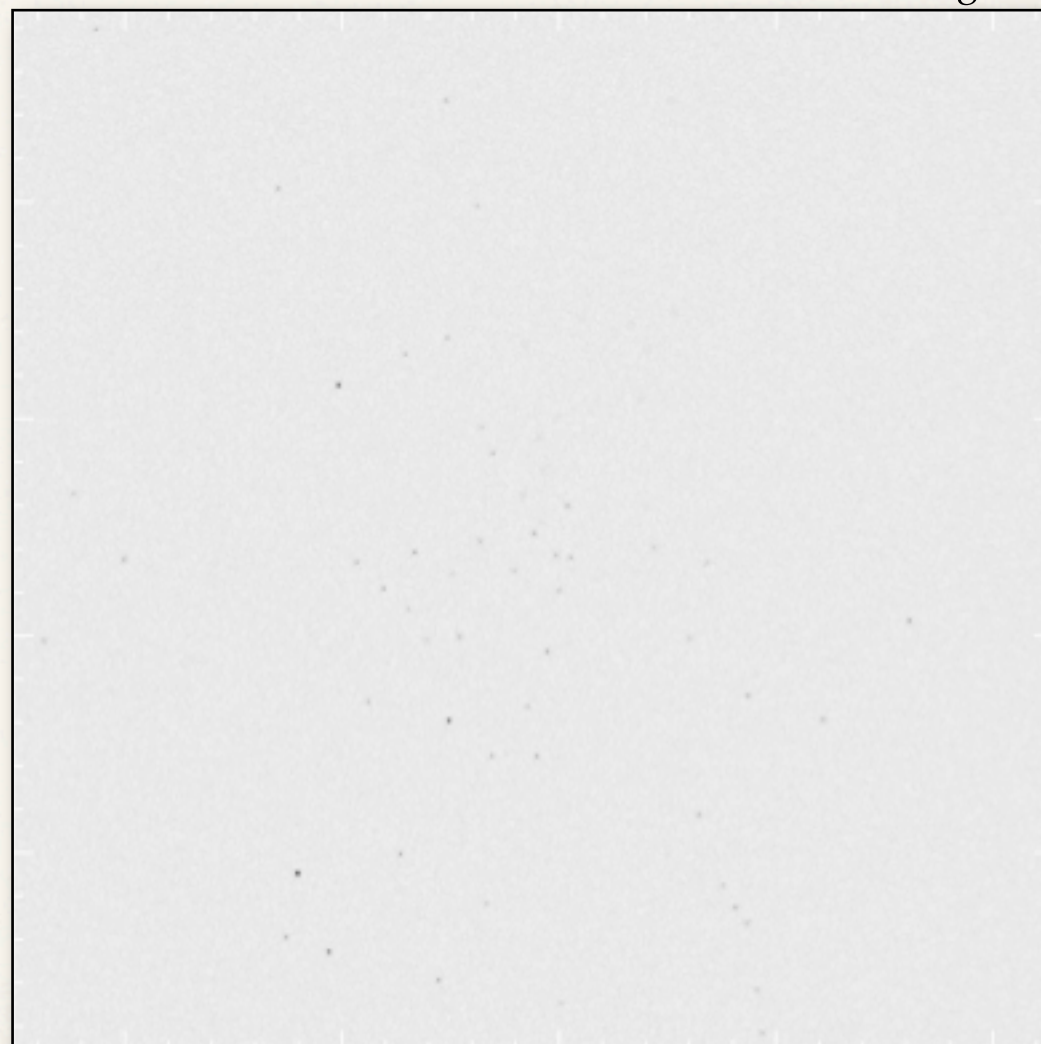

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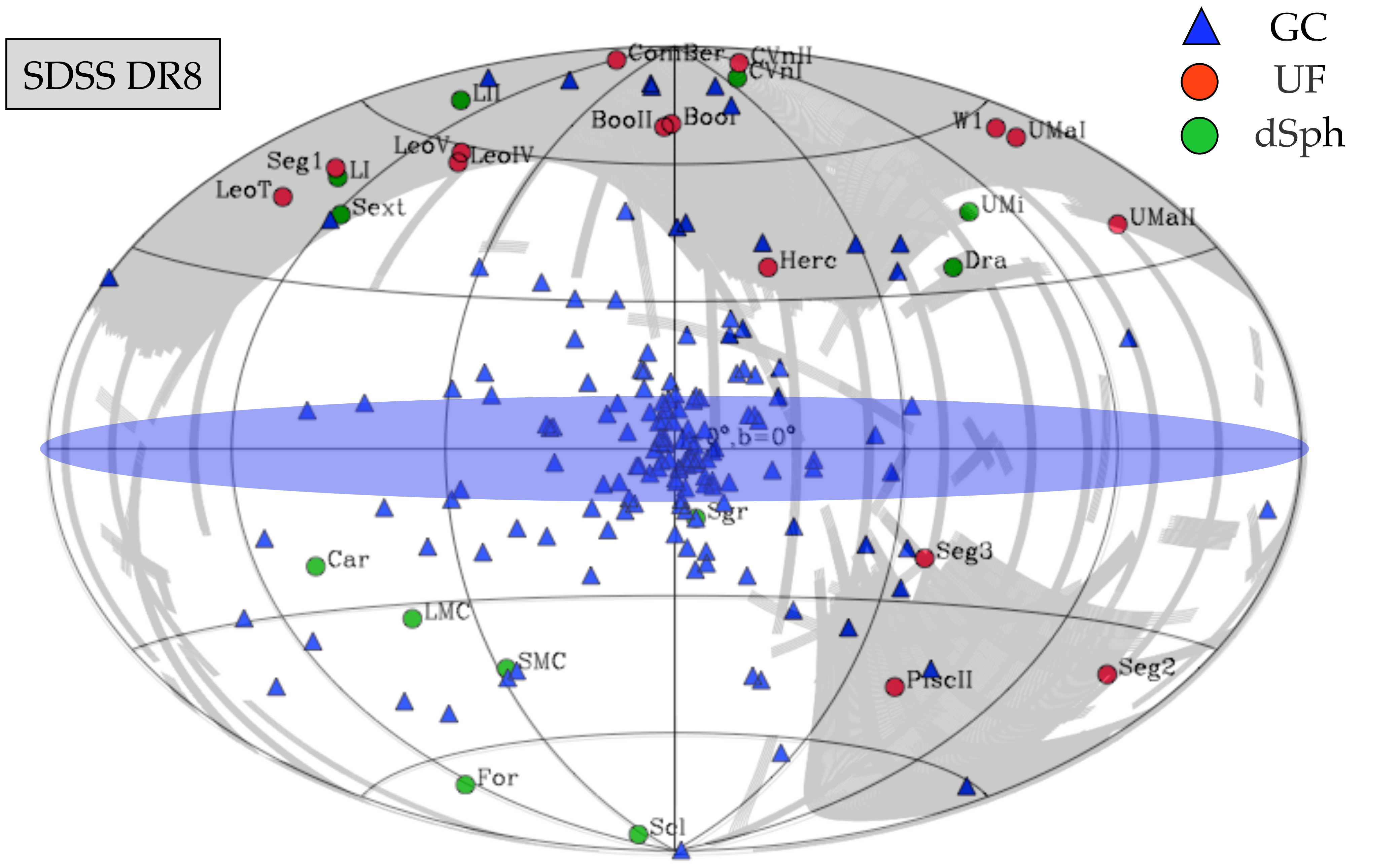
The Satellites of the Milky Way



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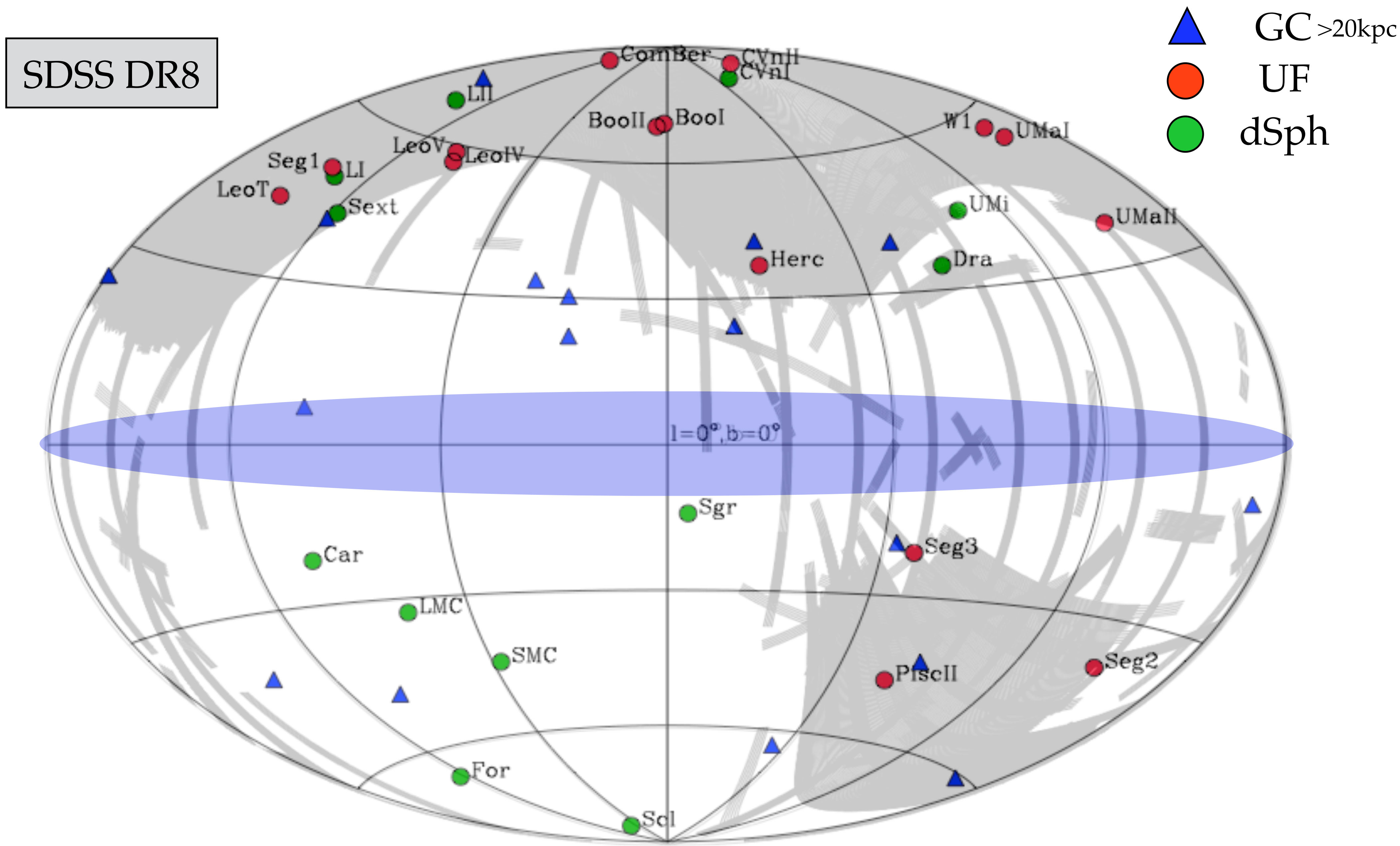

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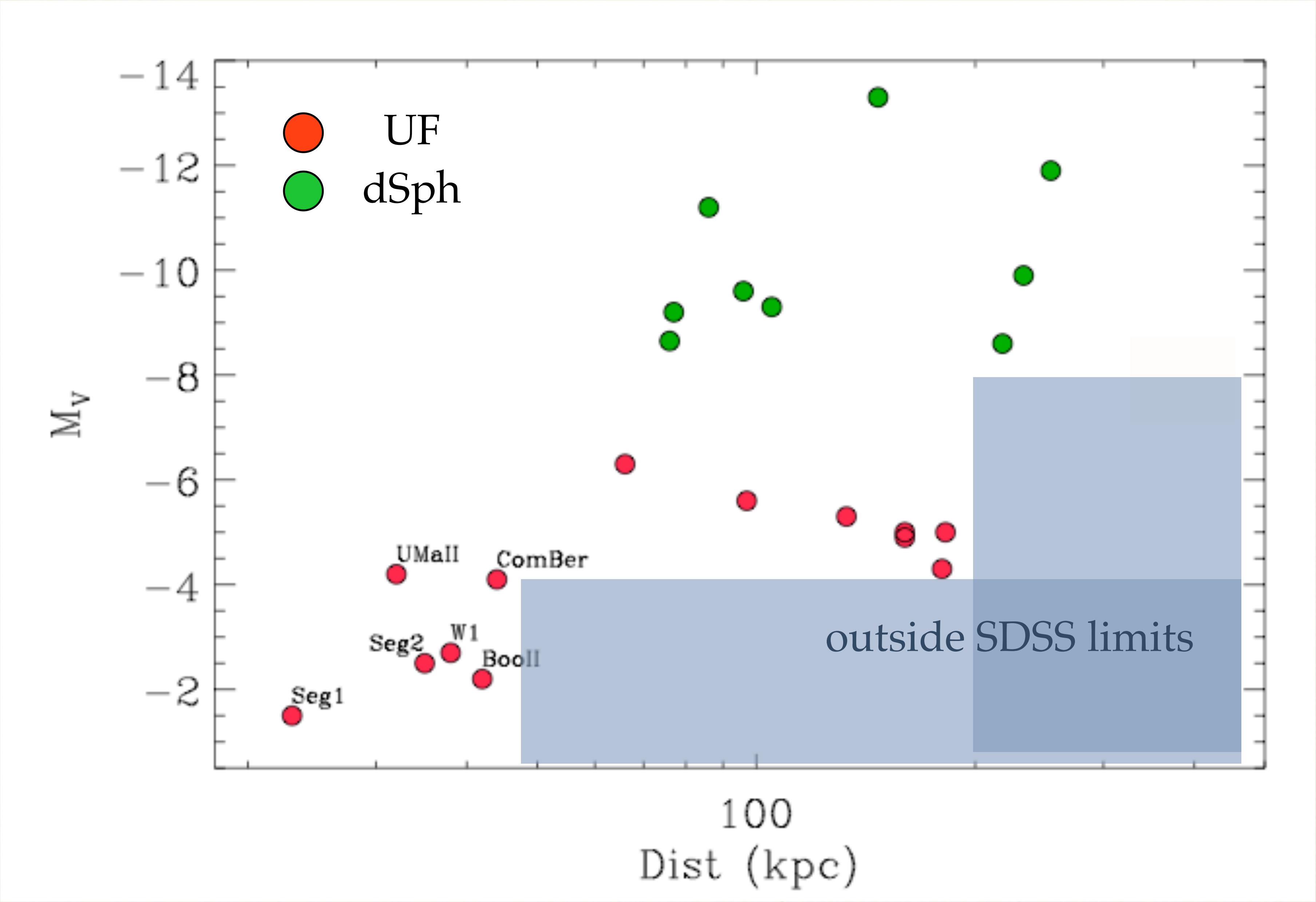
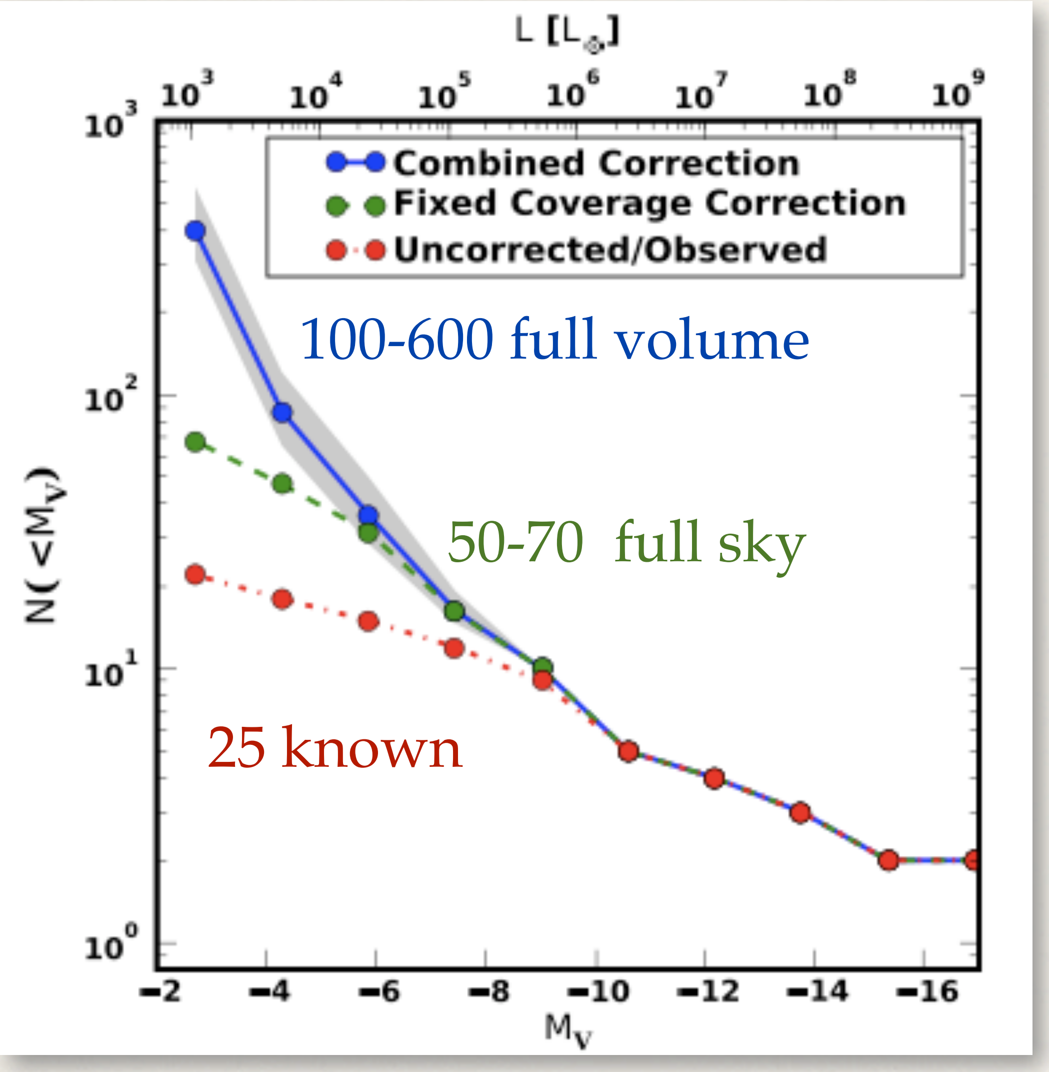


The Satellites of the Milky Way

Tollerud et al. (2008)



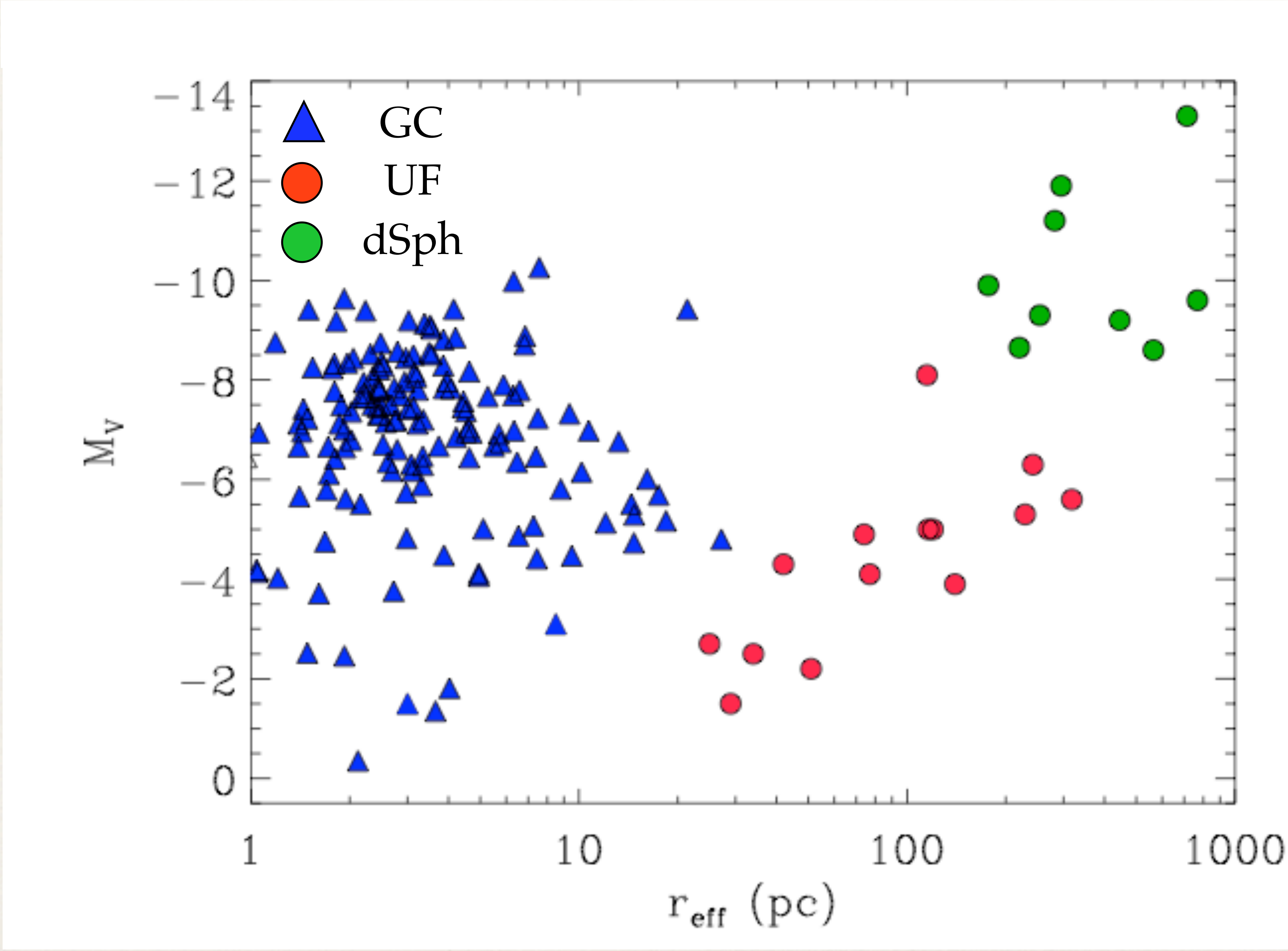
The least luminous dwarfs are particularly useful:

a) *Galaxy Formation:*
Highest M/L ratios, lowest [Fe/H]

b) *Cosmology:*
Φ(L), n(M) critical test of ΛCDM
"the missing satellite issue"

c) *Particle Physics:*
Indirect dark matter detection

The Satellites of the Milky Way



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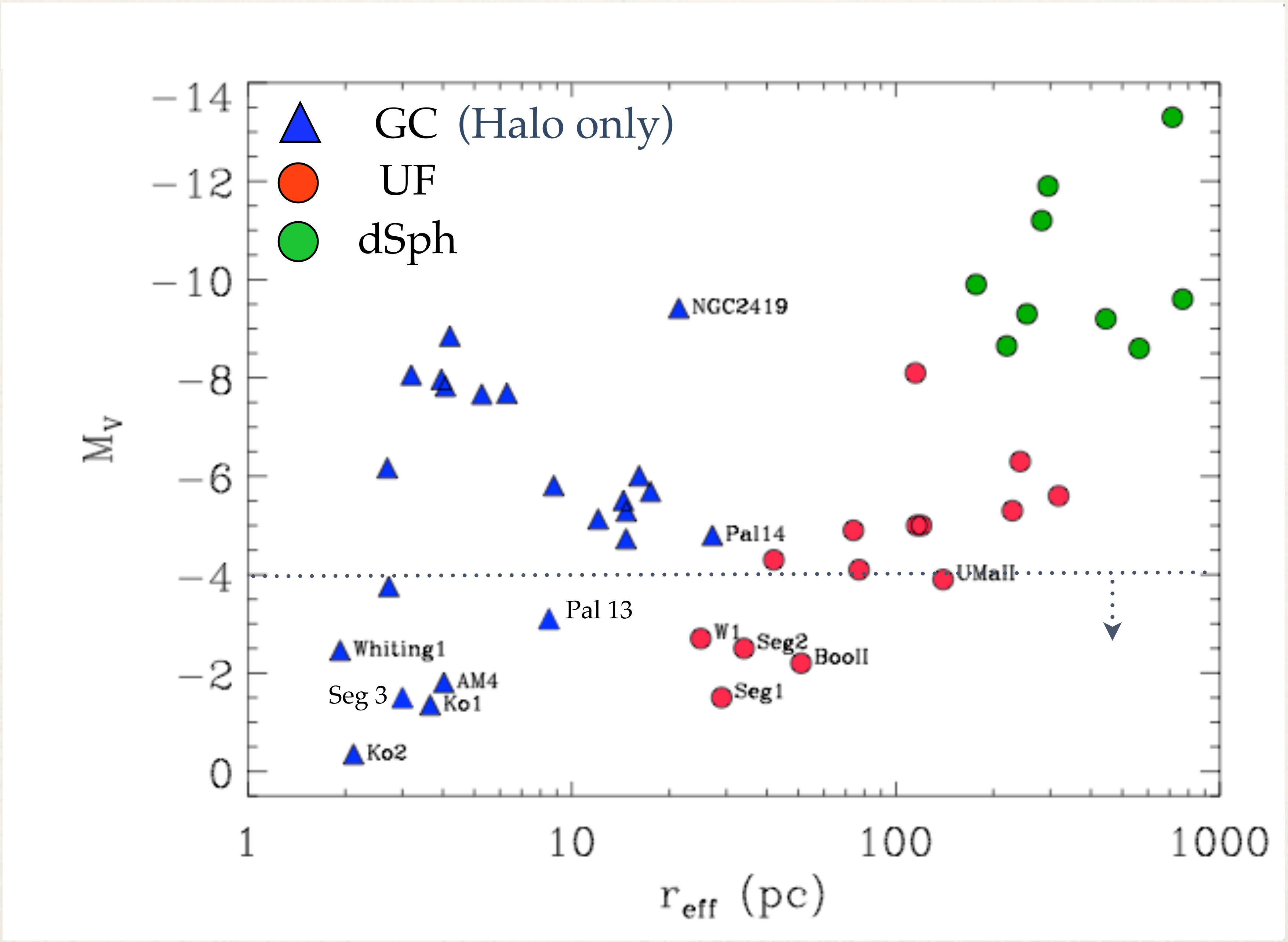


Kinematics with Keck/DEIMOS

DEIMOS Multi-Object Spectrograph

-- 150 stars per pointing

-- 6500 to 9000Å

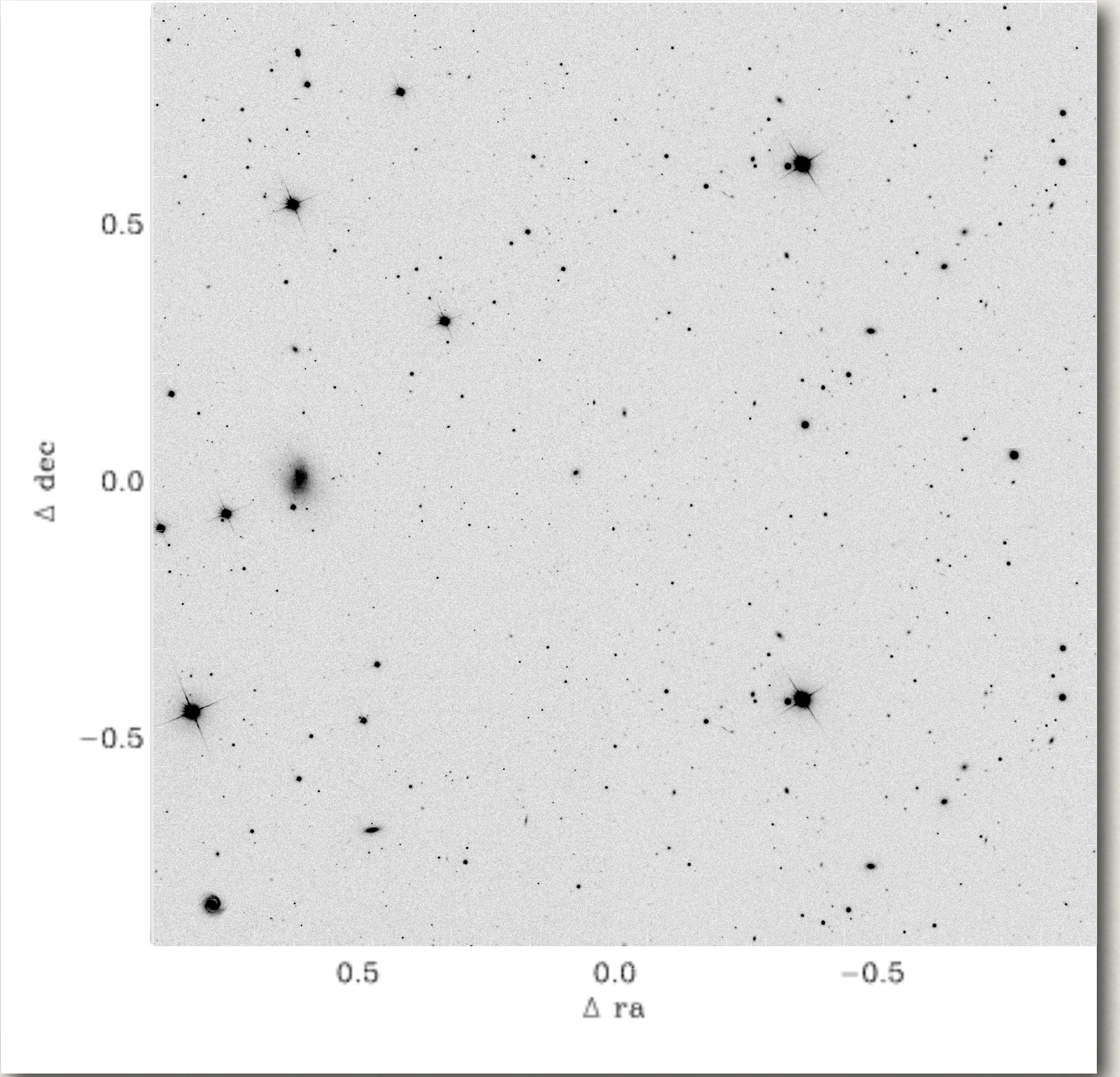
-- 0.33 Å $pixel^{-1}$, $\sigma_{sys} = 2$ km s^{-1}

DEIMOS spectral resolution and spatial field-of-view very well matched to the ultra-faint galaxies.

Stable instrument, well characterized systematics.

Studying Extremely Faint Stellar Systems

In regime where few (< 50) stars are detected for (spectroscopy or photometry), extreme caution is required.



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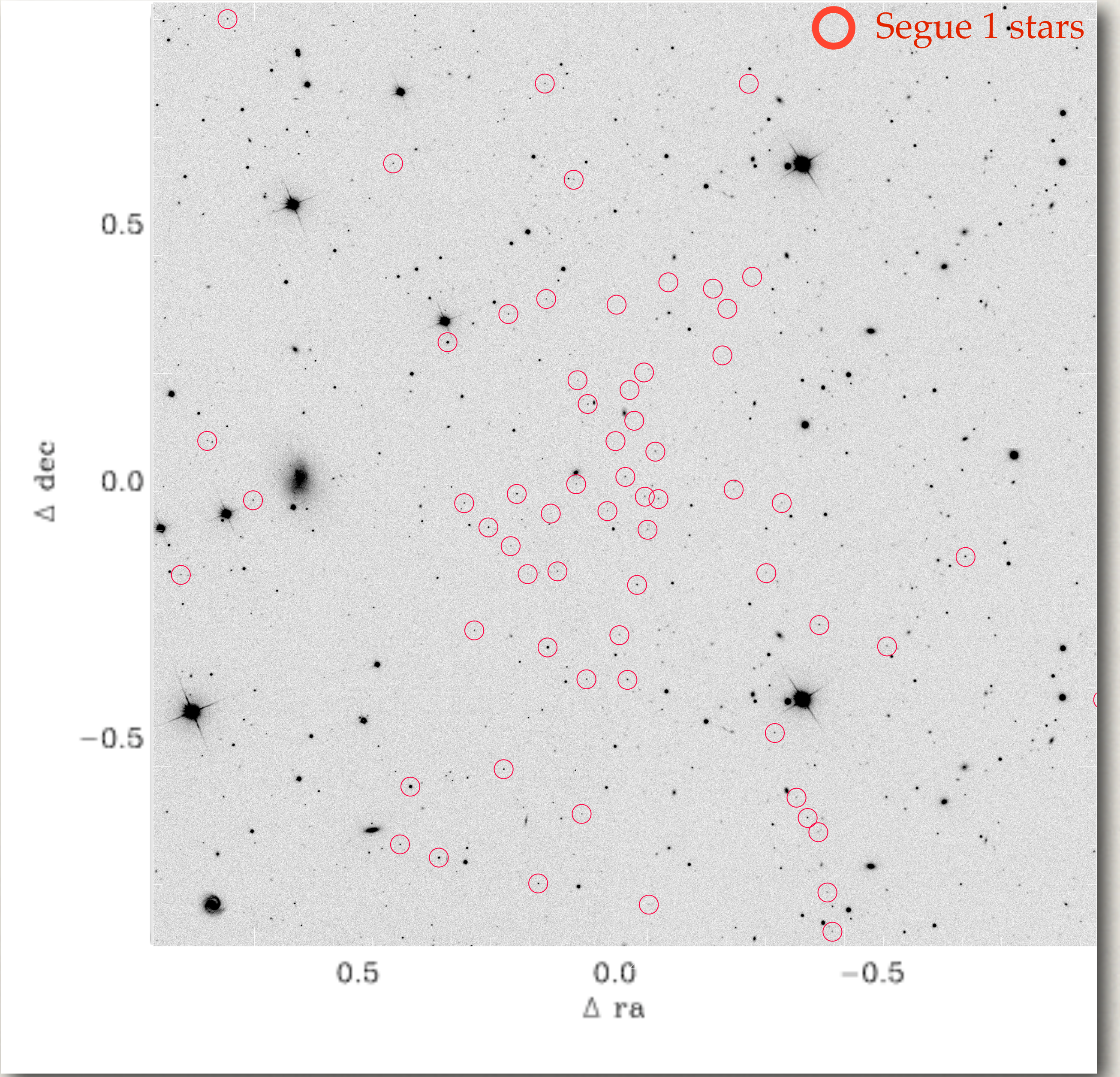
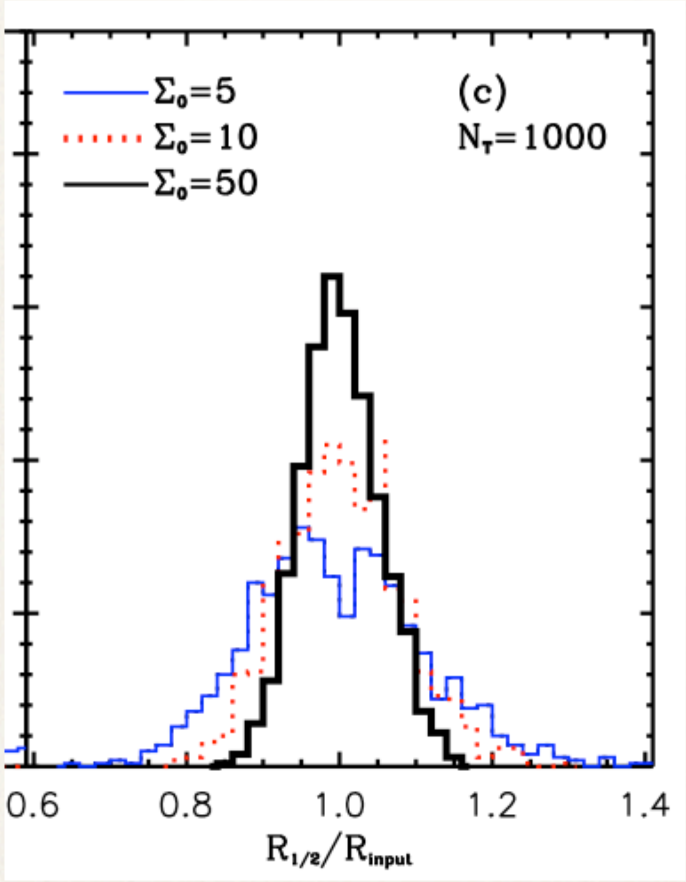


Studying Extremely Faint Stellar Systems

While small numbers in measuring *velocity dispersion* is appreciated (e.g. Haghi, Baumgardt & Kroupa 2011), there is similar problem in measuring *sizes/luminosities*.



Munoz, Padmanahban & Geha (2011)

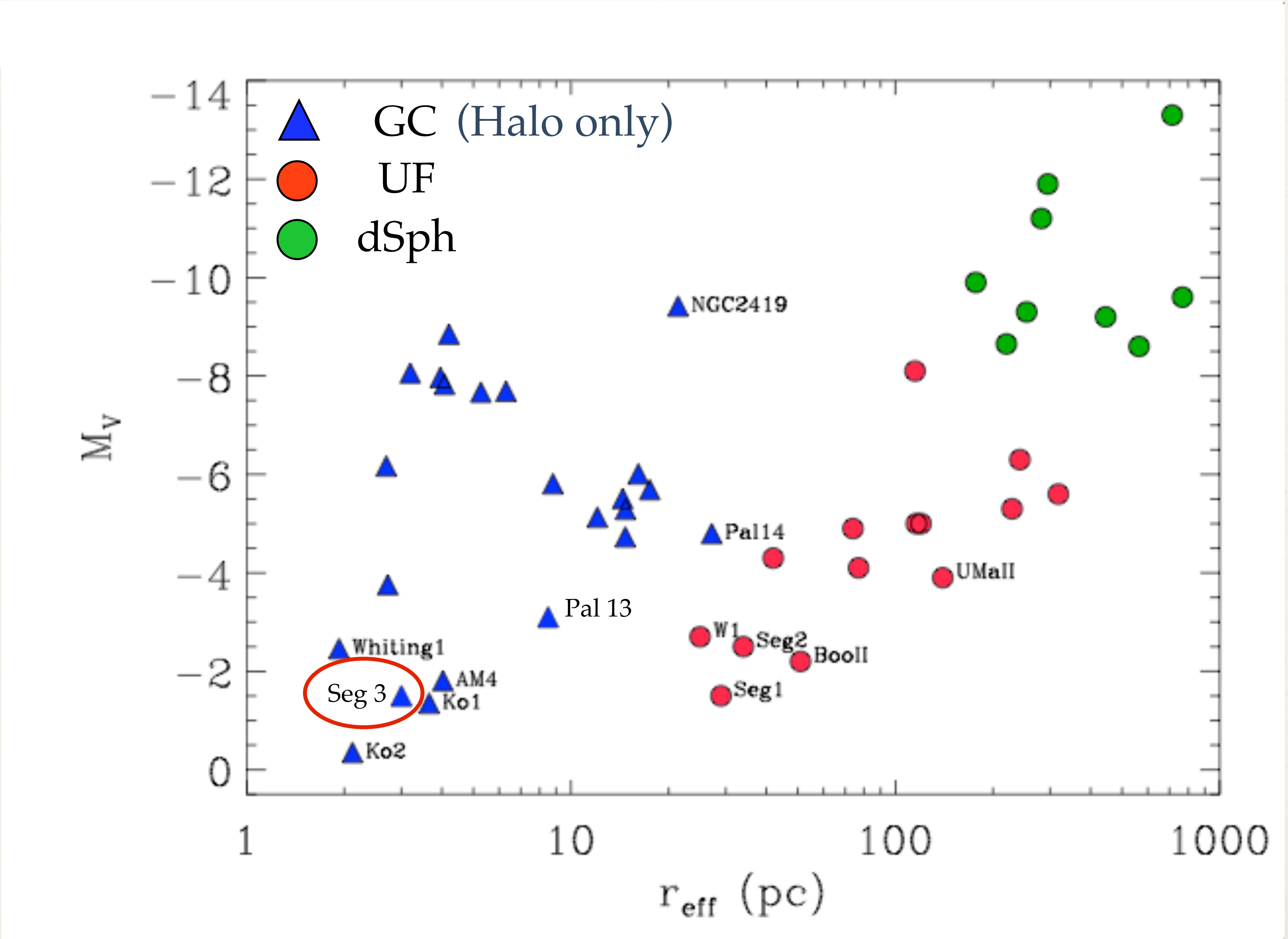
Simulated circular Plummer profiles on top of uniform backgrounds.

Blue - similar to faint UFs measured by SDSS.

=> Distribution is non-Gaussian

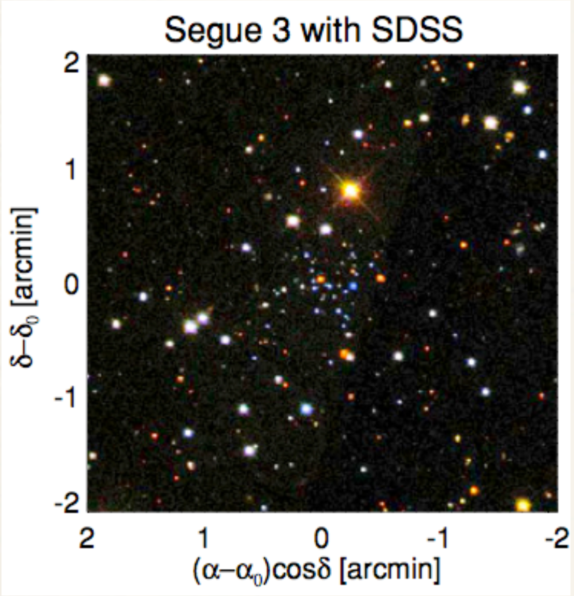
Black - UFs measured by deep follow-up.

The Satellites of the Milky Way



Segue 3:
A New Normal Globular Cluster

Belokurov et al. (2010)



Belokurov et al. (2010)

Globular cluster D= 16 kpc, M_V = -1.2

Segue 3:
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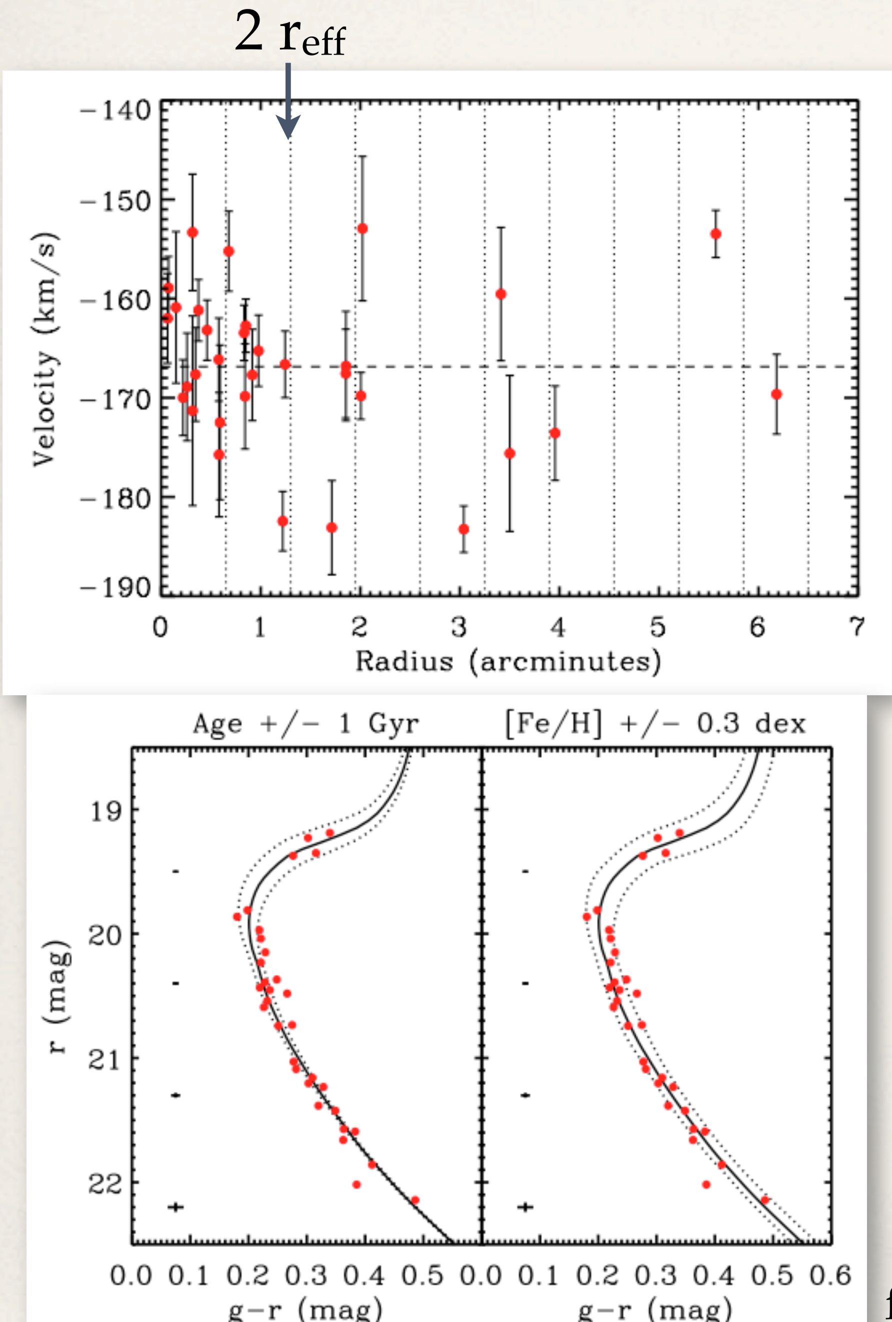


Belokurov et al. (2010)

Globular cluster D= 16 kpc, $M_V = -1.2$

Fadley, Willman, MG et al. (2011)

23 Segue 3 members

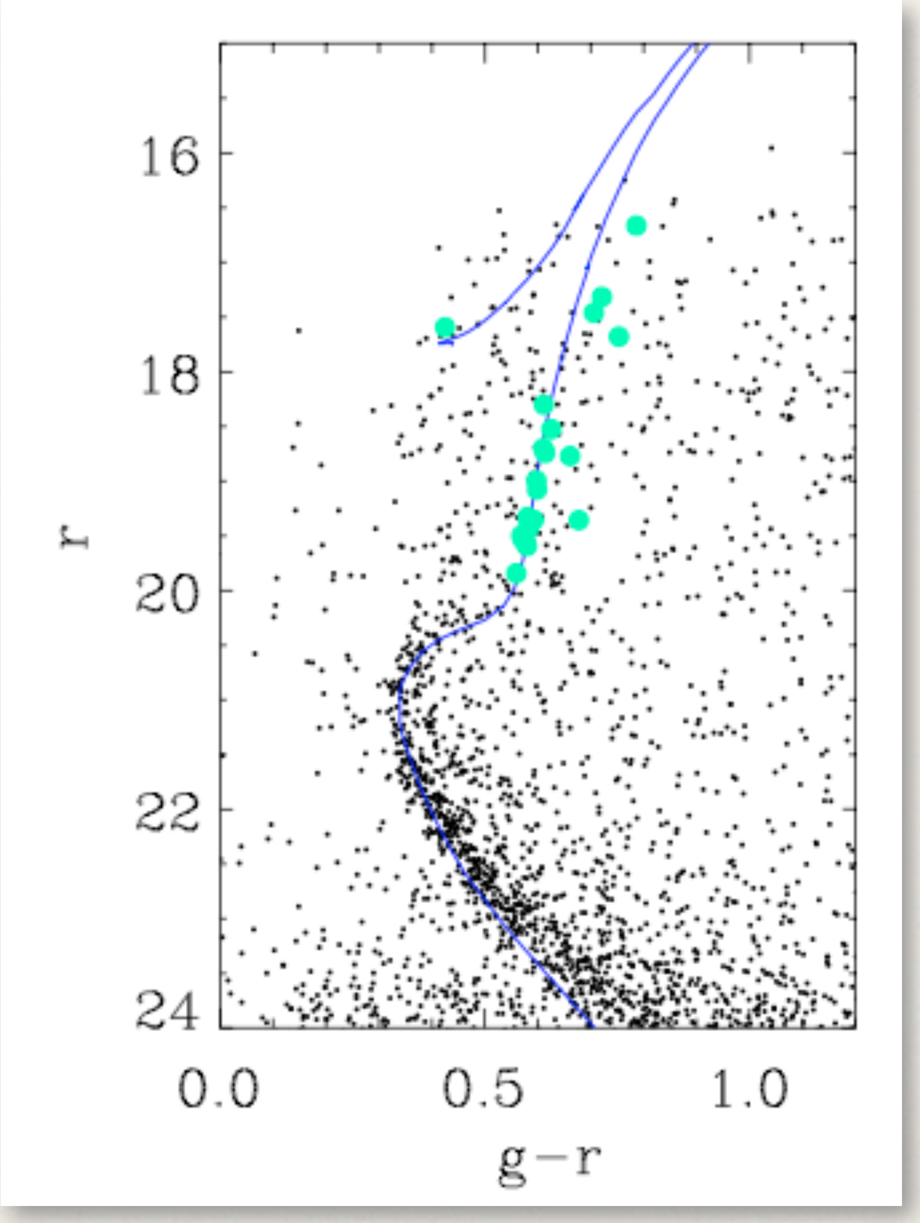
Inside $2r_{eff}$, $\sigma = 1.2 \pm 2.0$ km s^{-1}

Possible extra-tidal stars, but may also be from Hercules-Aquila cloud.

CMD consistent with SSP.

from S. Walsh

Palomar 13:
An Odd Globular Cluster?



<u>Coté et al. (2002):</u>

Velocity dispersion of Pal 13 = 2.2 km s^{-1}

Based on 21 Keck/HIRES stars

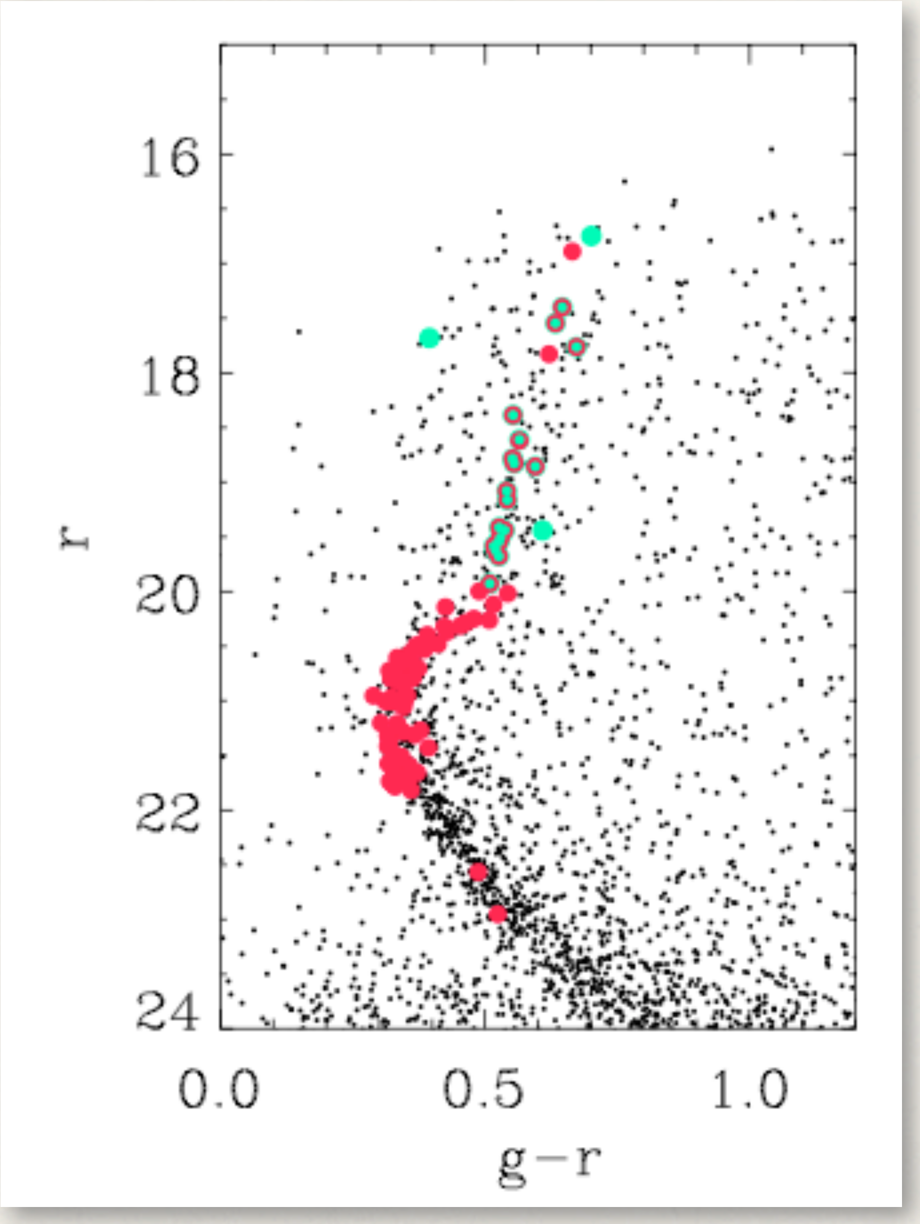
=> if undisturbed $M/L_V = 40^{+24}_{-17}$

=> last stages of tidal disruption

<u>Küpper, Mieske & Kroupa (2011)</u>

cannot fit observed dispersion, SB profile given measured orbit.

Palomar 13:
A Normal Globular Cluster



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Küpper, Mieske & Kroupa (2011)

cannot fit observed dispersion, SB profile given measured orbit.

J. Bradford, MG, Cote et al (2011)

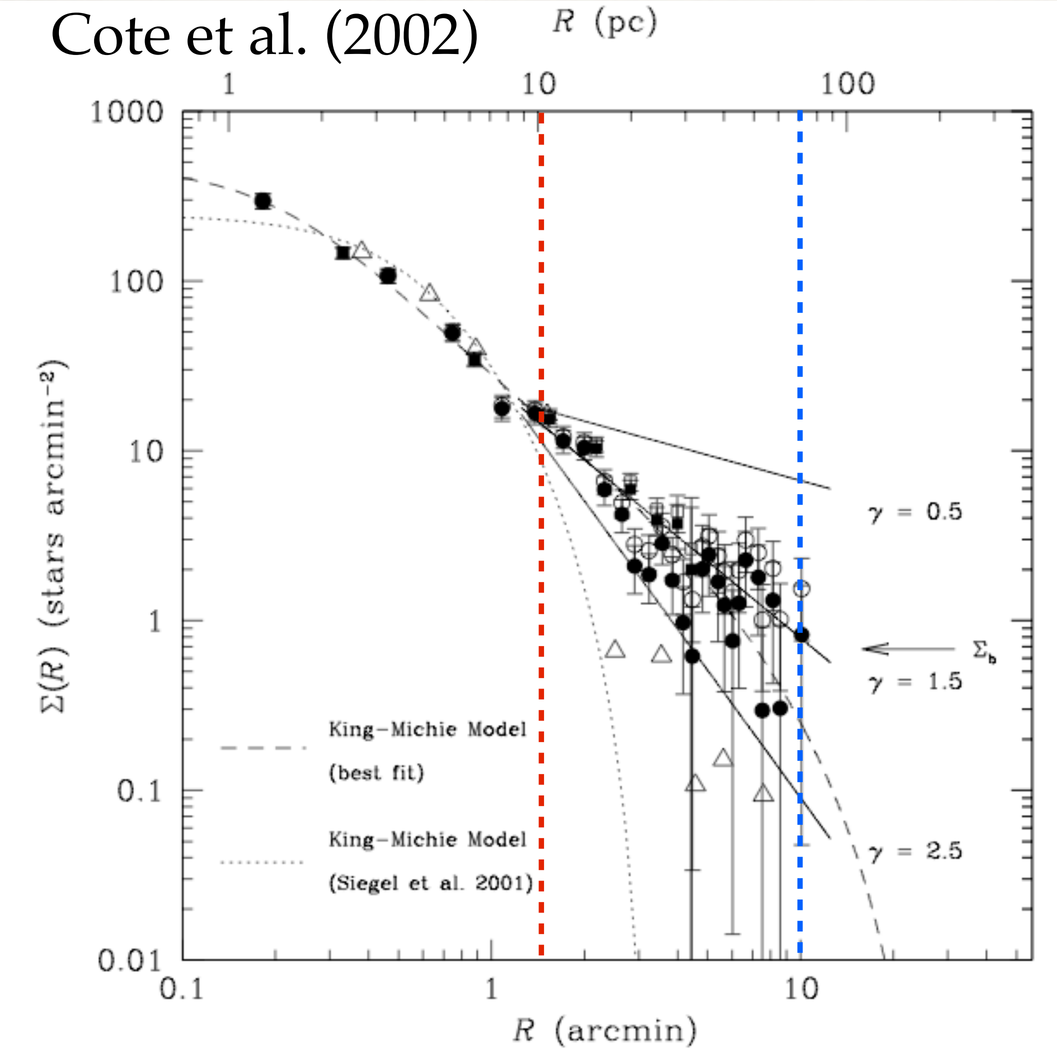
DEIMOS spectra for 90 members.

=> remove 2 velocity variables

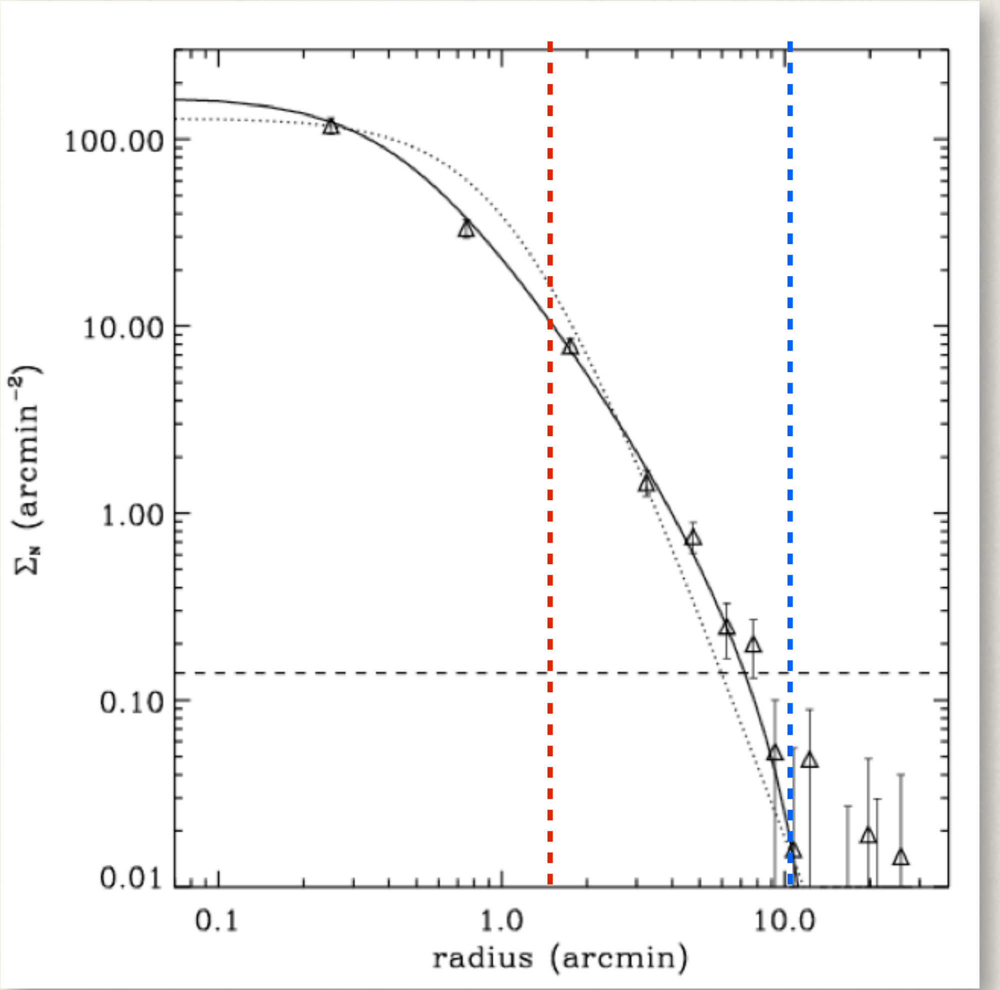
$\sigma = 0.0 \pm 1.2$ km s^{-1}

Palomar 13:
A Normal Globular Cluster

Cote et al. (2002)



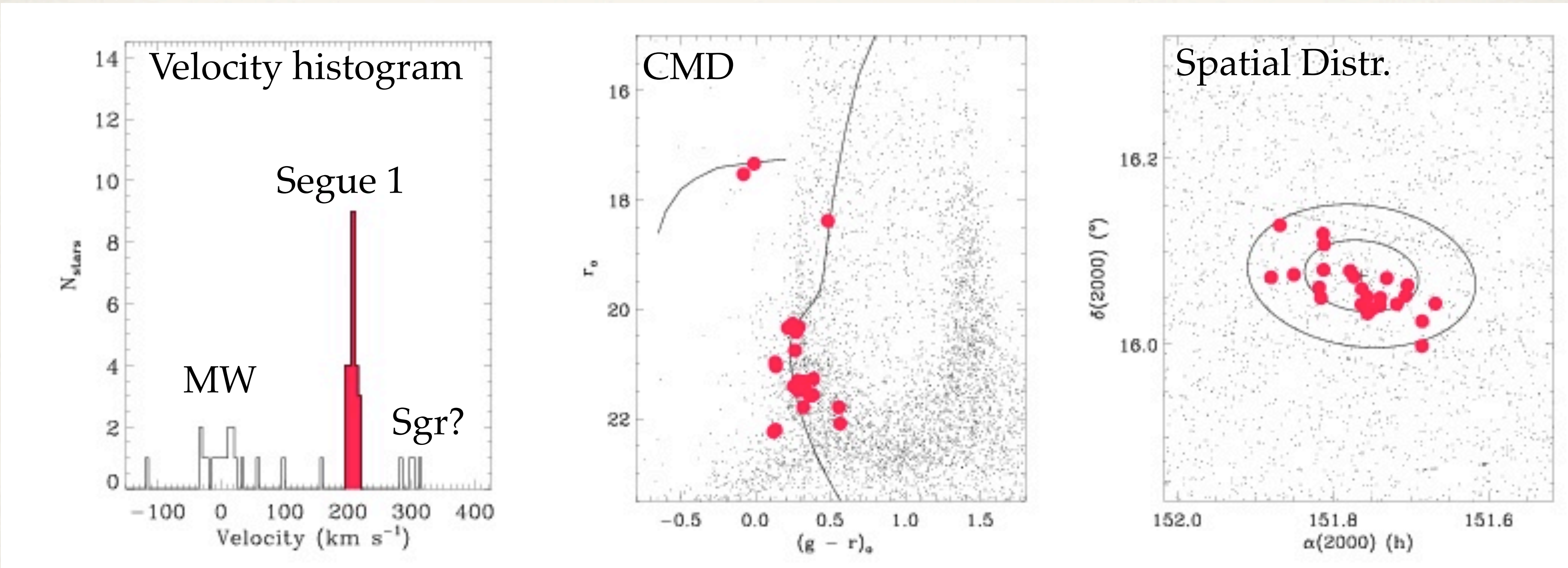
From R. Munoz



King profile fits well, but large r_{tidal}

Kinematics of Segue 1

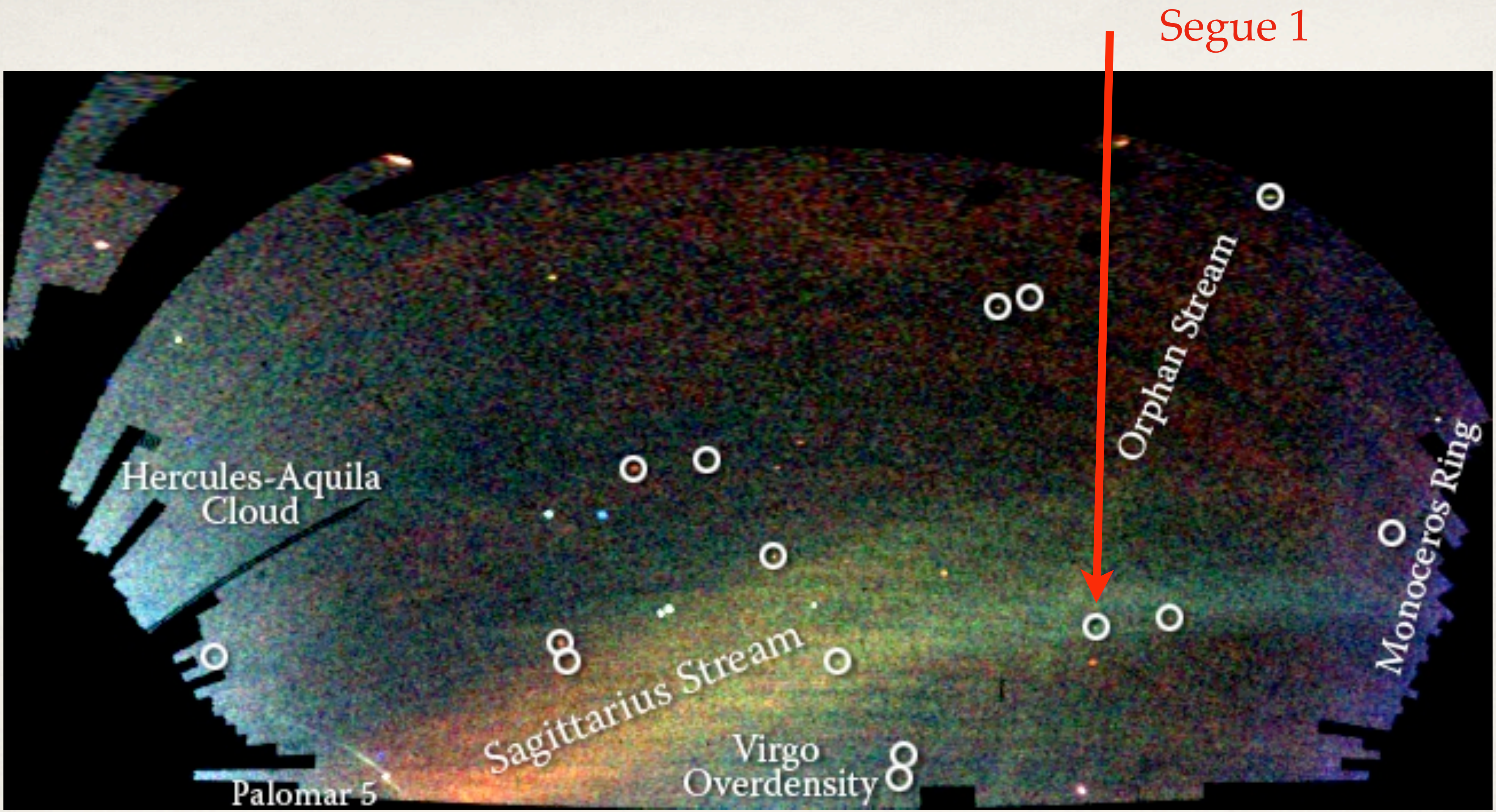
Geha et al (2009): 24 members stars



If mass from stars only = 0.4 km s^{-1}

Measured velocity dispersion = 4.5± 1 km s^{-1}

M/L = 2500 ± 1500



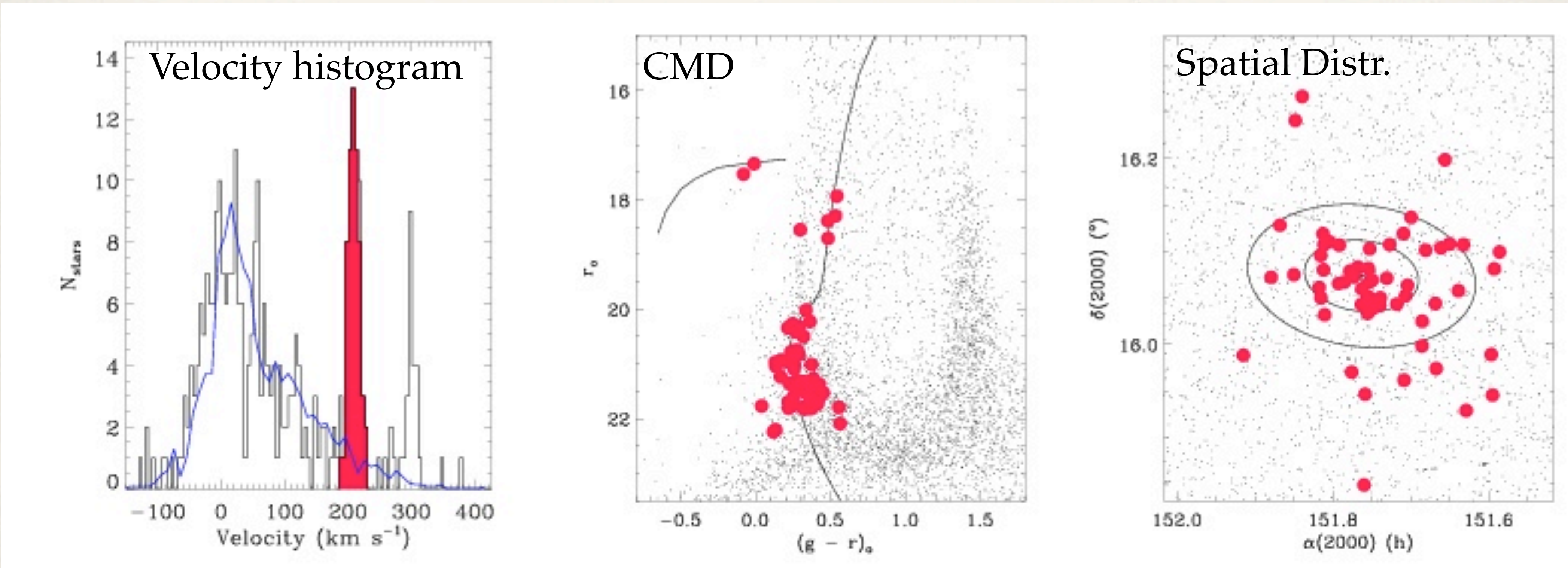
Given small sample, a few contaminant stars from Sgr stream could be inflating the velocity dispersion.

Kinematics of Segue 1

Spectroscopy of 99.1% of stars
to r ~ 22
out to 2 half-light radii.

Geha et al (2009): 24 members stars

Simon, MG et al (2010): 71 members



MG et al. (2009) = 4.5± 1 km s^{-1}

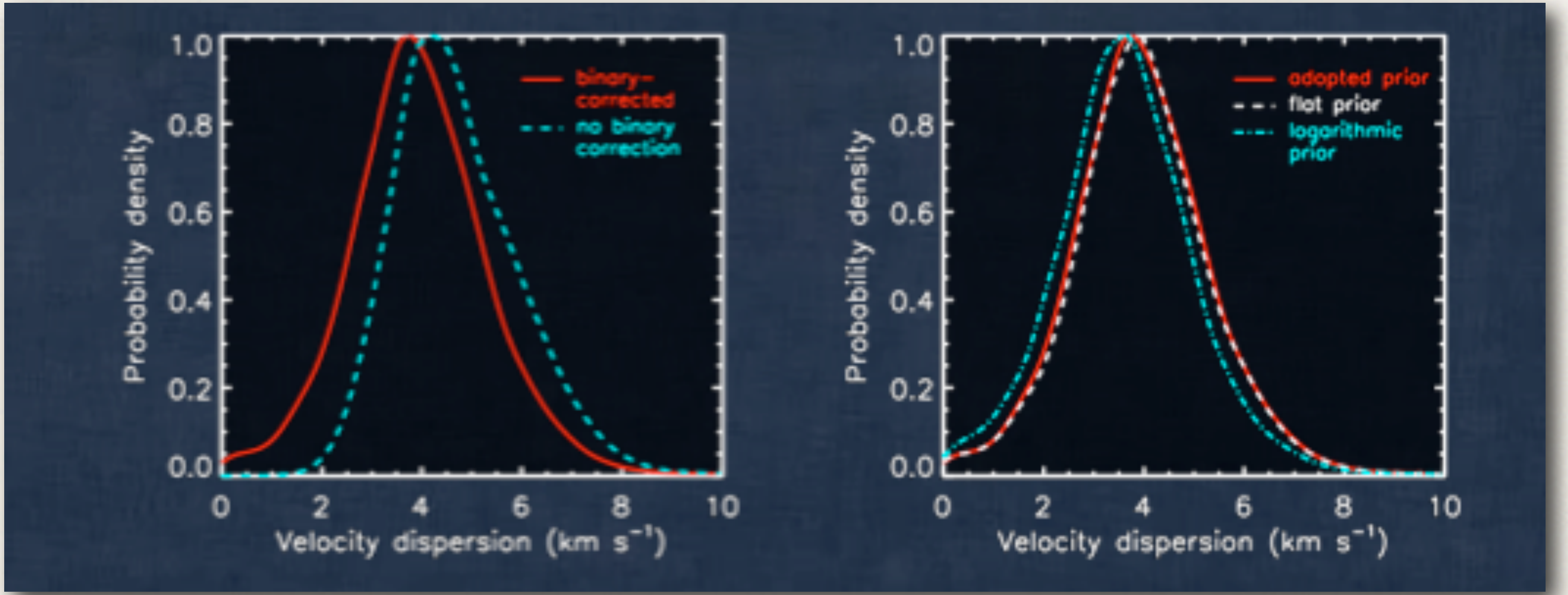
Simon et al. (2010) = 3.7 ± 1 km s^{-1}
(binary corrected Martinez et al. 2010)

Kinematics of Segue 1

Unresolved binary stars can inflate the measured velocity dispersion.

Repeat velocity measurements over time constrain contribution.

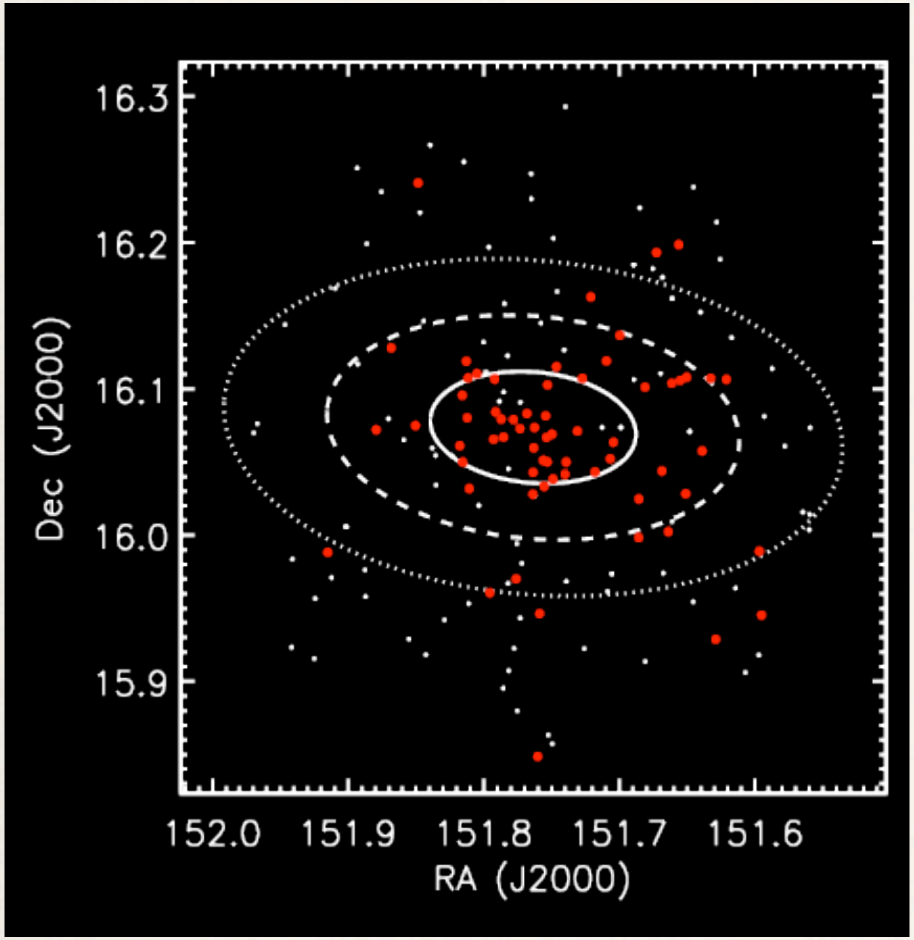
Martinez et al. (2010)



Binary stars contribute ~10% to velocity dispersion.

Kinematics of Segue 1

If no DM, tidal radius is 30 pc (inner ellipse)



- Signs of tidal disruption?
  - Velocity gradient no
  - Excess of stars at large radii no
  - Velocity dispersion increasing with radius no

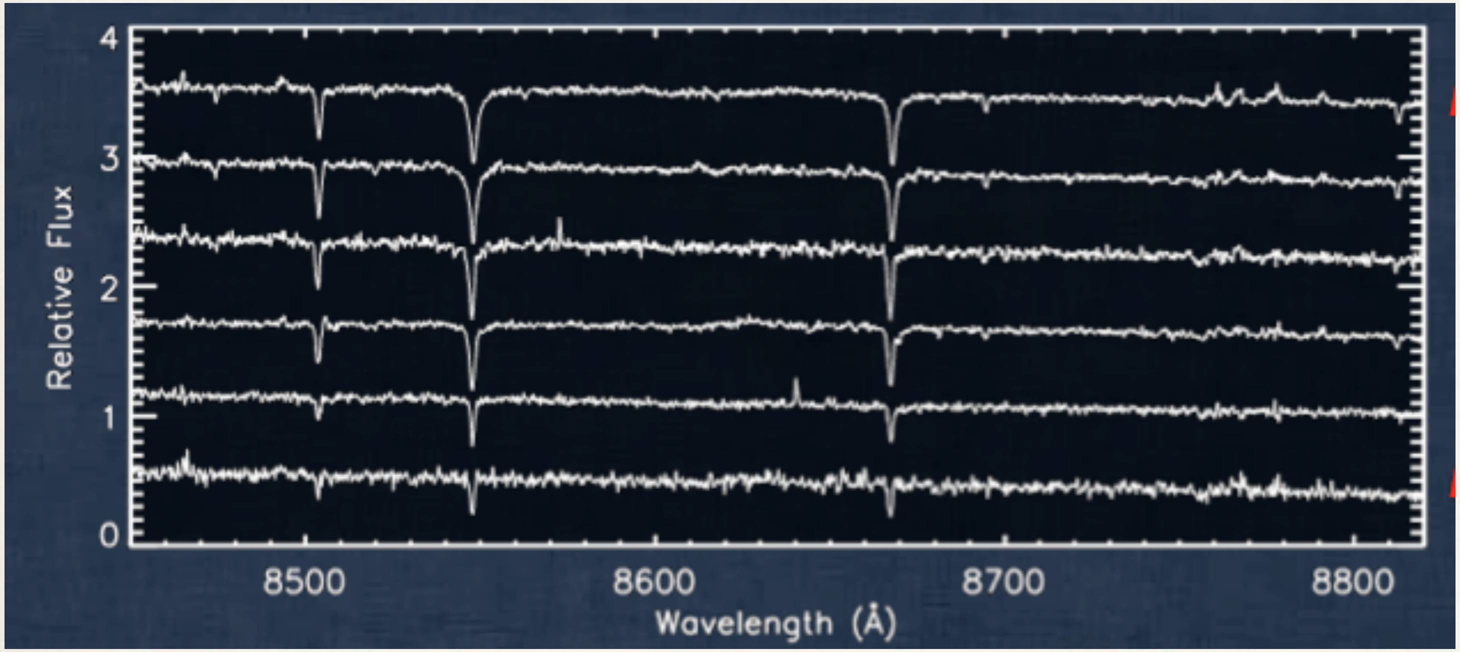
No evidence for tidal disruption in Segue 1.

Internal Metallicity Spread in Segue 1

Simon et al. (2010)

<[Fe/H]> = -2.5

Internal spread of 1.5 dex.

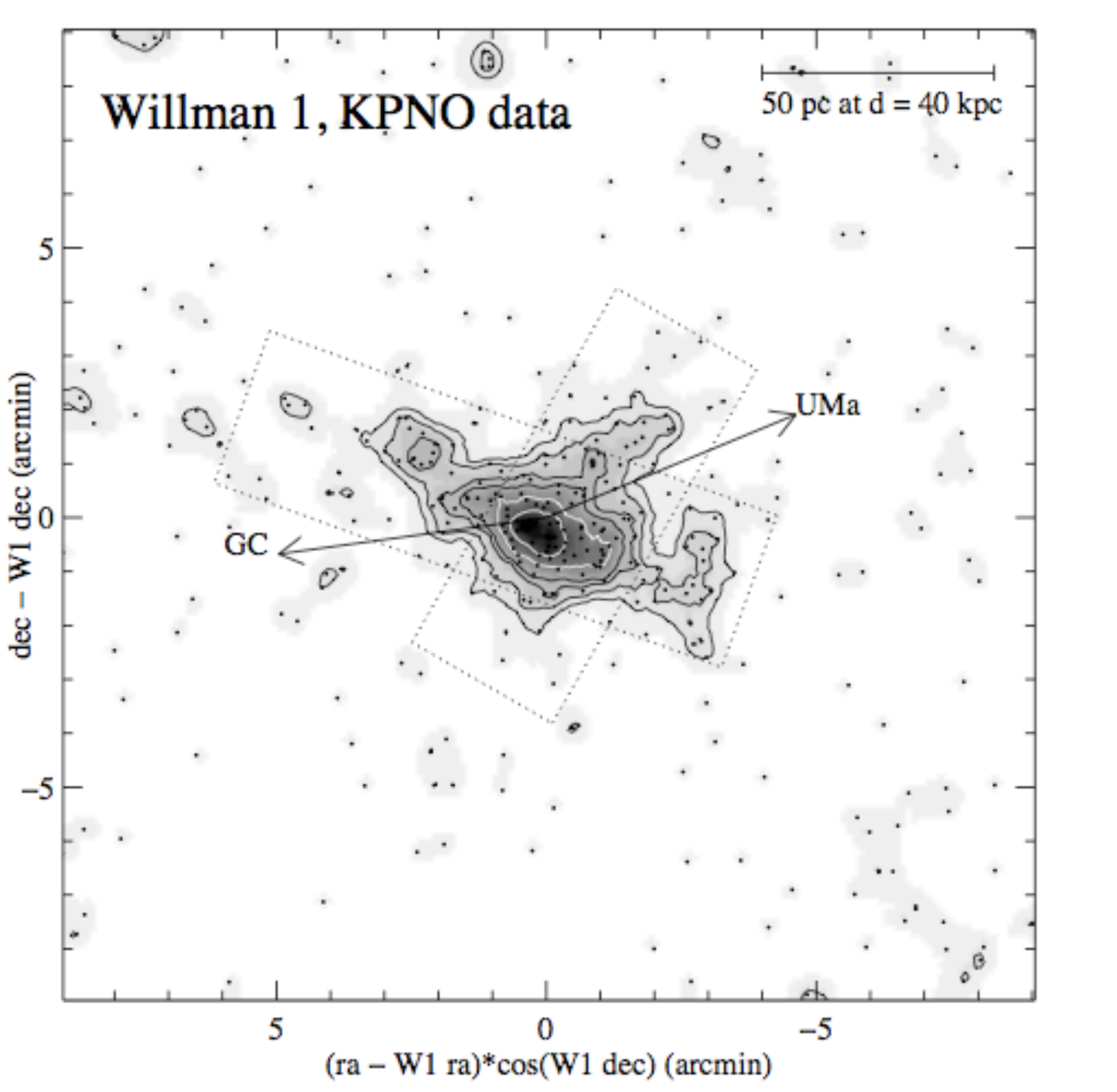


metal-rich

metal-poor

Segue 1 is a dark matter dominated galaxy.

Willman 1: From prototype to "enigmatic halo object"

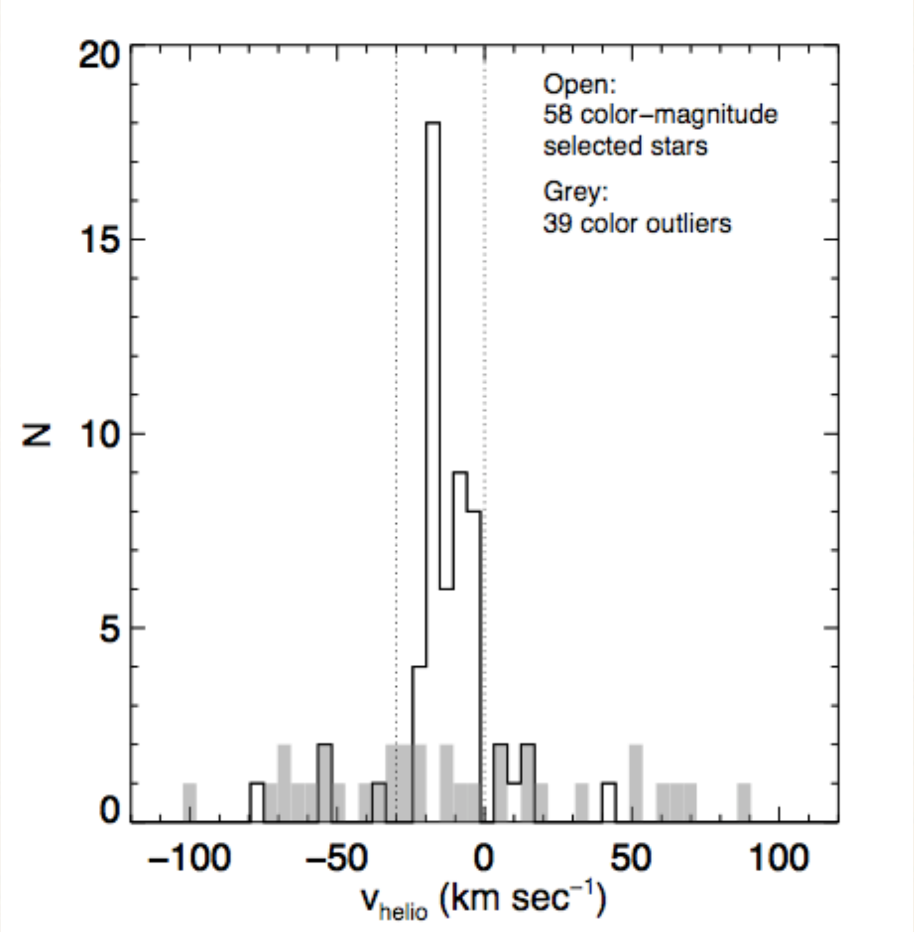


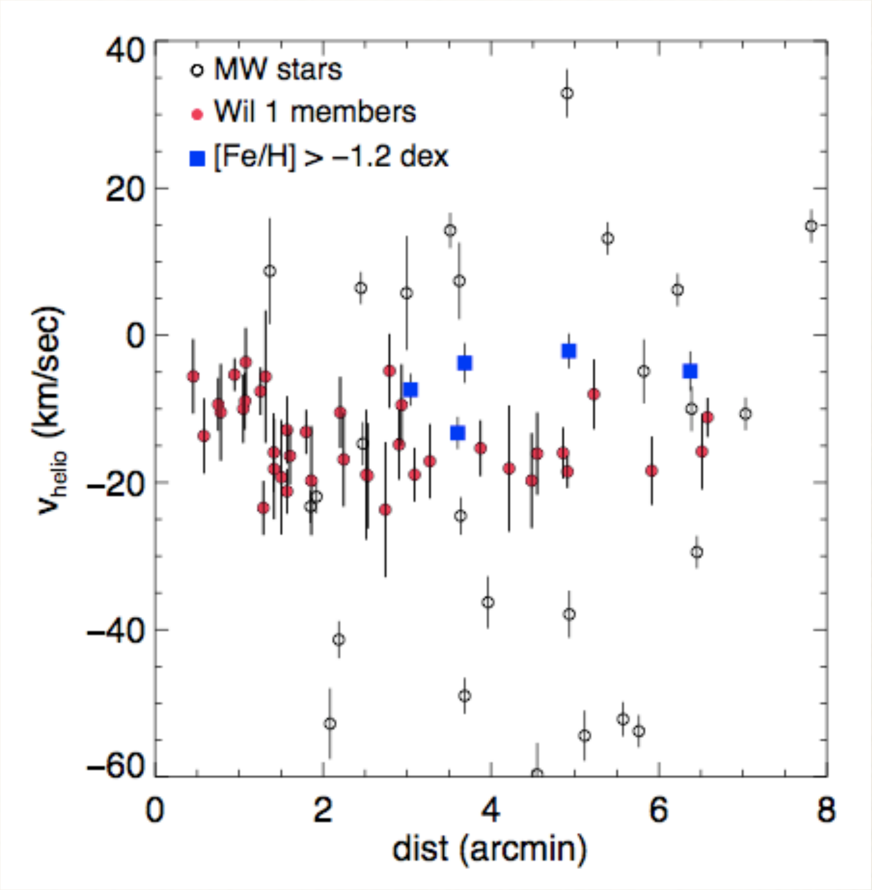
Willman 1 was first ultra-faint object discovered.

Photometry suggests multiple tidal tails.

Willman 1: From prototype to "enigmatic halo object"

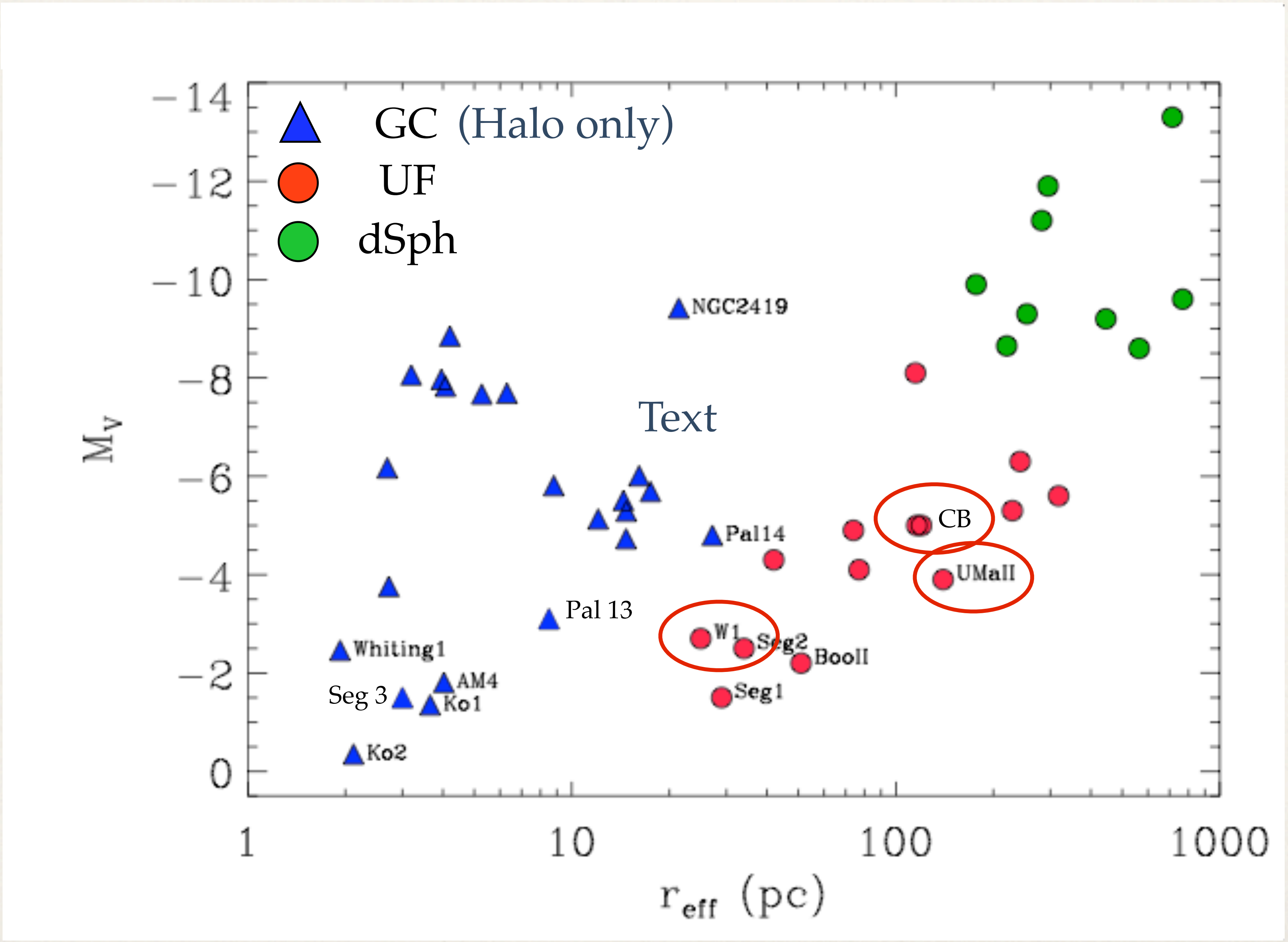
Willman, MG, Strader et al (2010)





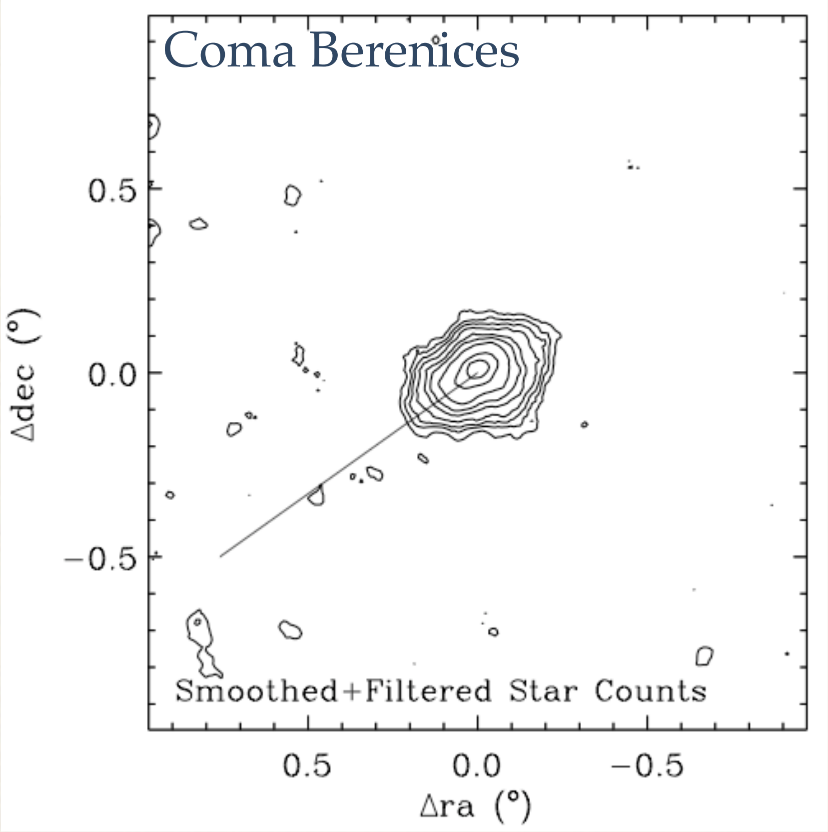
Based on metallicity spread of two confirm RGB stars, Willman 1 is (or was once) a dwarf galaxy.

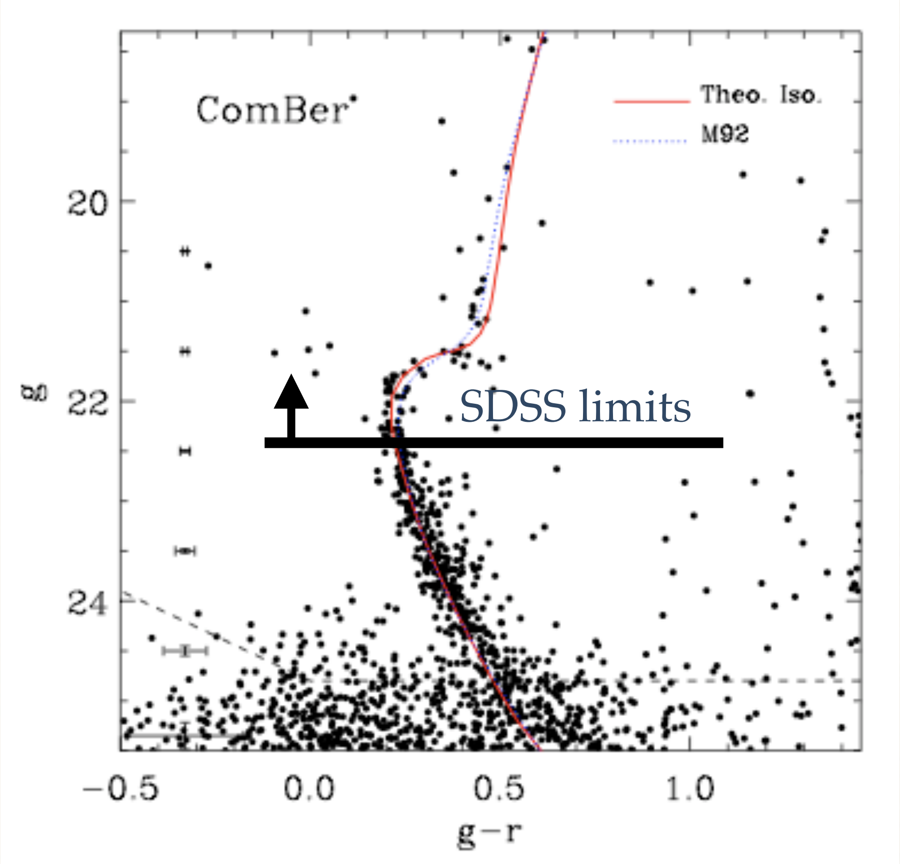
The Satellites of the Milky Way



Testing Tidal Stripping Another Way

<u>Munoz, MG & Willman (2009):</u> Deep CFHT MegaCam imaging

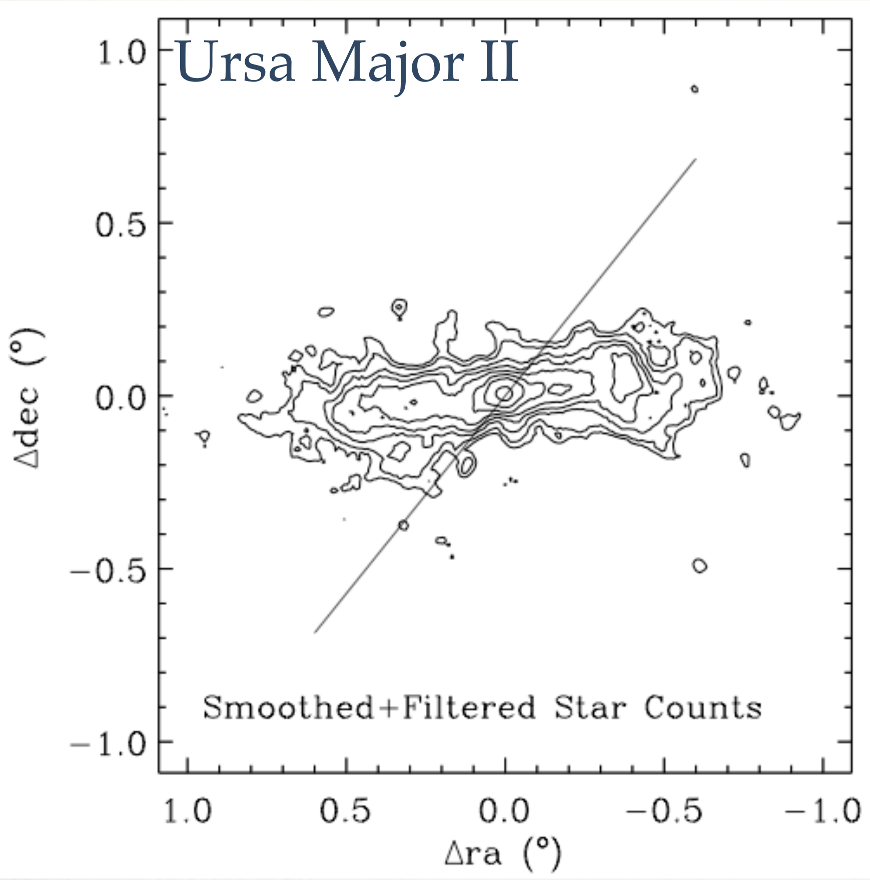


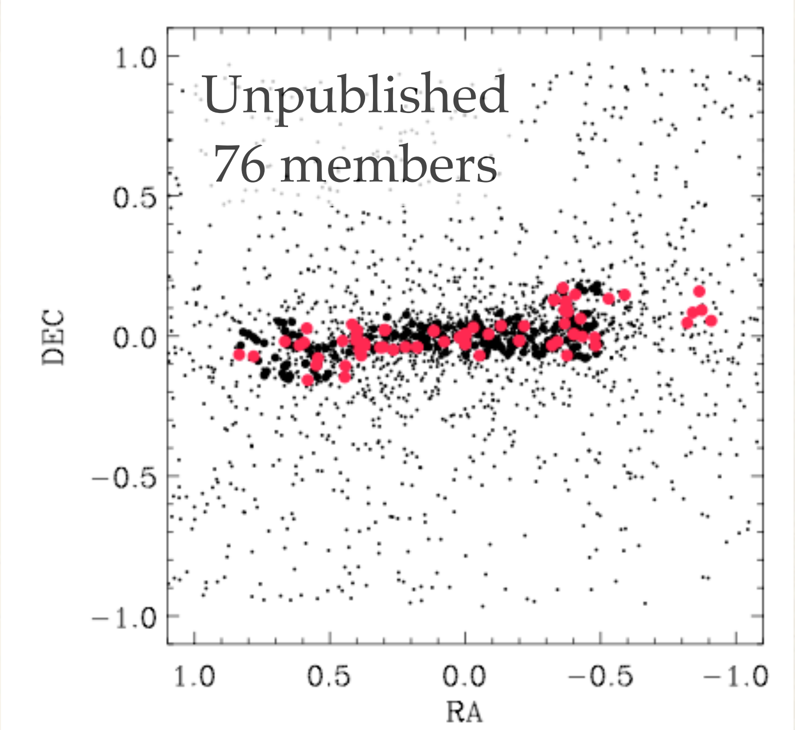


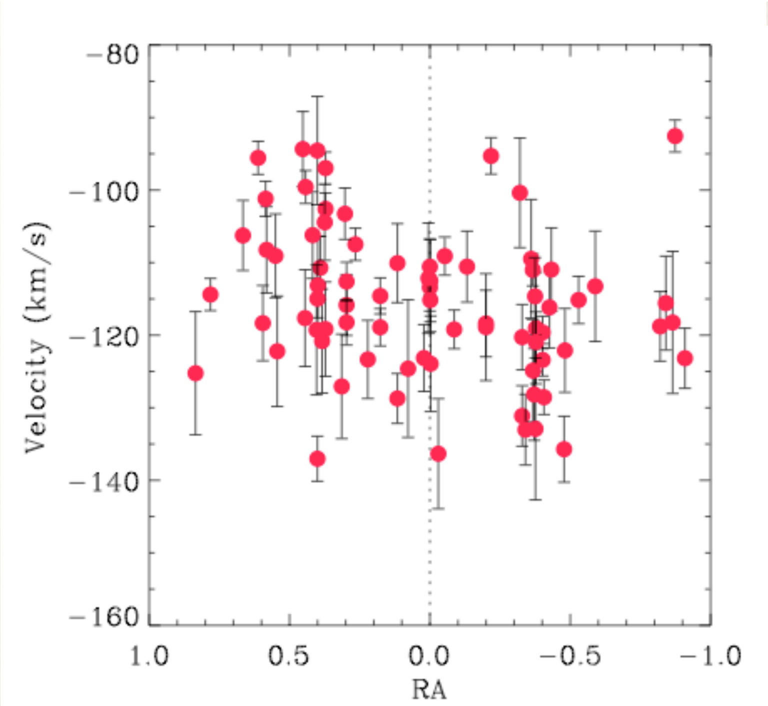
Coma does not show evidence for tidal stripping at large radius or low surface brightness (32.5 mag sq^{-2}).

Testing Tidal Stripping Another Way

In contrast, UMaII does show evidence for tidal interactions.







While a few ultra-faint objects which show signs of tidal disturbance, the majority show no evidence for interactions.

Faint Stellar System Round-up

Globular Clusters	Equilibrium galaxies	Disrupting?
Segue 3	Segue 1	Willman 1
Pal 13	Coma Berenices	Ursa Major II

The faintest systems require extreme care in interpreting dispersion/radii.