# The Ultra-Faint Dwarf Galaxies

## *Part 1: Kinematics*


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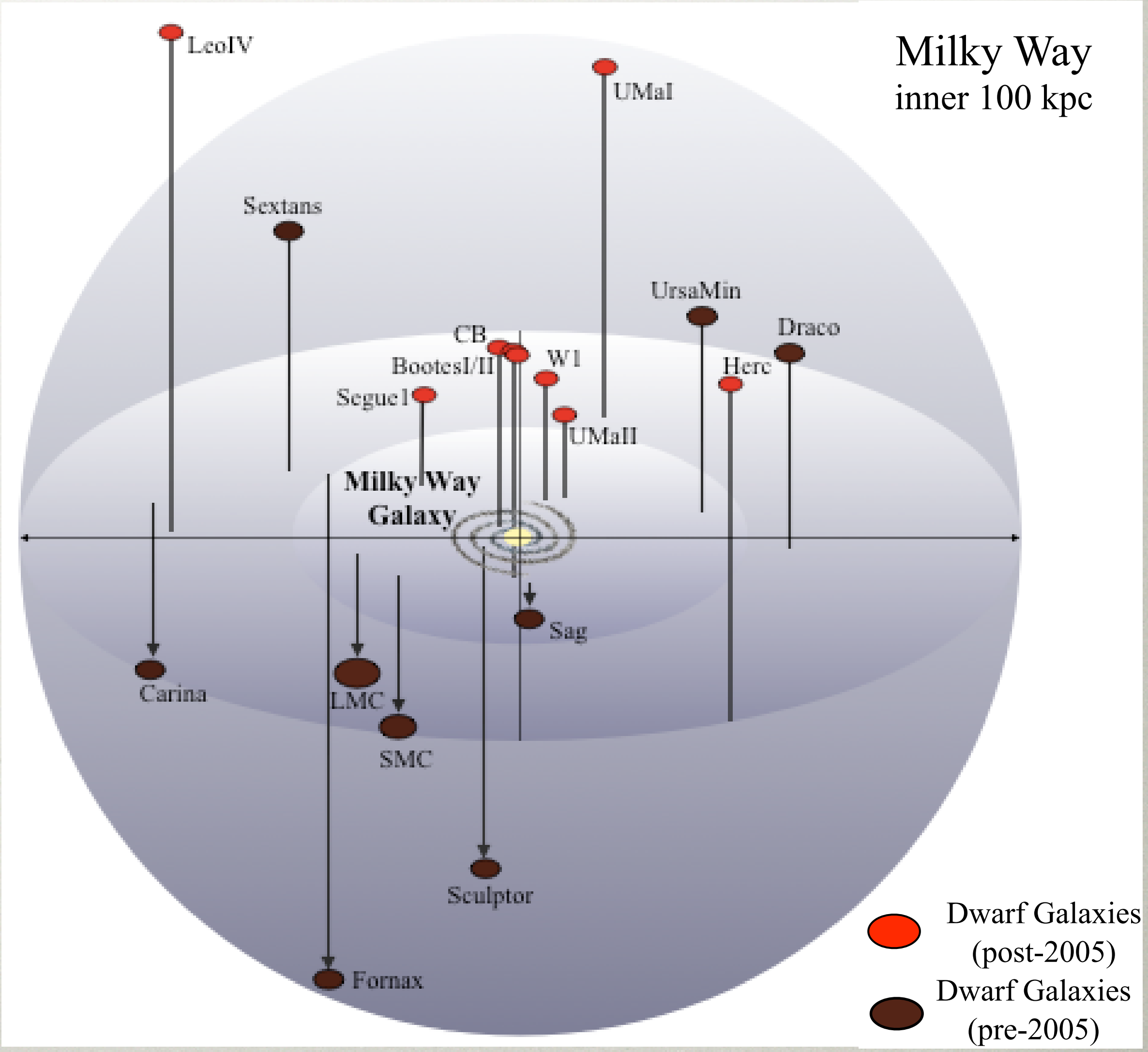
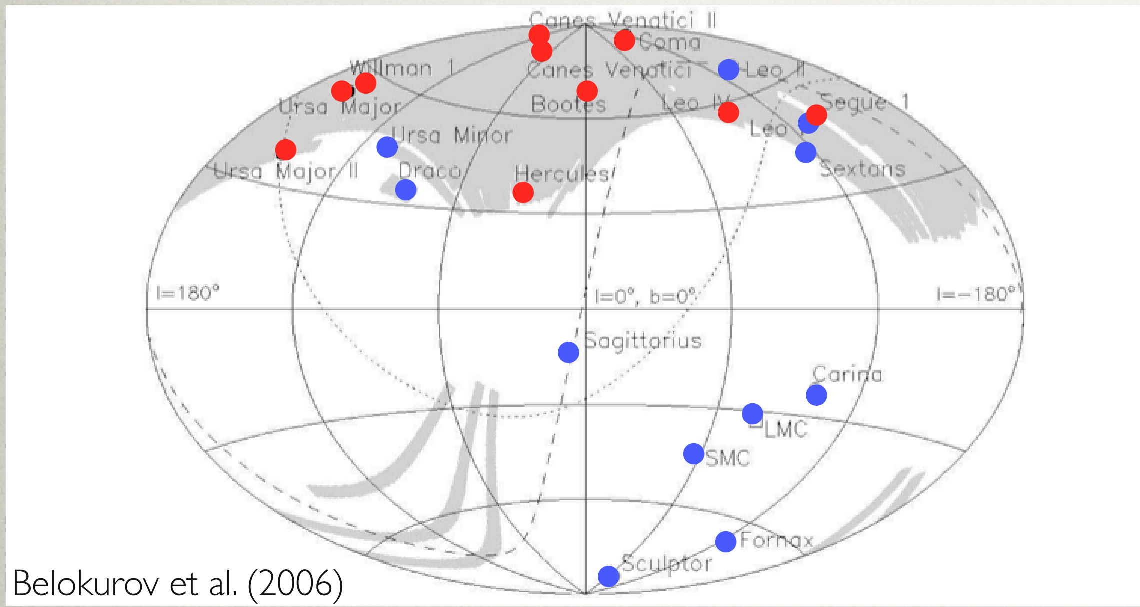


# New Milky Way Dwarf Galaxies

Sloan Digital Sky Survey (SDSS) coverage




Belokurov et al. (2006)

| Name | Year Discovered |
|---|---|
| LMC | B.C |
| SMC | B.C |
| Sculptor | 1937 |
| Fornax | 1938 |
| Leo II | 1950 |
| Leo I | 1950 |
| Ursa Minor | 1954 |
| Draco | 1954 |
| Carina | 1977 |
| Sextans | 1990 |
| Sagittarius | 1994 |
| Ursa Major I | 2005 |
| Willman I | 2005 |
| Ursa Major II | 2006 |
| Bootes I | 2006 |
| Canes Venatici I | 2006 |
| Canes Venatici II | 2006 |
| Coma Berencies | 2006 |
| Segue I | 2006 |
| Leo IV | 2006 |
| Hercules | 2006 |
| Leo T | 2007 |
| Bootes II | 2007 |

Leo V 2008

<u>The Satellite Numbers:</u>

Classical dSphs = 11

Ultra-Faint dSphs = 13

24

To SDSS depth, full sky = 11 + 4*13 = 63

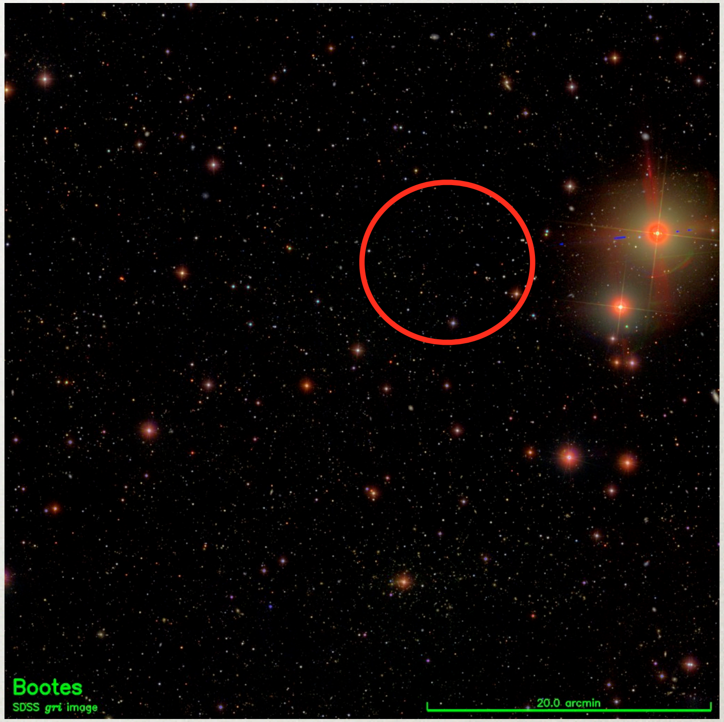
To LSST depth, full sky > 400 MW dwarfs (see poster by E. Tollerud)

# Why Were the 'New' Satellites Missed?

The newest dwarf have luminosities of globular clusters, but sizes of galaxies.

'Old' Dwarf Galaxy


'New' Dwarf Galaxy

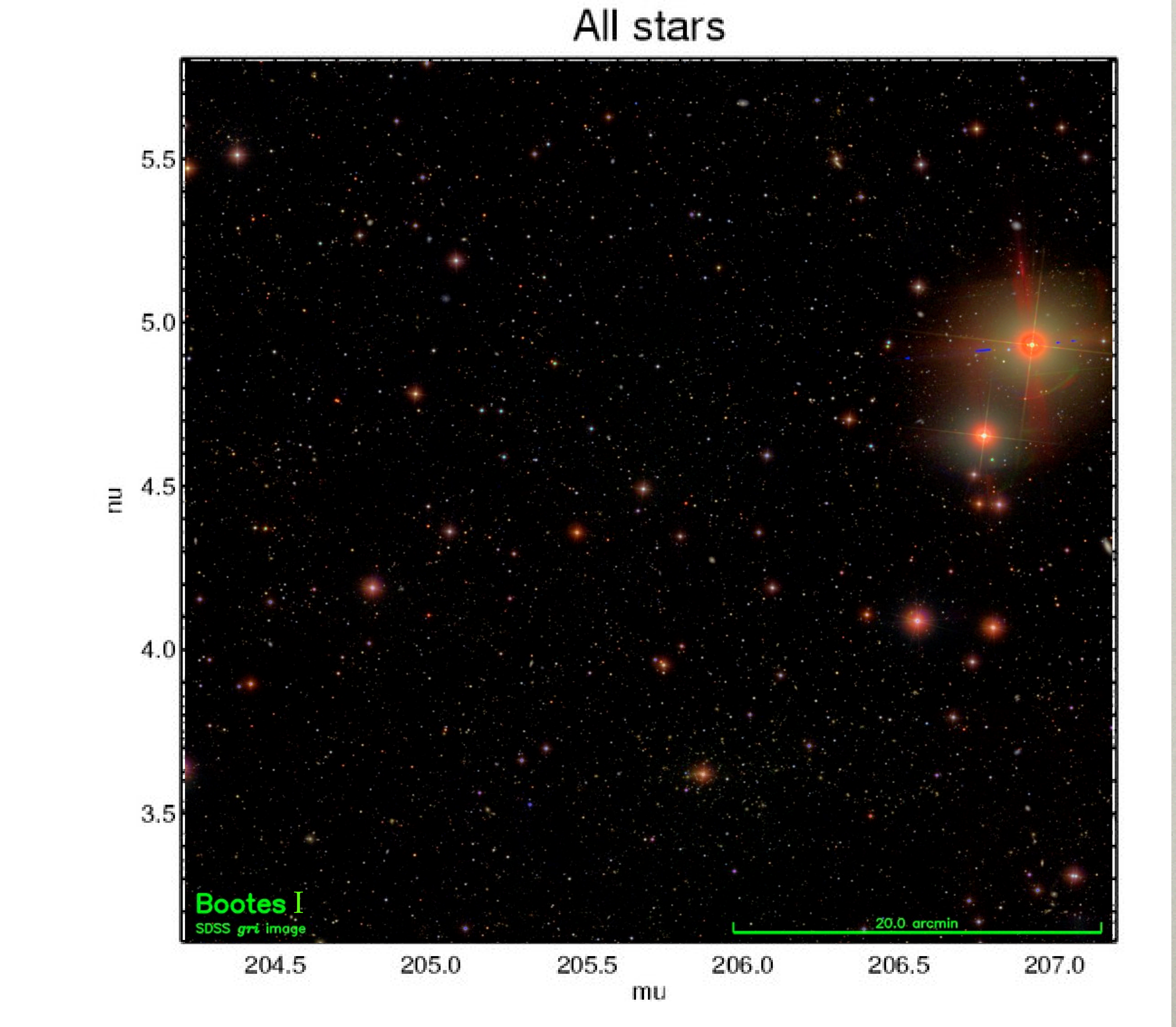



How were the new satellites found?

Willman et al (2005a,b)
Zucker et al (2006a,b)
Belokurov et al (2006a,b)
Irwin et al (2007)
Walsh et al. (2007)
Belokurov et al (2008)

# How Were the New Satellites Found?

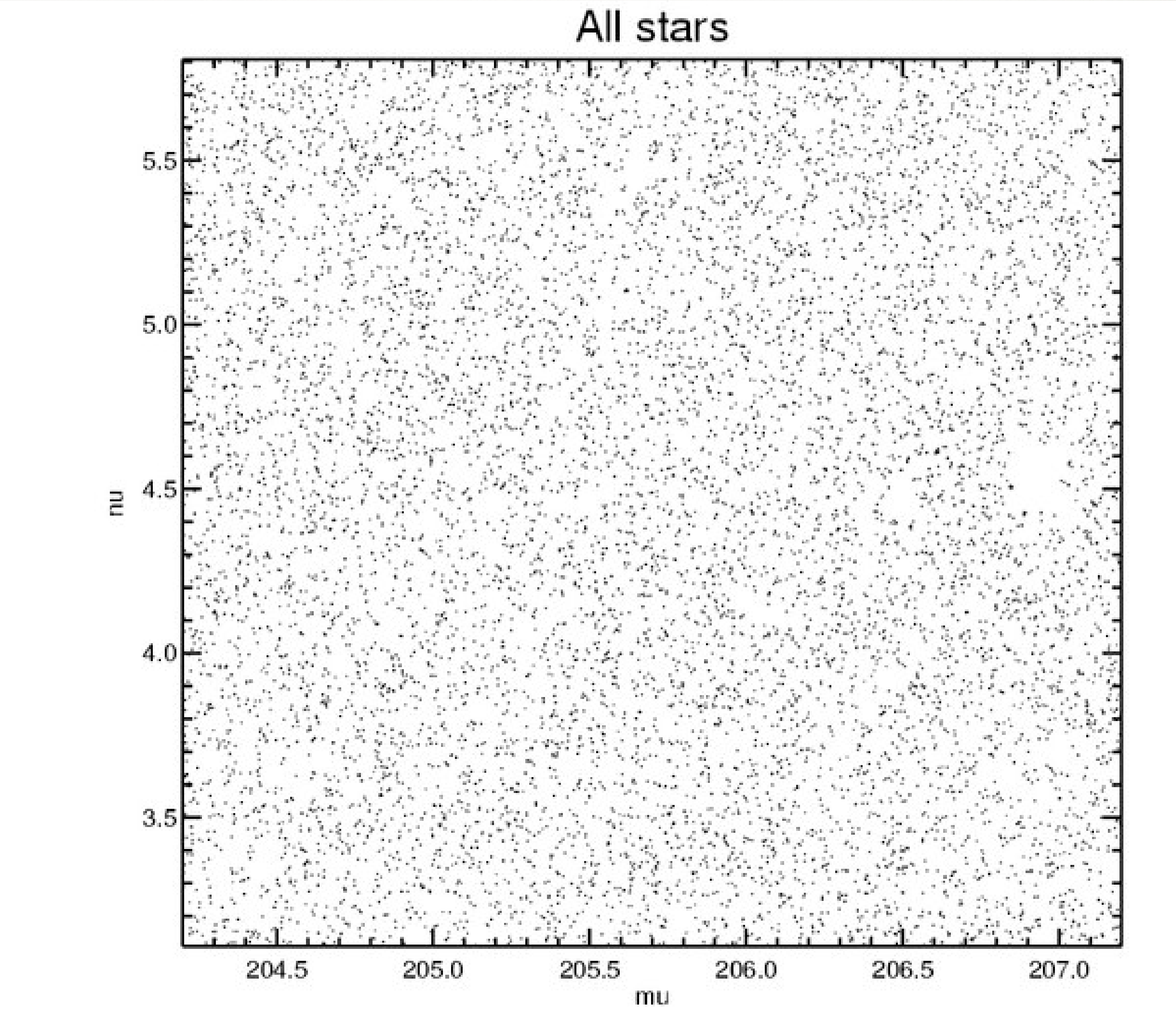
'Background' is too high to see galaxy directly.



# How Were the New Satellites Found?

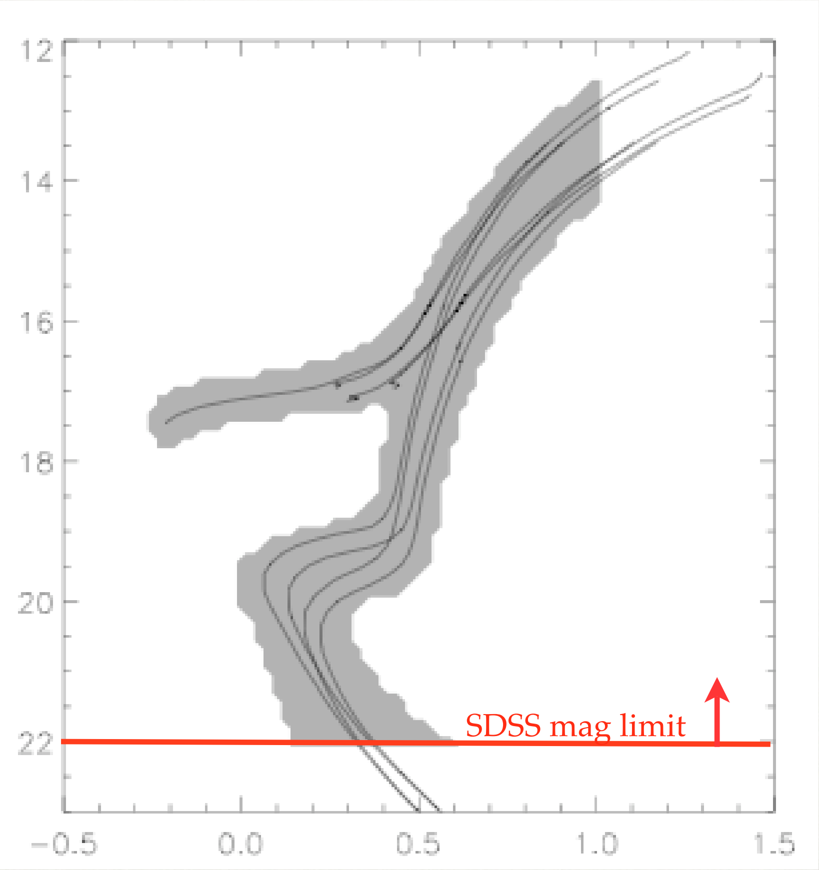
'Background' is too high to see galaxy directly.

Need to filter image according to an assumed set of dwarf galaxy properties.



# How Were the New Satellites Found?

Assume dwarf galaxies are old, metal-poor population, this defines a narrow region in color-magnitude space.




Walsh, Willman & Jerjen (2008)

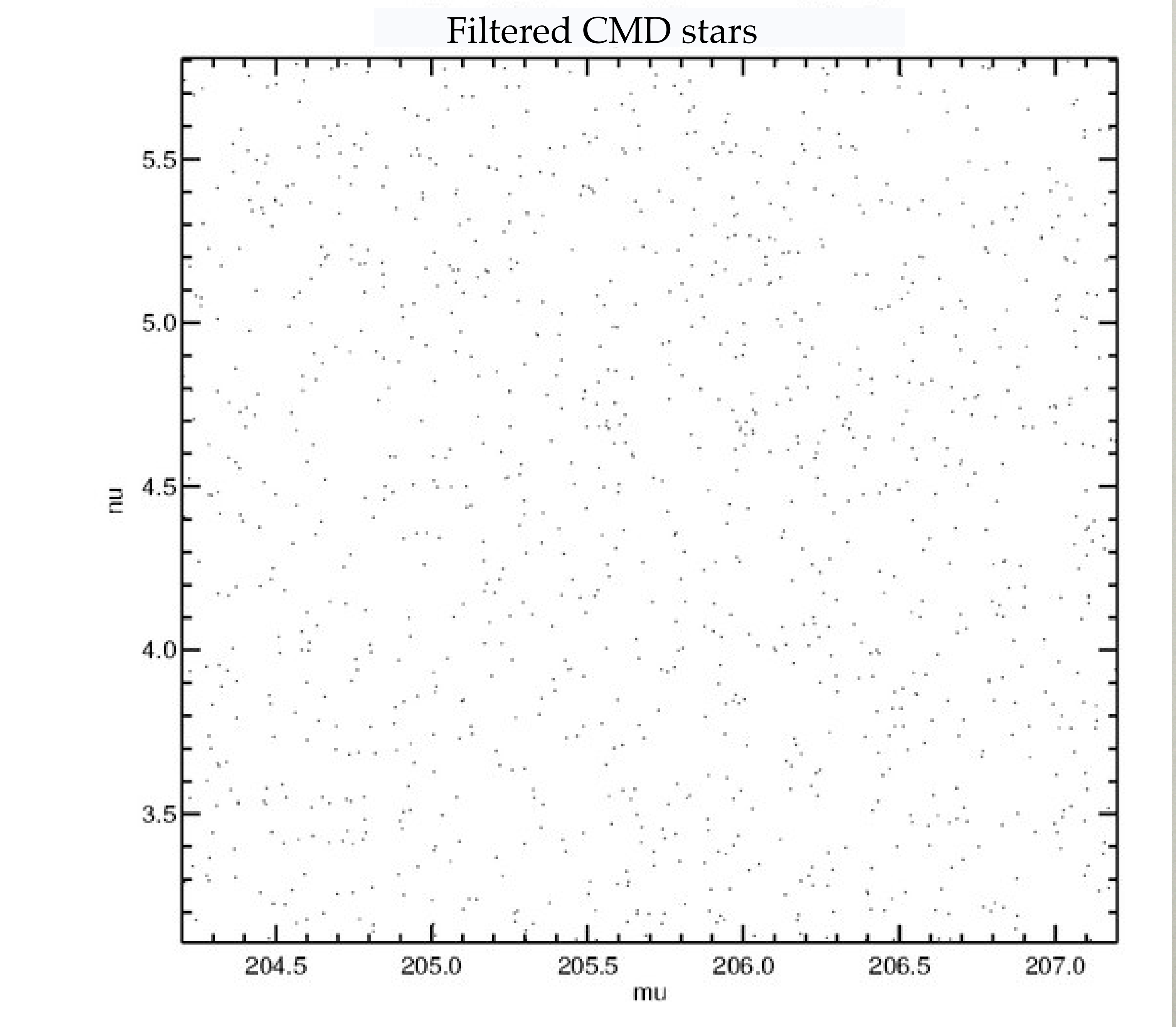
A generous definition of old and metal-poor:

age = 8 to 14 Gyr

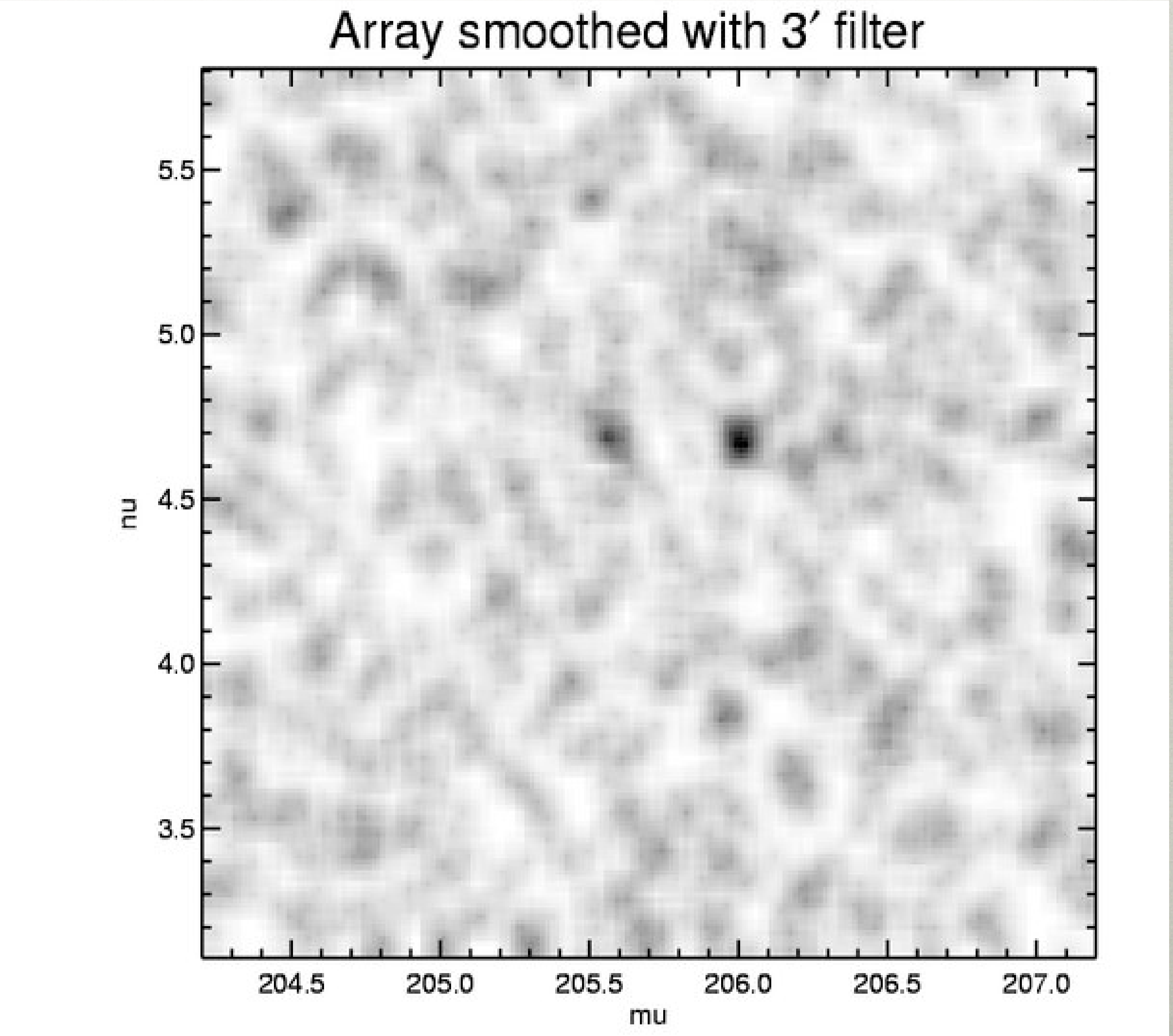
[Fe/H] = -1.5 to -2.3

Distance = 20 kpc

# How Were the New Satellites Found?

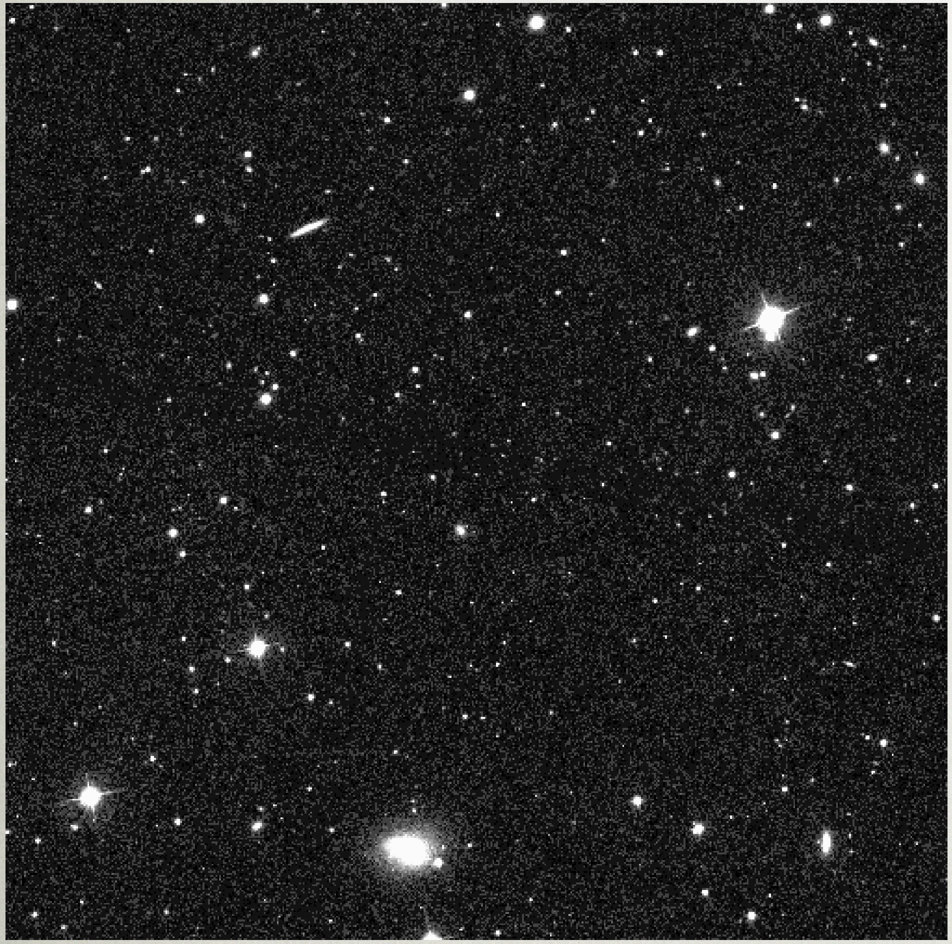


# How Were the New Satellites Found?

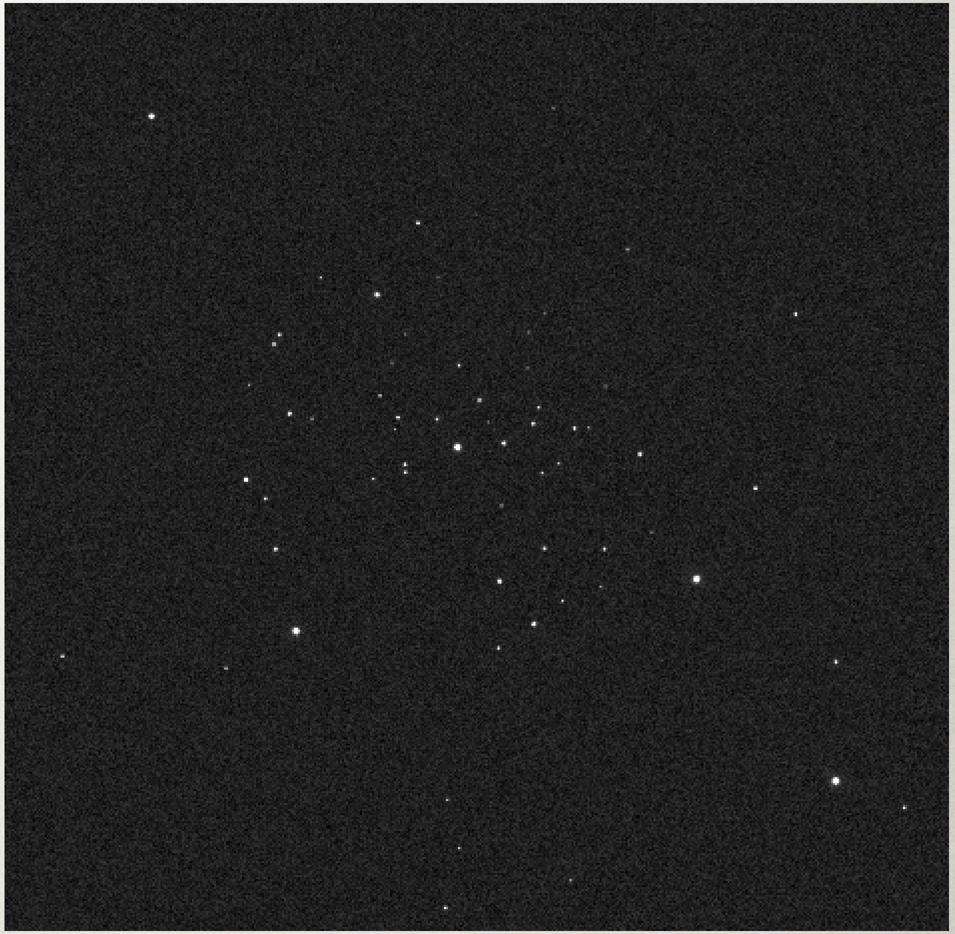


# How Were the New Satellites Found?

Raw SDSS image



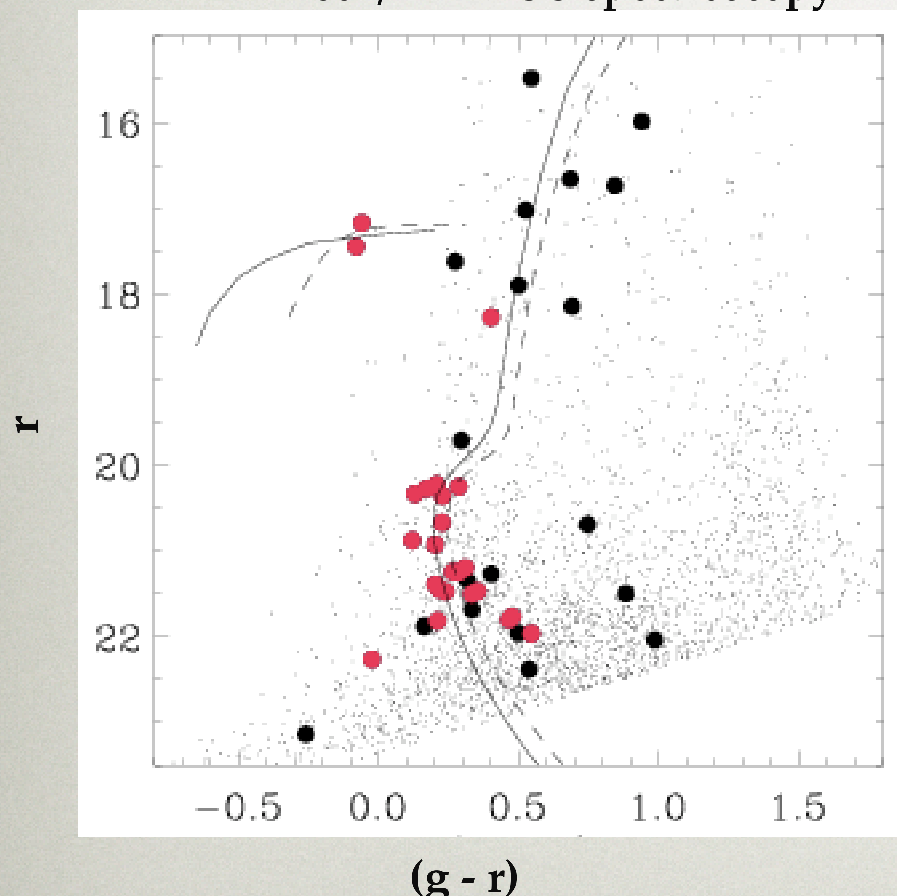
Candidate Member
Stars only



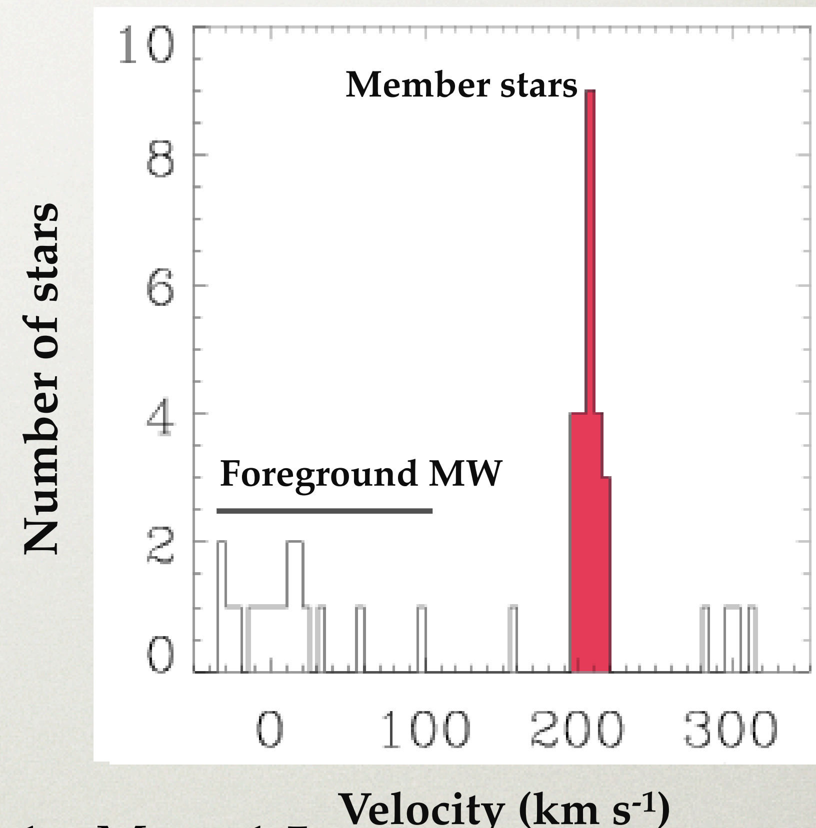
# Spectroscopic Follow-up

Spectroscopic follow-up is required to determine whether or not these stellar over-densities are indeed gravitationally bound structures.

● = Star targeted for Keck/DEIMOS spectroscopy




Velocity Histogram



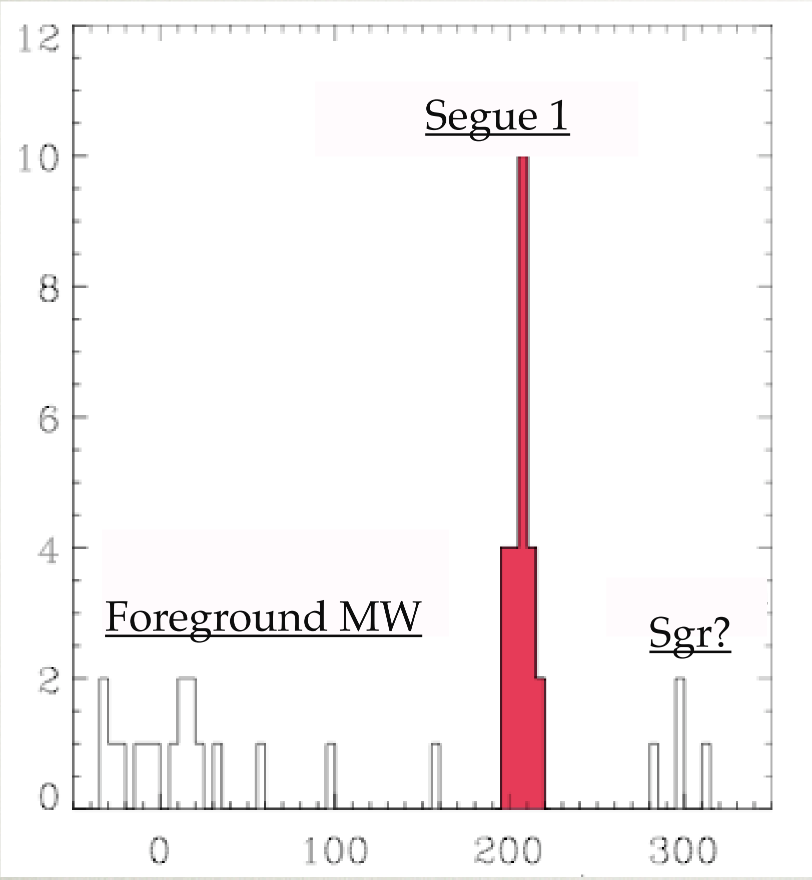

Segue 1: $M_V = -1.5$

$L_V = 340\ L_{sun}$

(Martin et al. 2008)

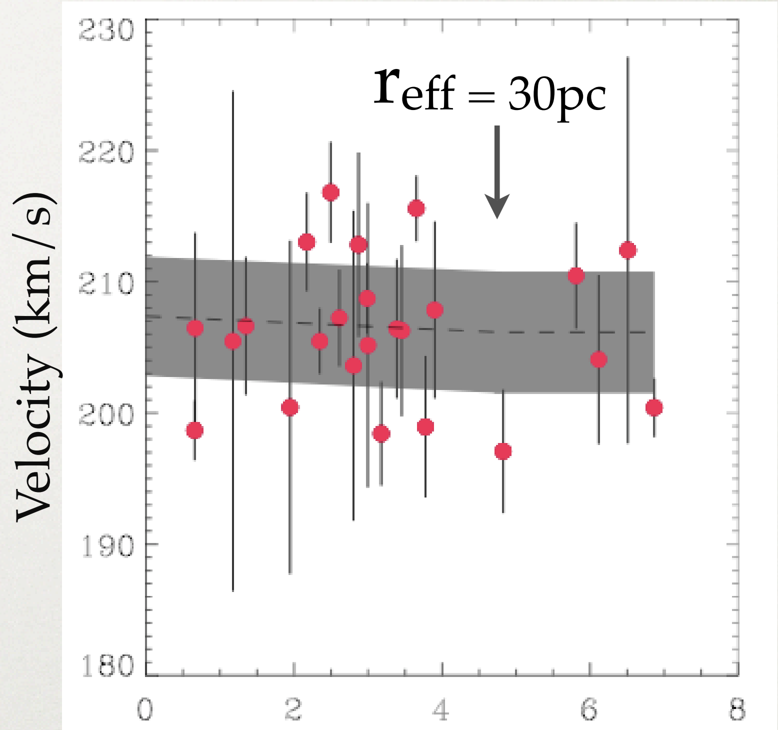
Geha et al (2008)

# Spectroscopic Follow-up




$N_{stars}$

Velocity (km/s)




Radius (arcmin)

Segue 1:

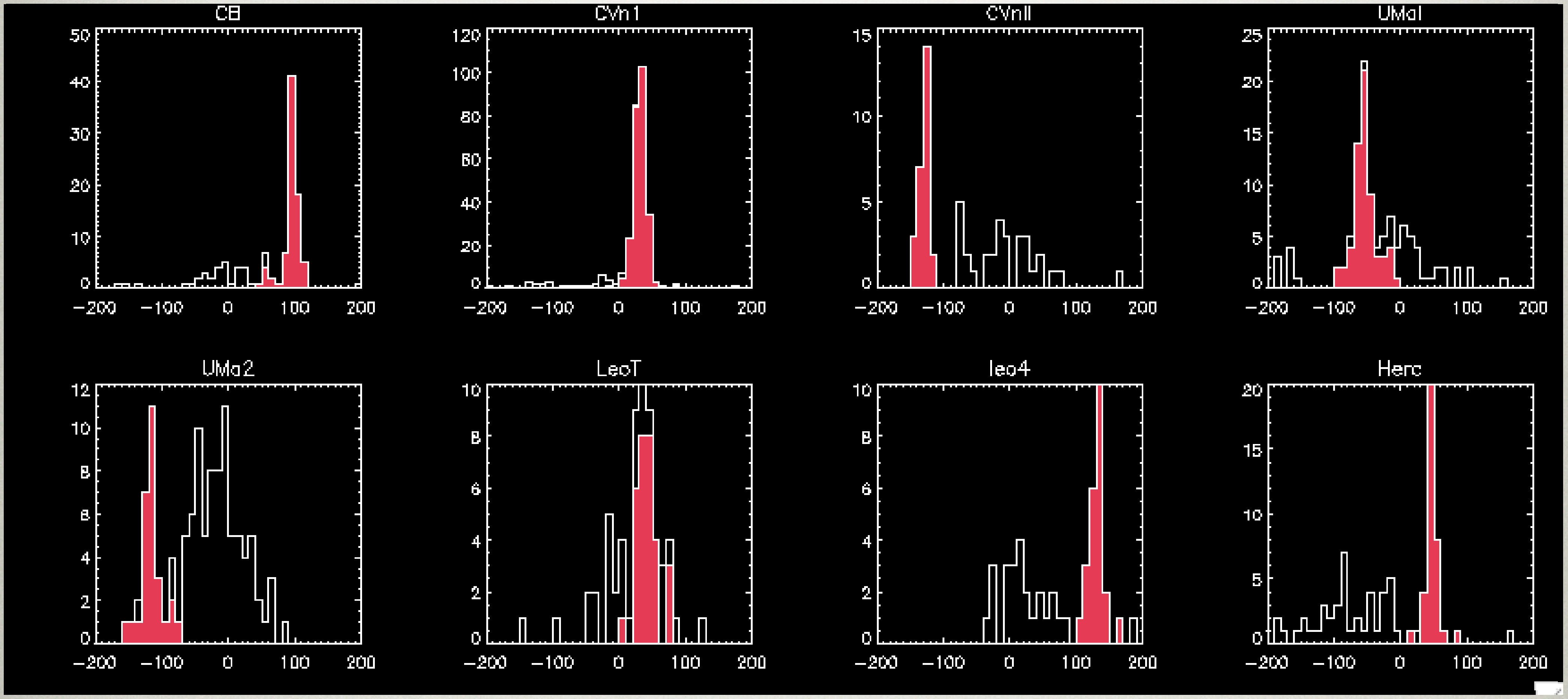
$\sigma = 4.5 \pm 1.2$ km $s^{-1}$ (24 member stars)

If mass was from stars only: 0.4 km $s^{-1}$

Geha et al (2008)

# Measuring Velocity Dispersions

Simon & Geha (2008)

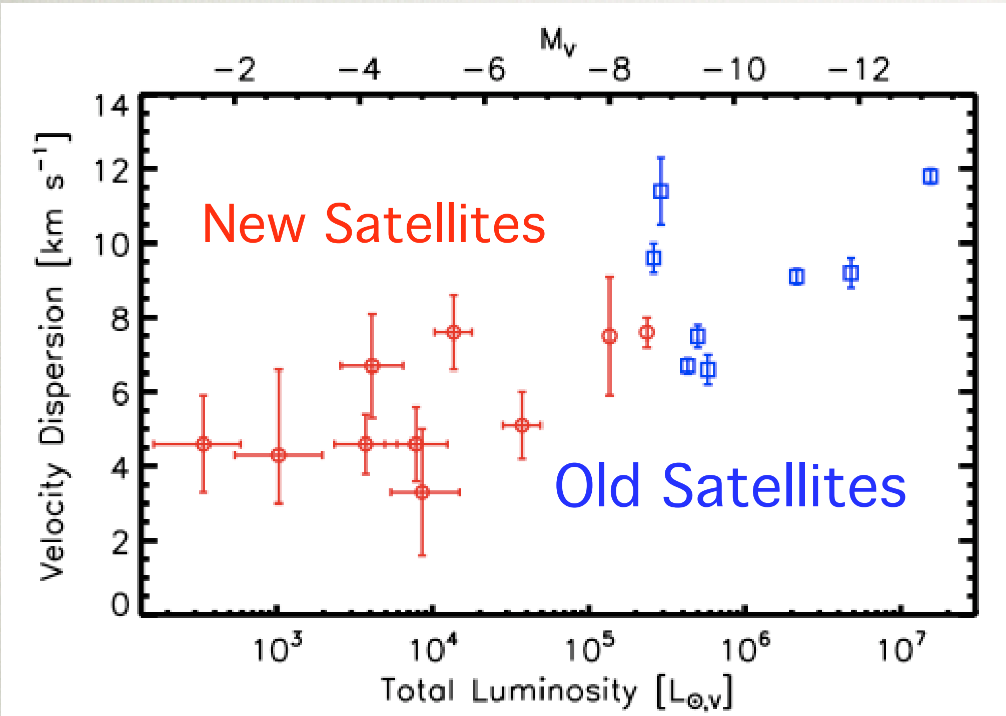


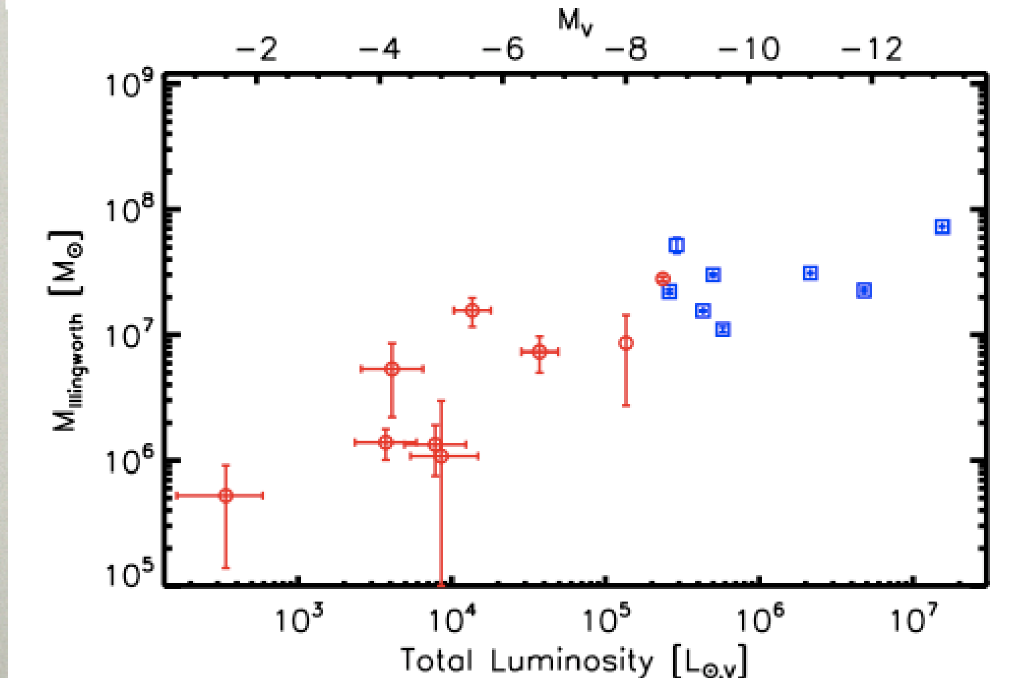

Velocity (km $s^{-1}$)

**All have clear velocity peak with width 3-8 km/s.**

Martin et al 2007
Munoz et al. 2006

# Estimating Mass




We can calculate mass under the simplest possible assumption:

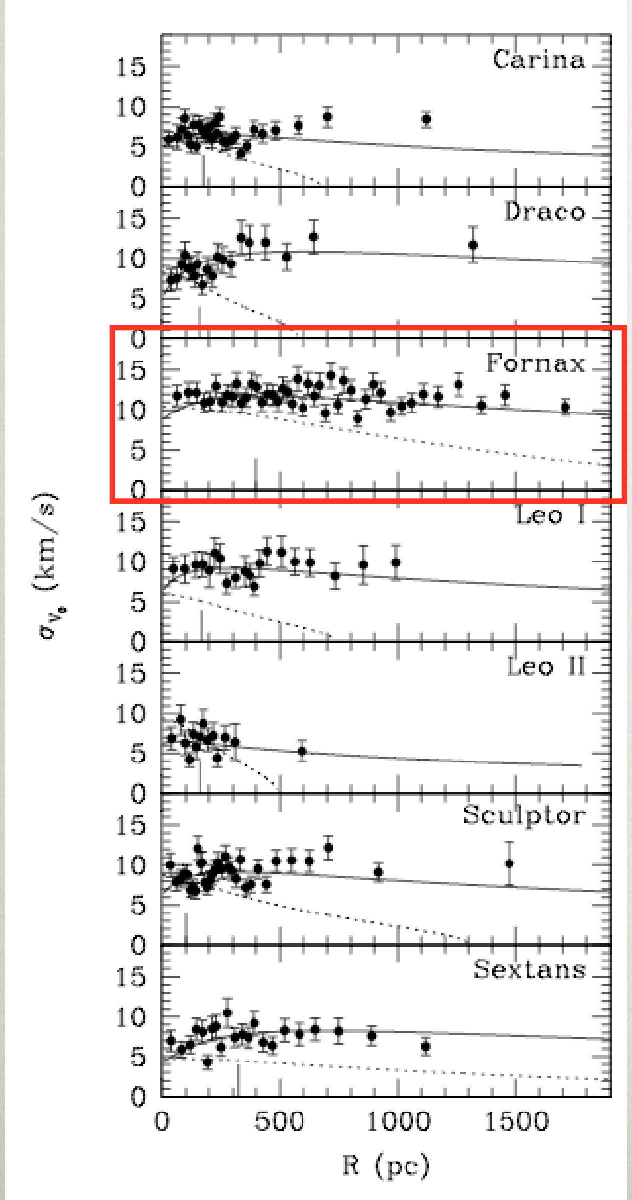
(1) Spherical
(2) Dynamical equilibrium
(3) Isotropic velocity dispersion
(4) Light traces mass (King profile).

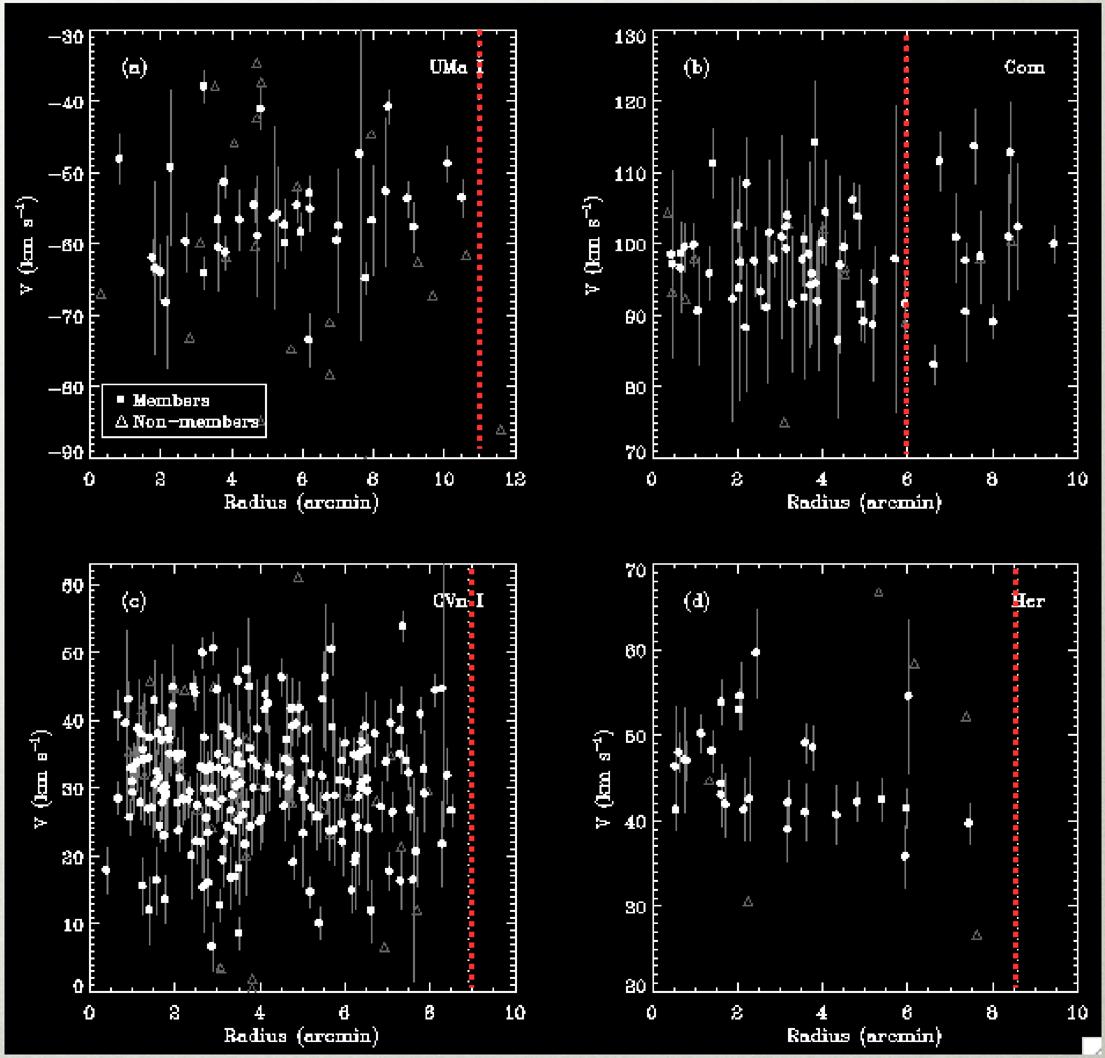
If mass-follows-light:

$$M_{\rm tot} \propto r_c \sigma^2$$

# Estimating Mass

In both the classical and ultra-faint dSphs, the assumption that mass-follows-light is incorrect.



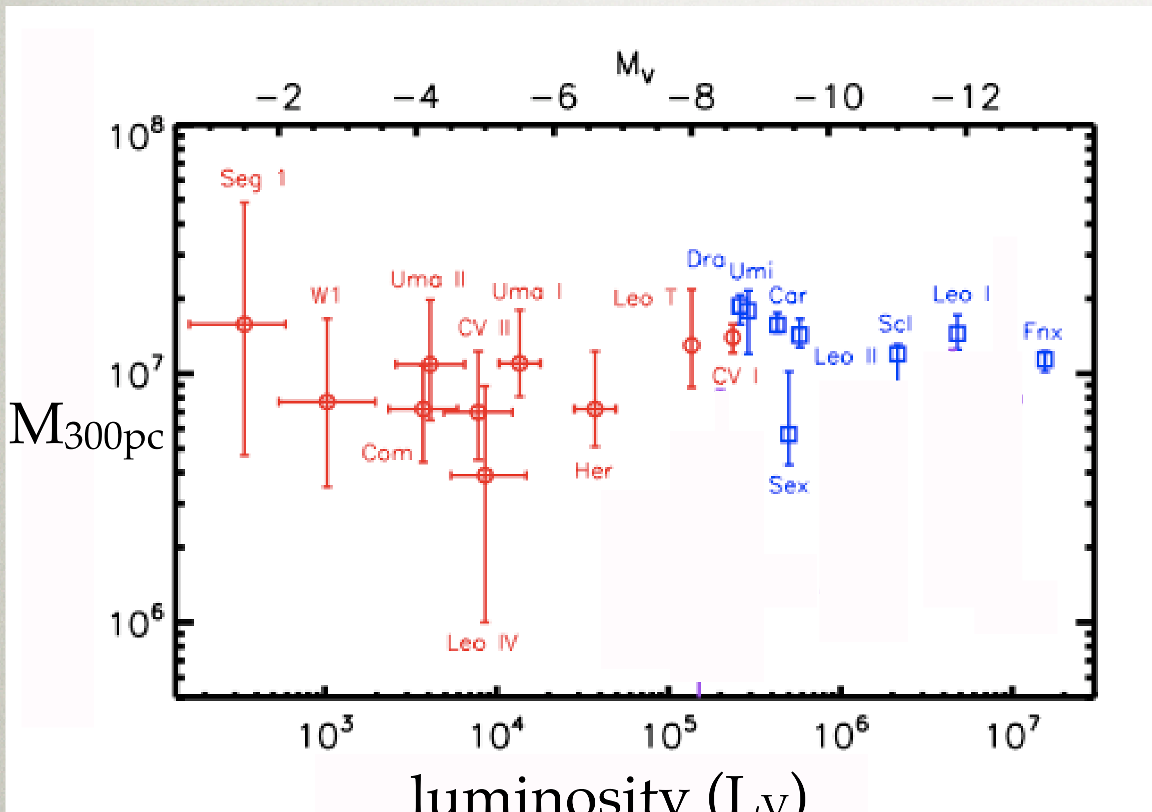



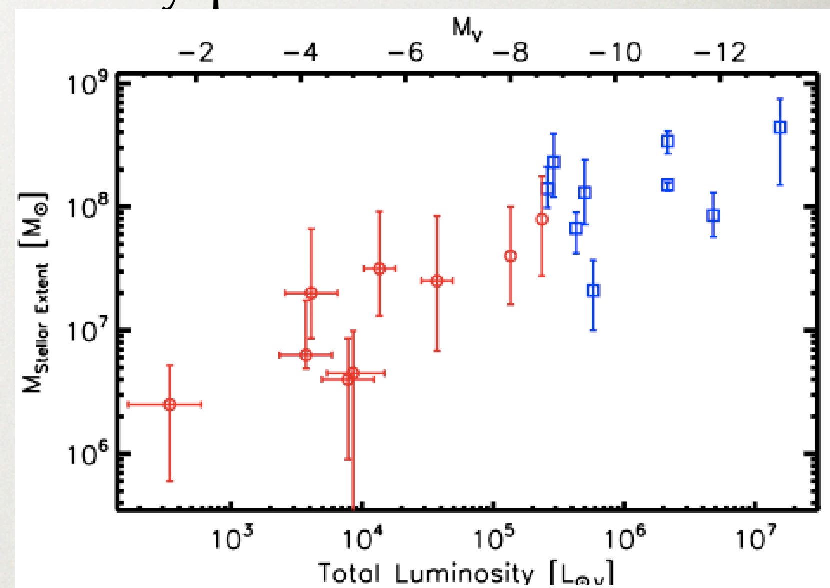

Walker et al. (2007)

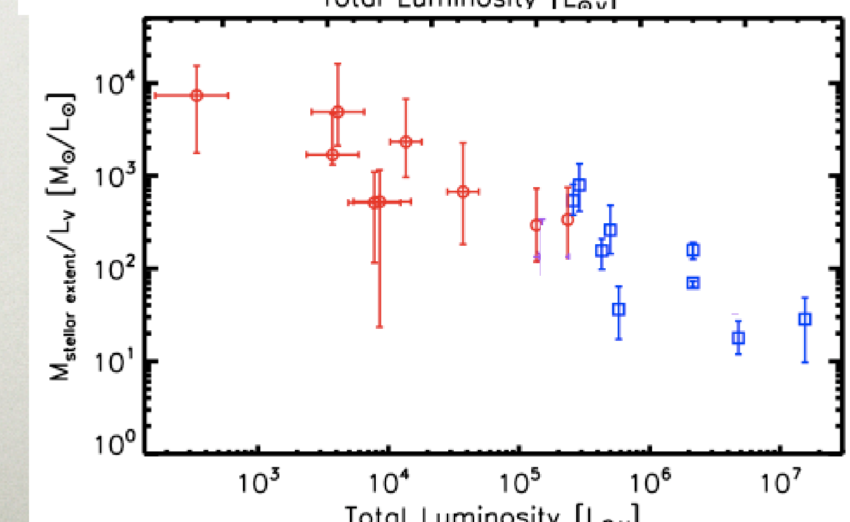
# Estimating Mass

A more sophisticated approach Strigari et al. (2007, 2008):

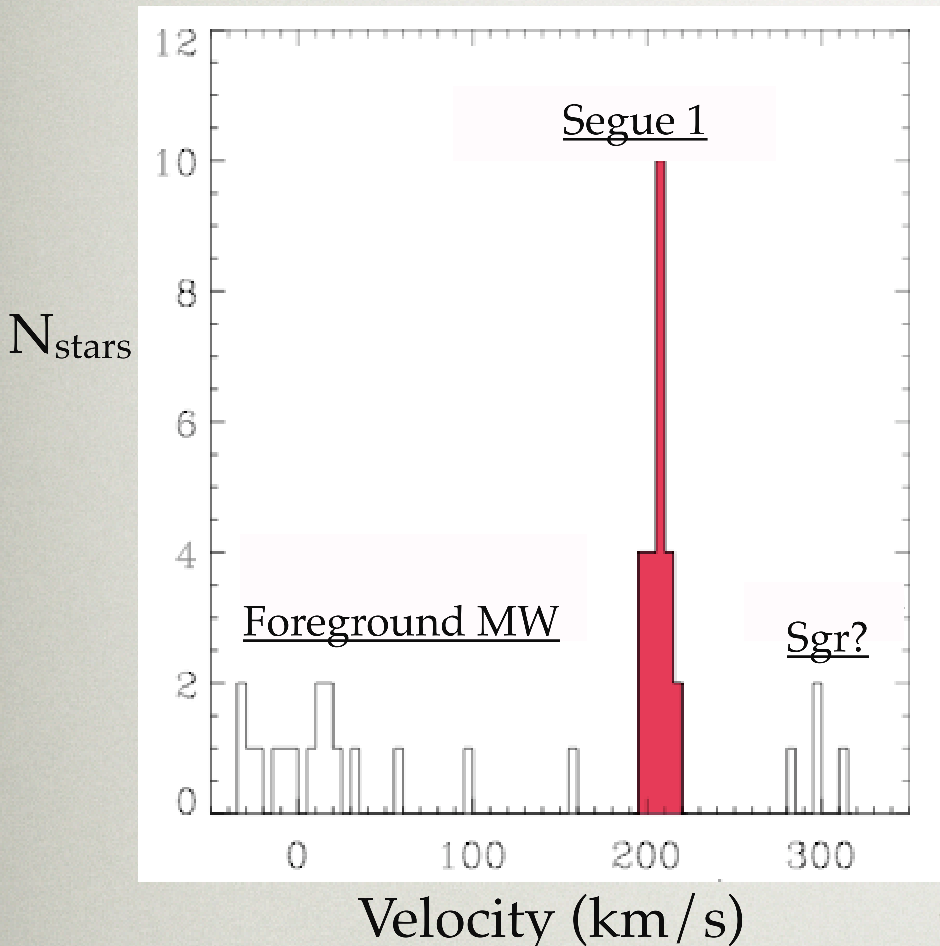
1. Use all measured individual velocities
2. Assume light/mass have different density profiles

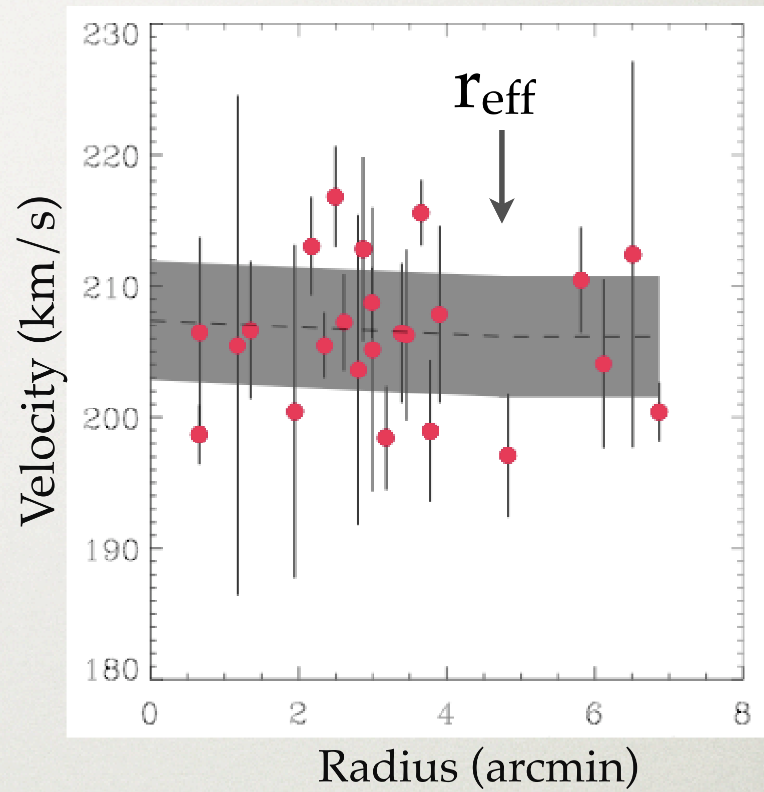


# Segue 1: Dwarf Galaxy




Mass_50pc $= 8^{+13}_{-5.2} \times 10^5\ M_{sun}$

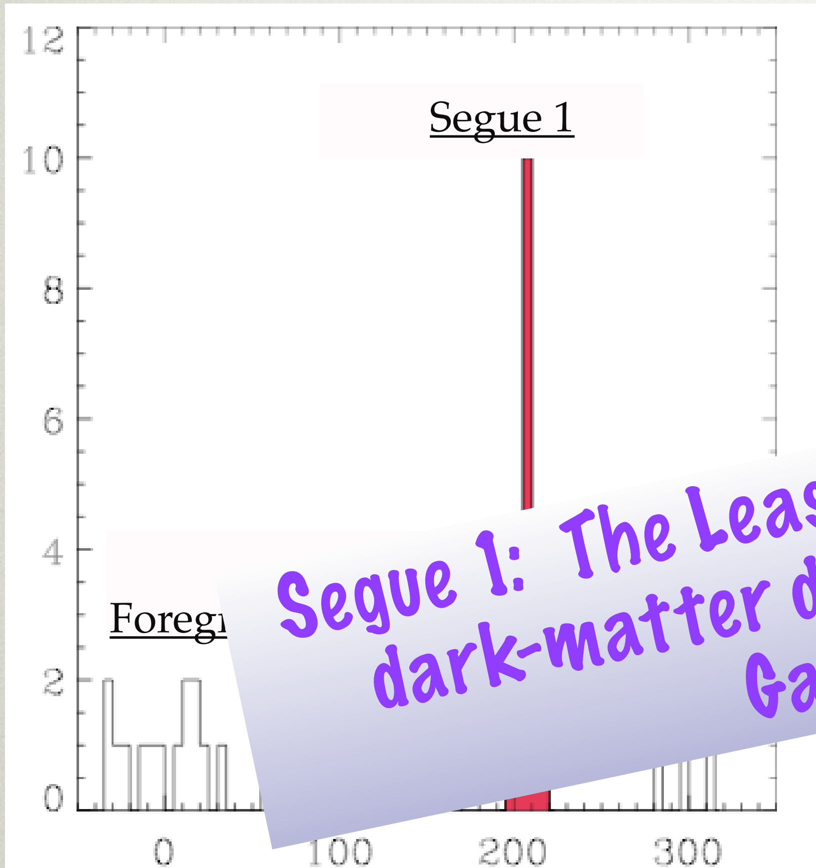
Mass_300pc $= 1 \times 10^7\ M_{sun}$

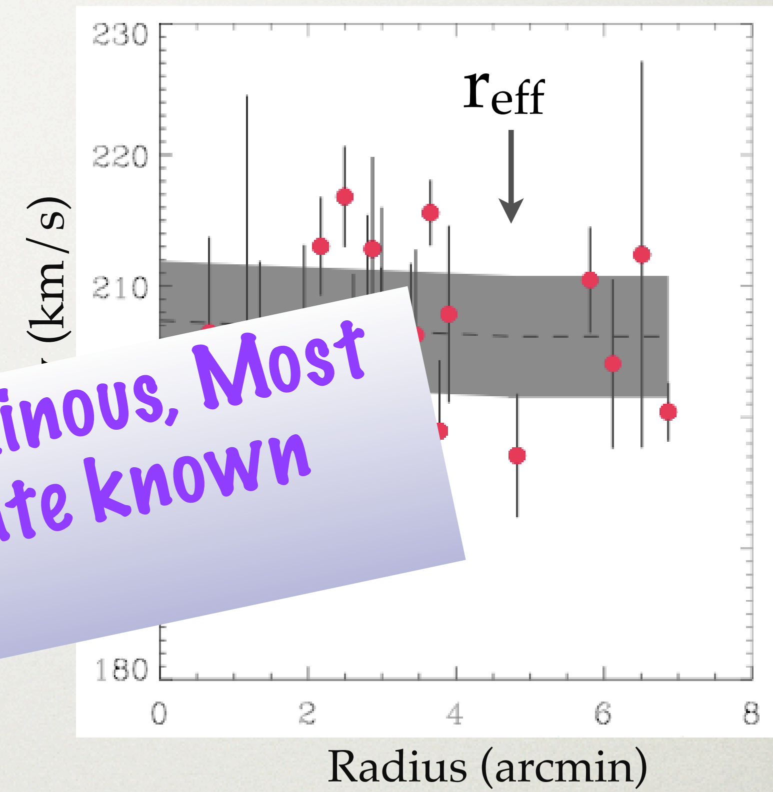
L_stars $= 340\ L_{sun}$

Mass_stars $= 1 \times 10^3\ M_{sun}$

$M/L = 2300^{+1600}_{-1700}$

# Segue 1: Dwarf Galaxy




Segue 1: The Least Luminous, Most dark-matter dominate known Galaxy!

Mass_50pc $= 8^{+13}_{-5.2} \times 10^5\ M_{sun}$

Mass_300pc $= 1 \times 10^7\ M_{sun}$

L_stars $= 340\ L_{sun}$

Mass_stars $= 1 \times 10^3\ M_{sun}$

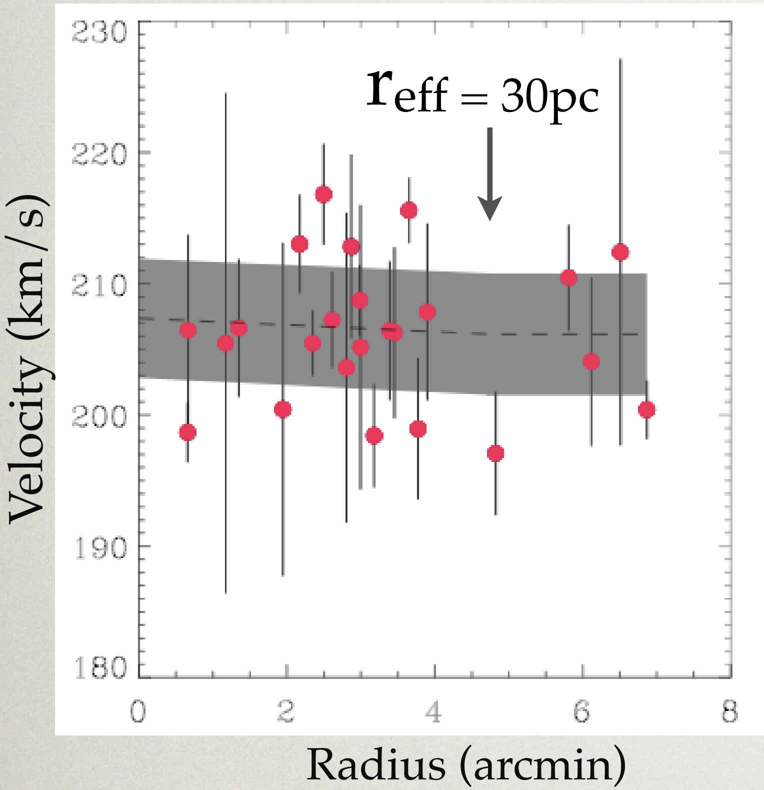
$M/L = 2300^{+1600}_{-1700}$

# However,

Our mass estimates rest entirely on the assumption that the measured stars are **gravitationally bound** and are in **dynamical equilibrium** (eg. velocities faithfully trace the gravitational potential).

Is there evidence for *on-going* tidal disruption in the ultra-faint dSphs?

# Segue 1: Any Evidence for Tidal Interactions?




$D_{GC}$ = 28 kpc
$v_{GSR}$ = 100 km $s^{-1}$

1. Are the stars in Segue 1 currently disrupting?

   $r_{tidal}$ = 200pc (mass-follows-light)
   $r_{tidal}$ = 600pc (Strigari mass @ 50pc)

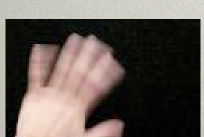
   Tidal radius + lack of outlier velocities suggests stars are not influenced by tides right now.

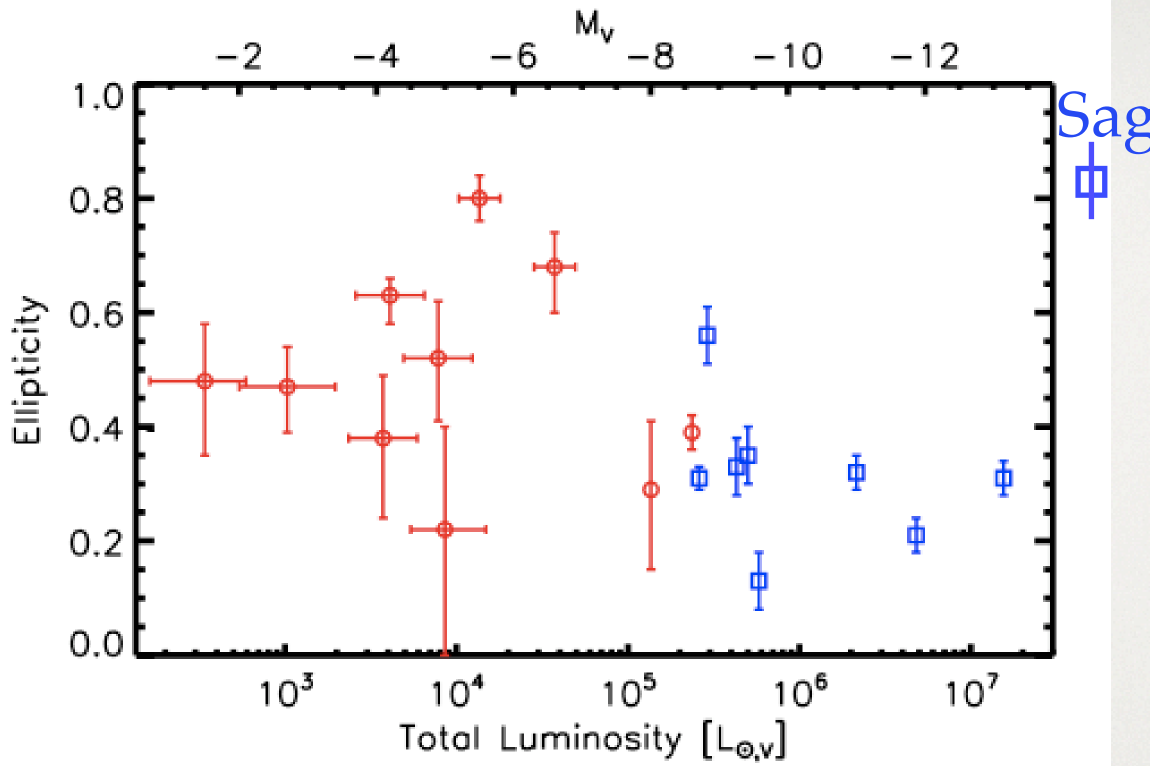
2. Is this a completely unbound group of stars?

   Cross time = $10^7$ years
   Segue 1 moves ~1 kpc in one crossing time.

   MW potential not changing significantly in 1 kpc. If site of disruption farther away, Segue1 would have already dissolved.

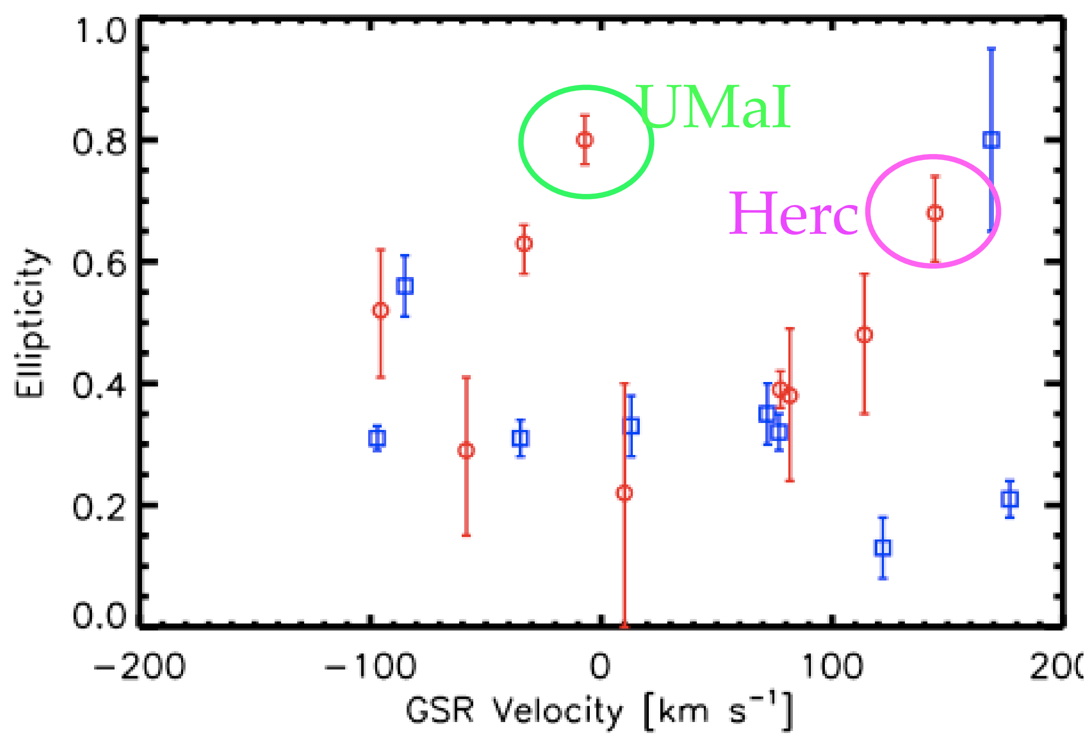
but see poster by Niederste-Ostholt!

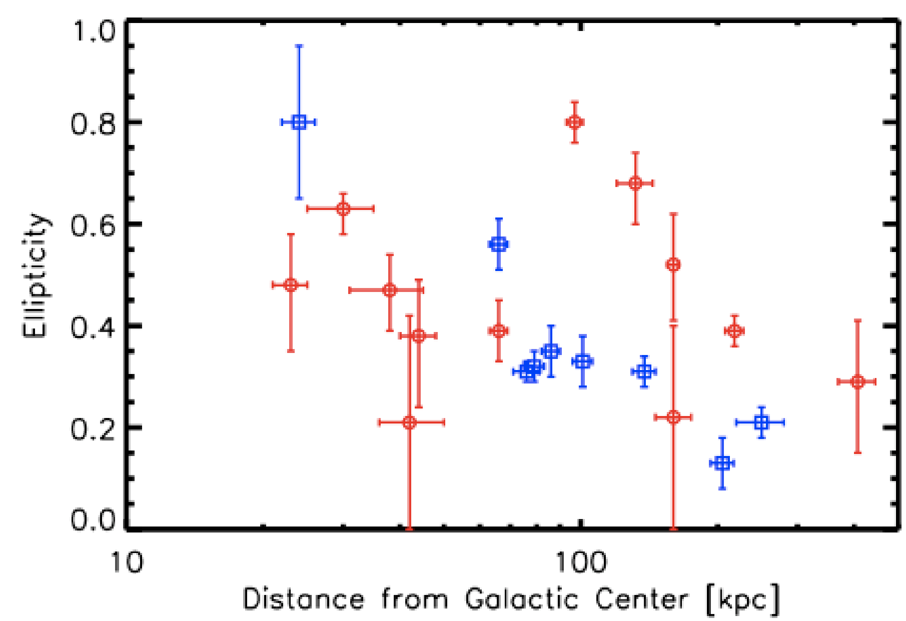





The ultra-faint dSphs are more elongated as compare the to classical dSphs.

Is this intrinsic or tidal origin?

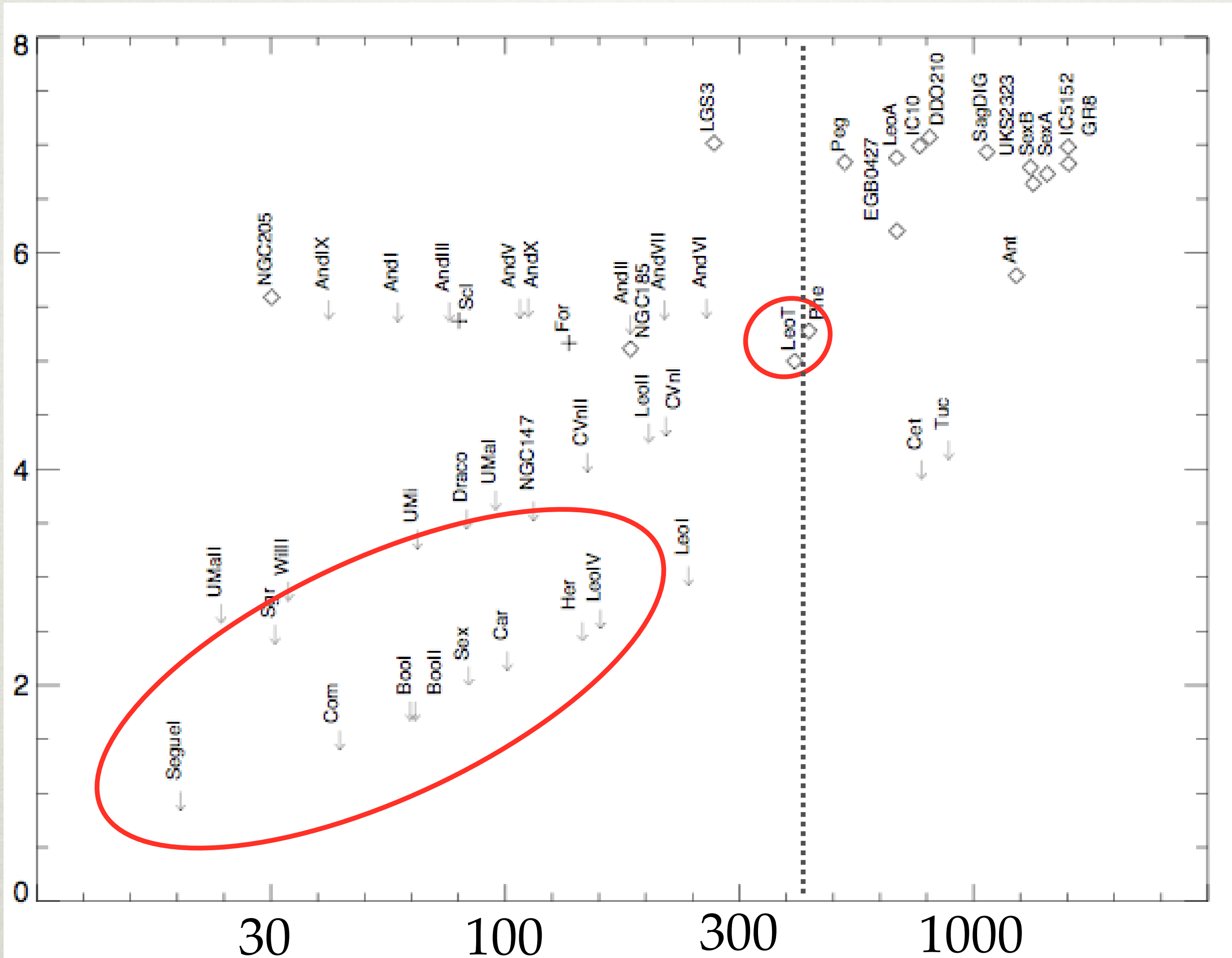


# HI Gas Limits

dSph have been affected by their environment.

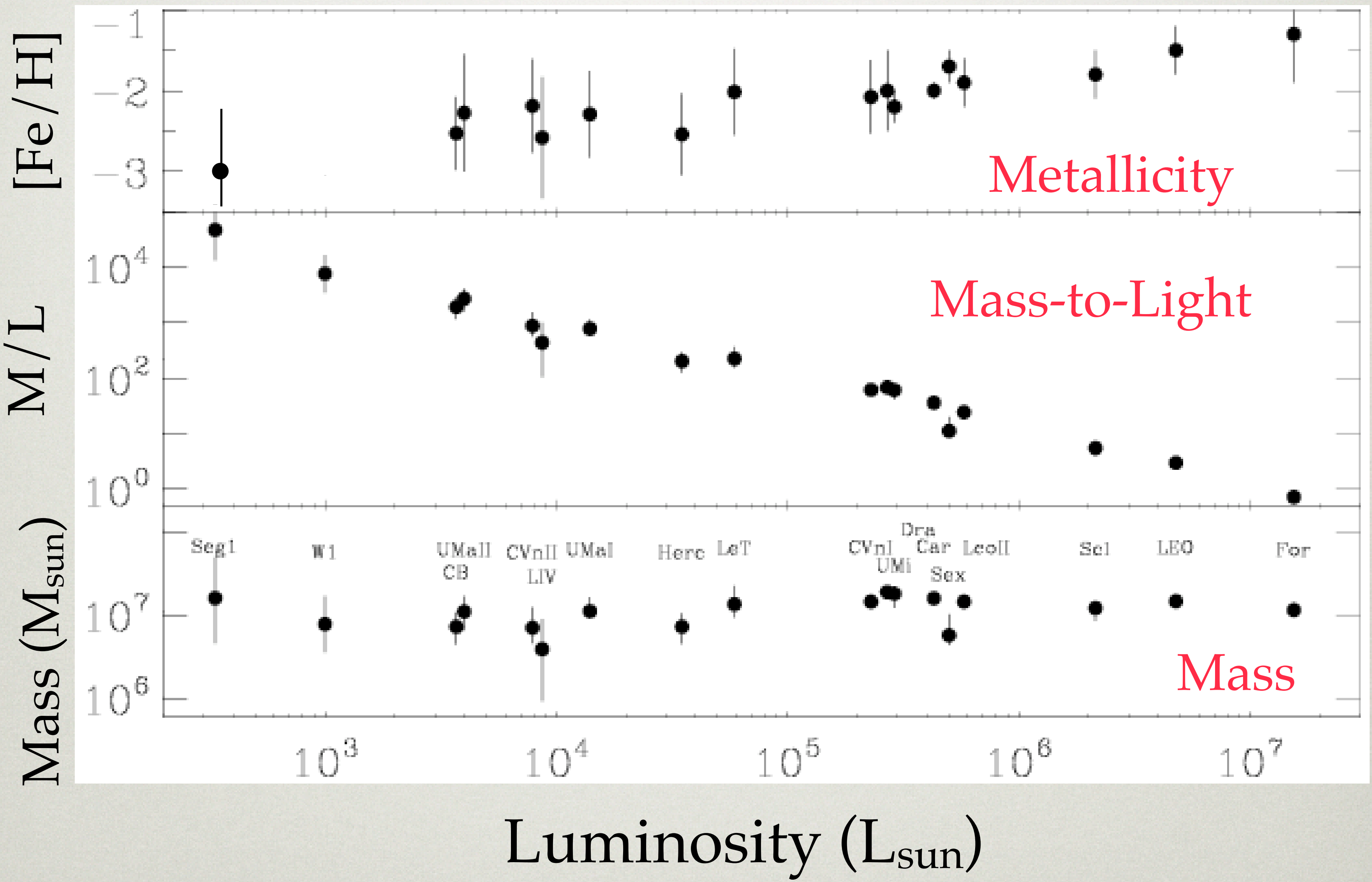
Log ($M_{HI}$)



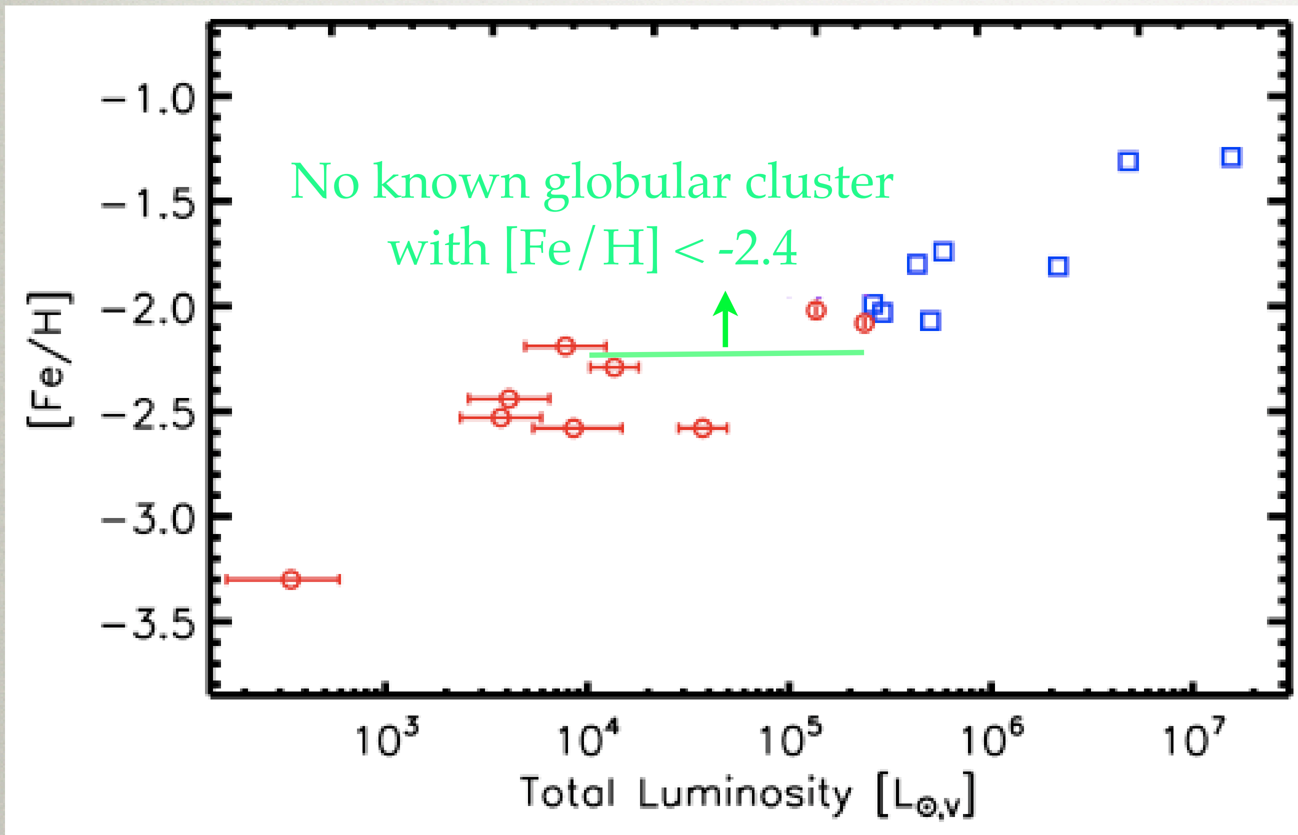

Distance (kpc)

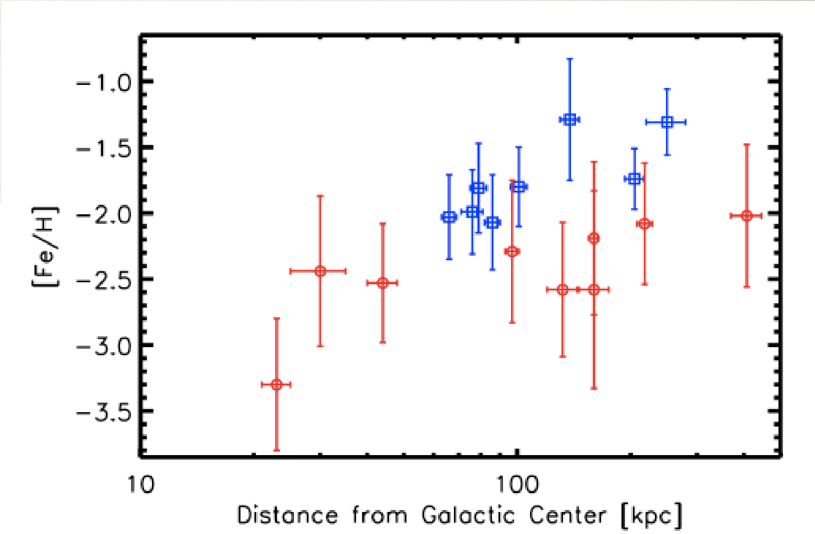
Putman, Grcevich & Peek 2008

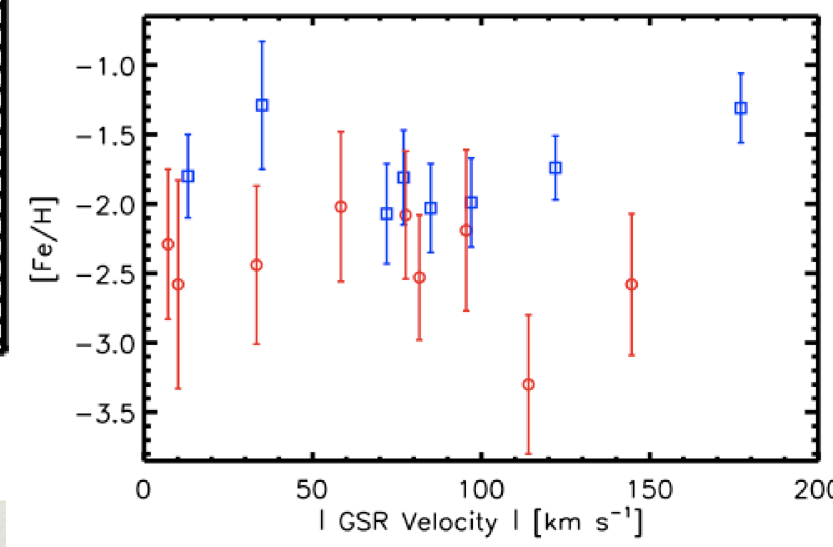
# Putting it Together



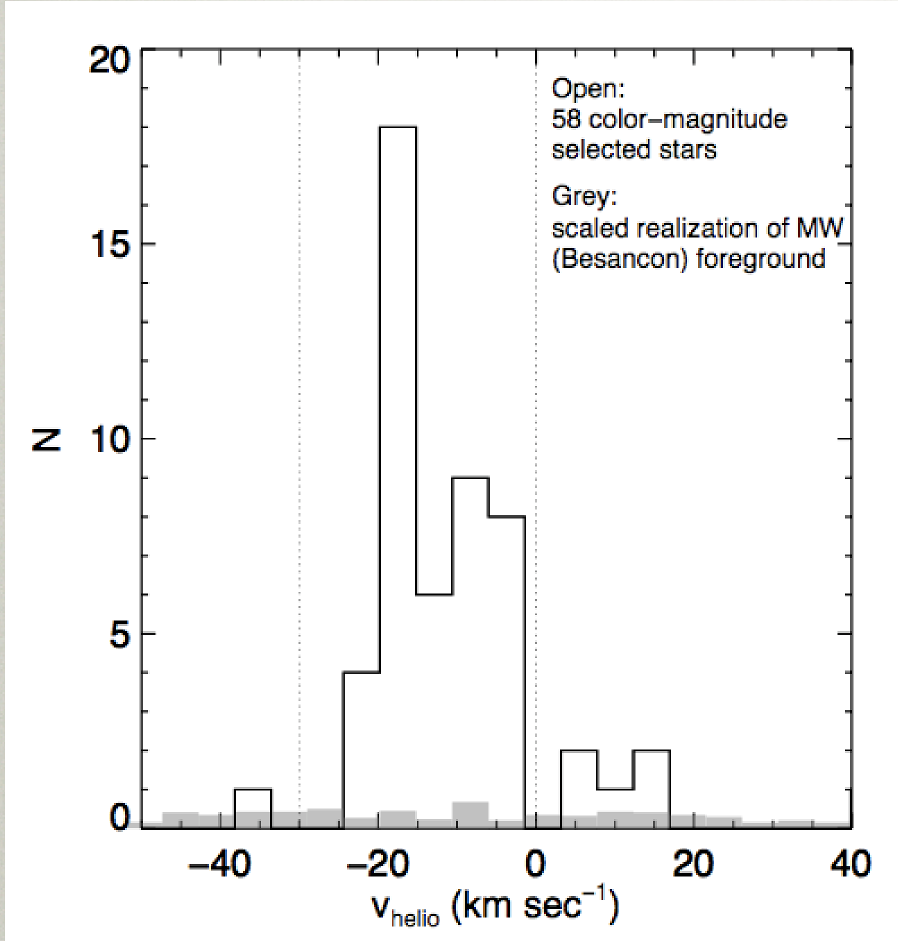
# Metallity-Luminosity Reln.

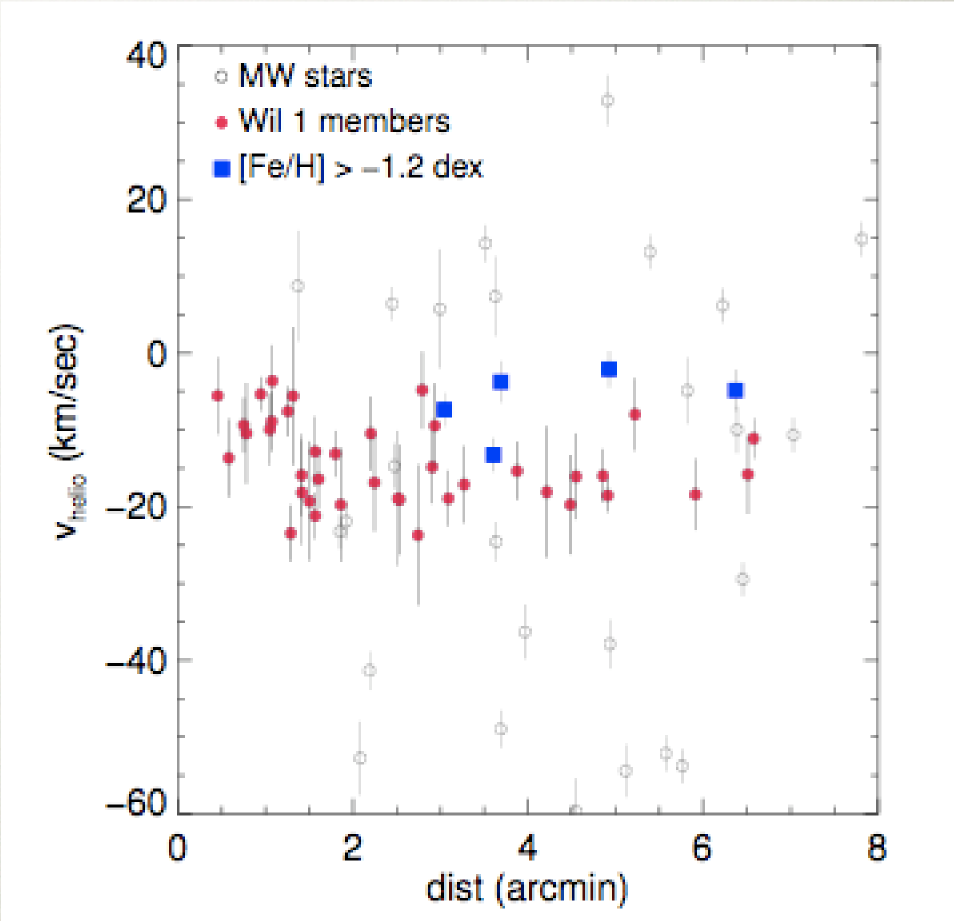


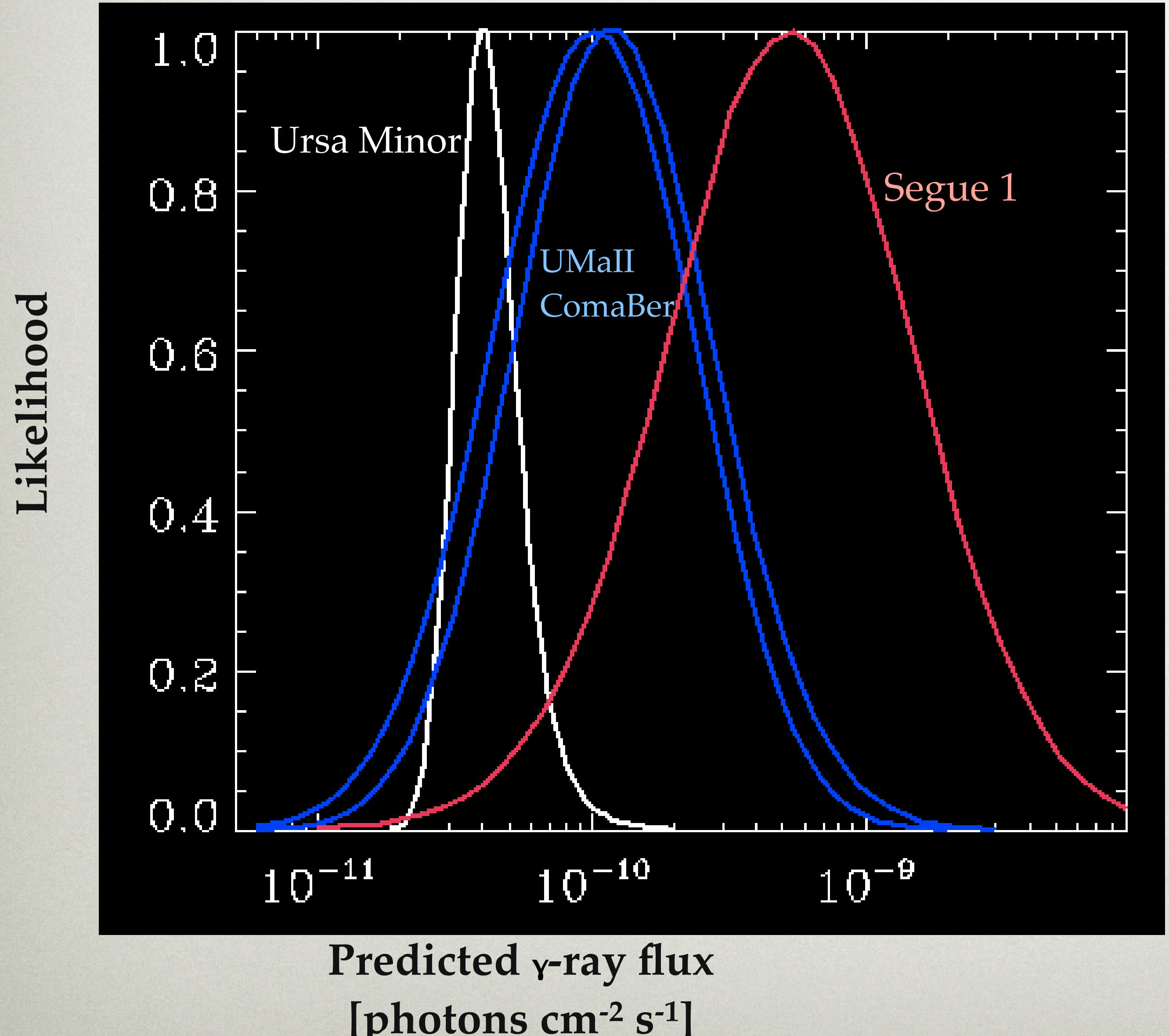
# Willman 1: Galaxy or Something else?



# Indirect Dark Matter Detection?


Dark matter particles annihilation to produce $\gamma$-rays.




Nearby dwarf galaxies are 'clean': dark matter-dominated with few intrinsic gamma-ray sources.

Strigari et al. (2008)

# Summary

The ultra-faint dwarfs are extreme in every sense:

- Less luminous galaxies ($300 < L_\odot < 100{,}000$).
- Highest mass-to-light ratios ($M/L > 100$).
- Most metal-poor stellar systems ($[Fe/H] \sim -2.5$)

Urgent: Understand to what extend tides influence the observed kinematics.