

Dwarf Galaxies and Dark Matter

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Introduction to Dwarf Galaxies

$$\text{Mass} < 10^{10} M_{\text{sun}} \quad | \quad M_V > -18$$

Dwarfs with gas



Dwarfs without gas



SDSS dwarf



Leo T



$$\text{Mass} \sim 10^5 M_{\text{sun}} \quad | \quad M_V > -5$$



Leo I

Segue 1

Formation of the Milky Way Galaxy

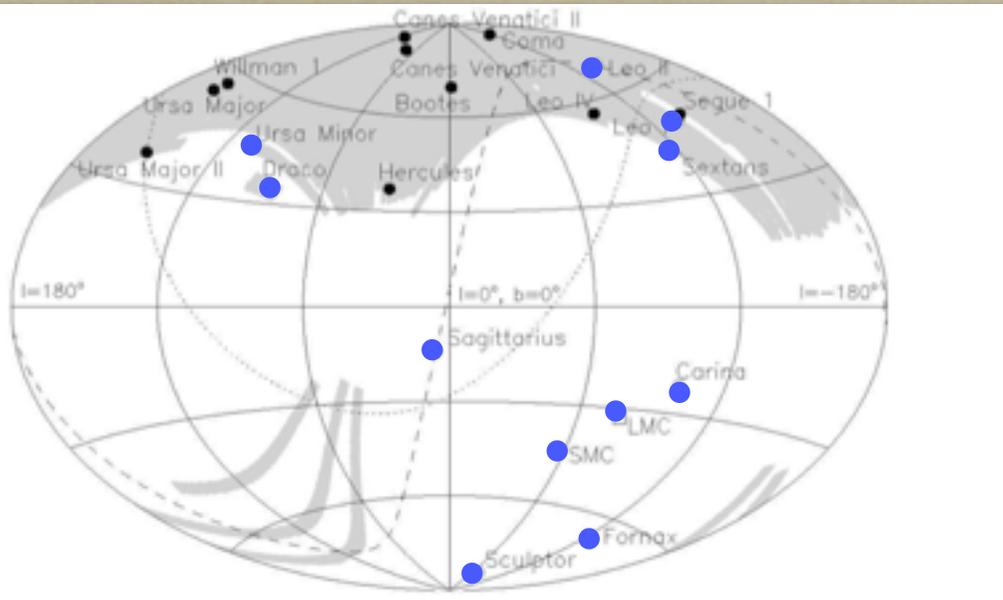
$z=0.0$



Diemand, Kuhlen, Madau 2006

The Milky Way Satellite Census

■ Sloan Digital Sky Survey (SDSS) coverage



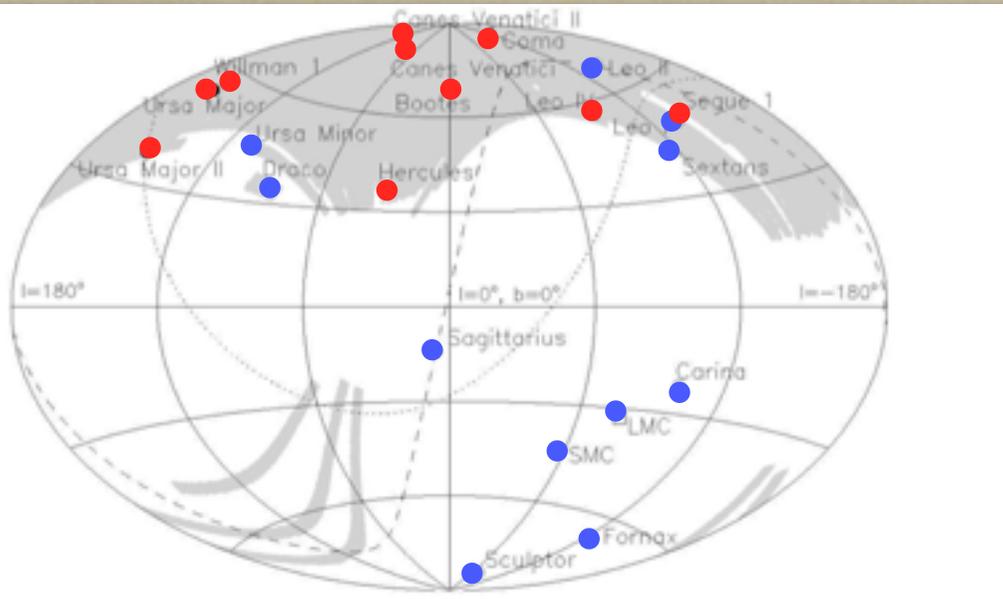
<u>Name</u>	<u>Year Discovered</u>
LMC	B.C
SMC	B.C
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarius	1994

2003 Milky Way Census Data:

● Classical dSphs = 11

The Milky Way Satellite Census

Sloan Digital Sky Survey (SDSS) coverage

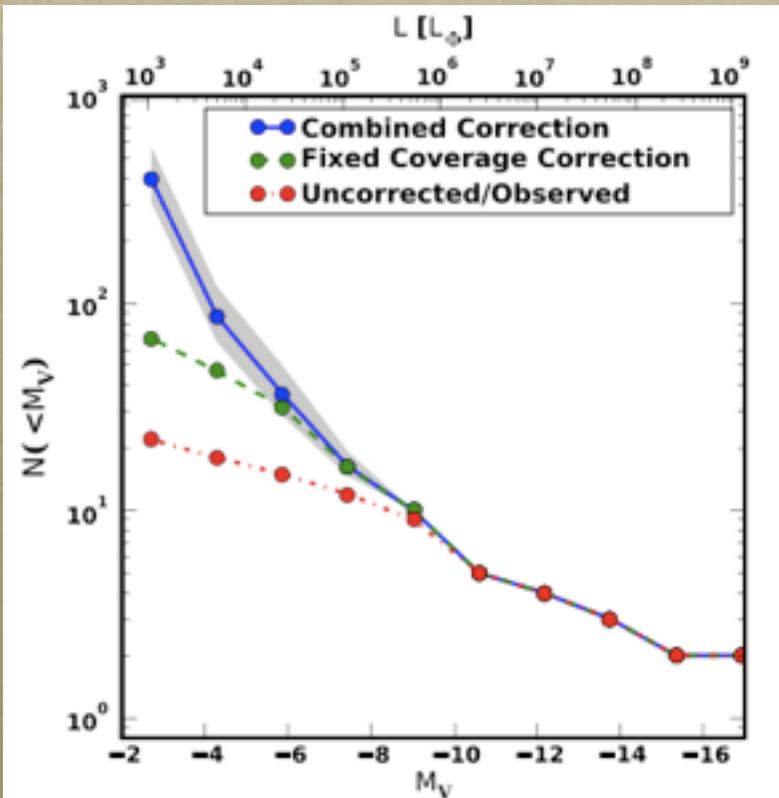


2009 Milky Way Census Data:

- Classical dSphs = 11
- Ultra-Faint dSphs = 14

<u>Name</u>	<u>Year Discovered</u>
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 Berencis	2006
Segue I	2006
Leo IV	2006
Hercules	2006
Leo T	2007
Bootes II	2007
Leo V	2008
Segue II	2009

The Milky Way Satellite Census



Tollerud et al. (2008)

There are **25** known Milky Way satellite galaxies.
The total satellite population is between **70 - 500**.

The least luminous satellites are particularly useful:

a) ***Galaxy Formation:***

Highest M/L ratios, lowest [Fe/H]

b) ***Cosmology:***

$\Phi(L)$, $n(M)$ critical test of Λ CDM

“the missing satellite issue”

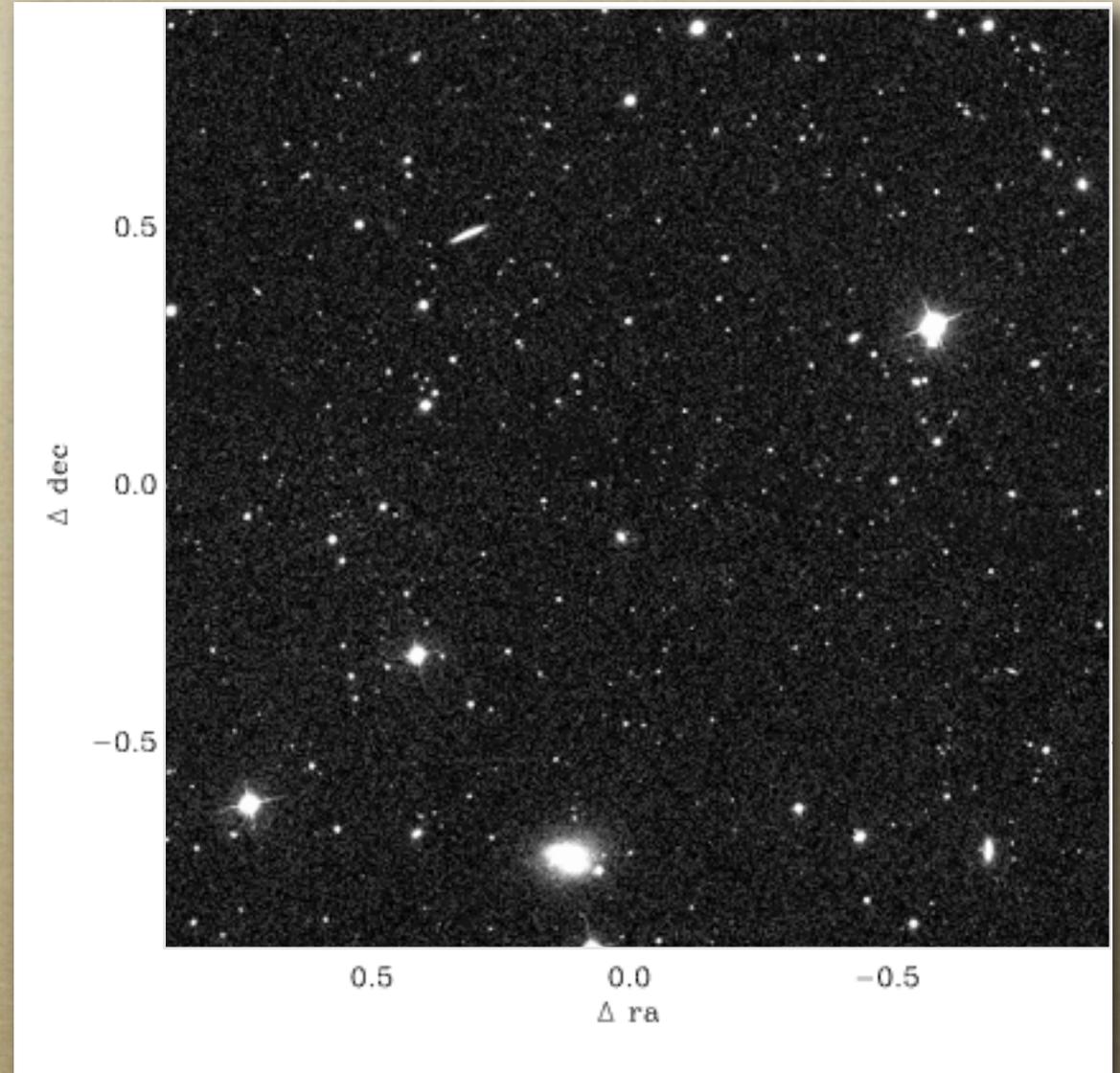
c) ***Particle Physics:***

Indirect dark matter detection

Finding the Milky Way Ultra-Faint Galaxies

The ultra-faint galaxies are found via over-densities of resolved stars.

Milky Way stellar foreground overwhelms the dwarf galaxy.



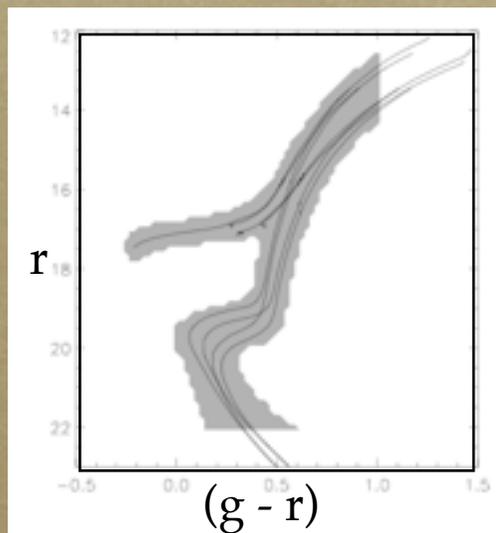
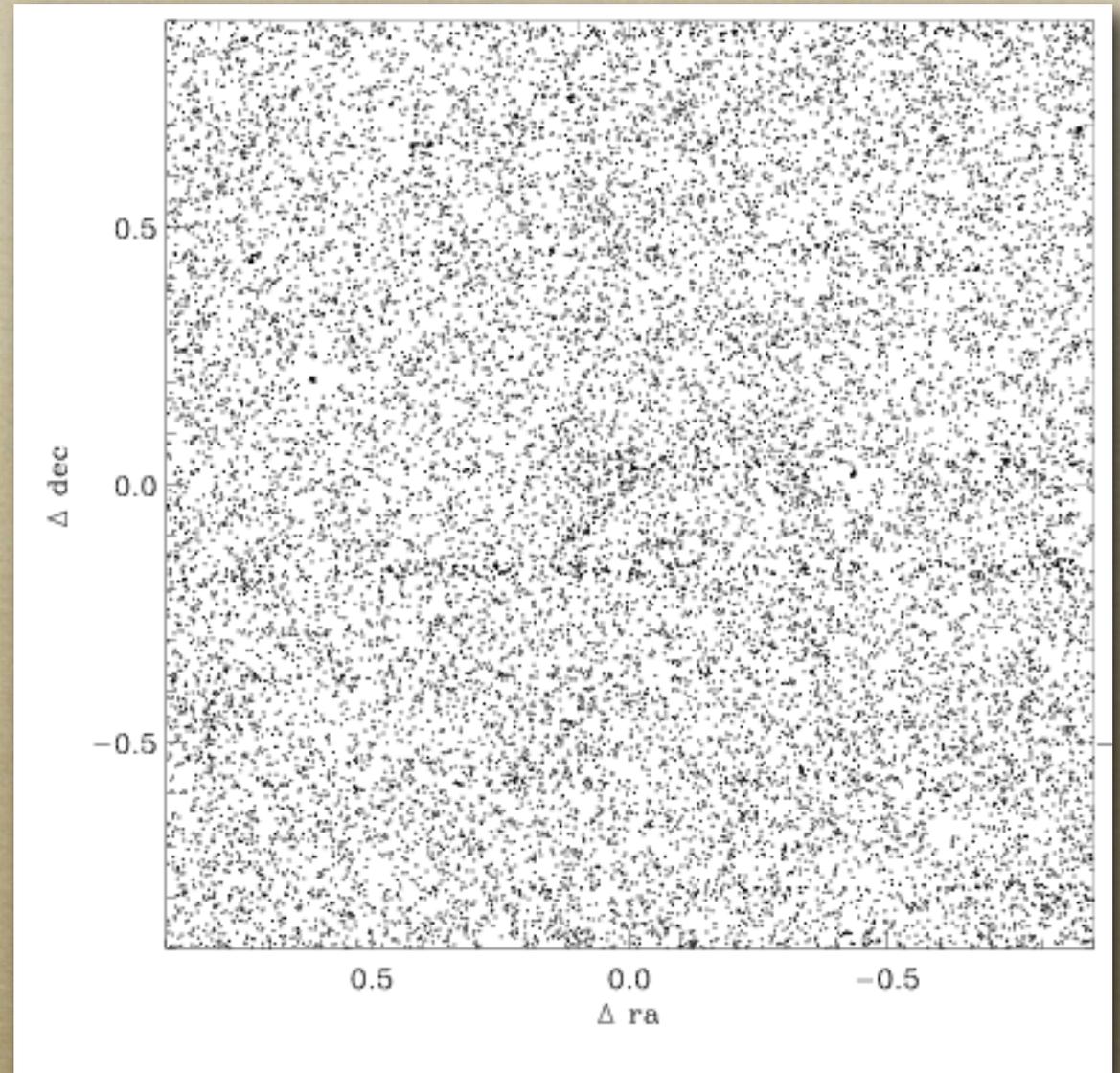
Finding the Milky Way Ultra-Faint Galaxies

Full Star Counts

The ultra-faint galaxies are found via over-densities of resolved stars.

Milky Way stellar foreground overwhelms the dwarf galaxy.

Apply CMD filter to star count maps, search for over-densities.

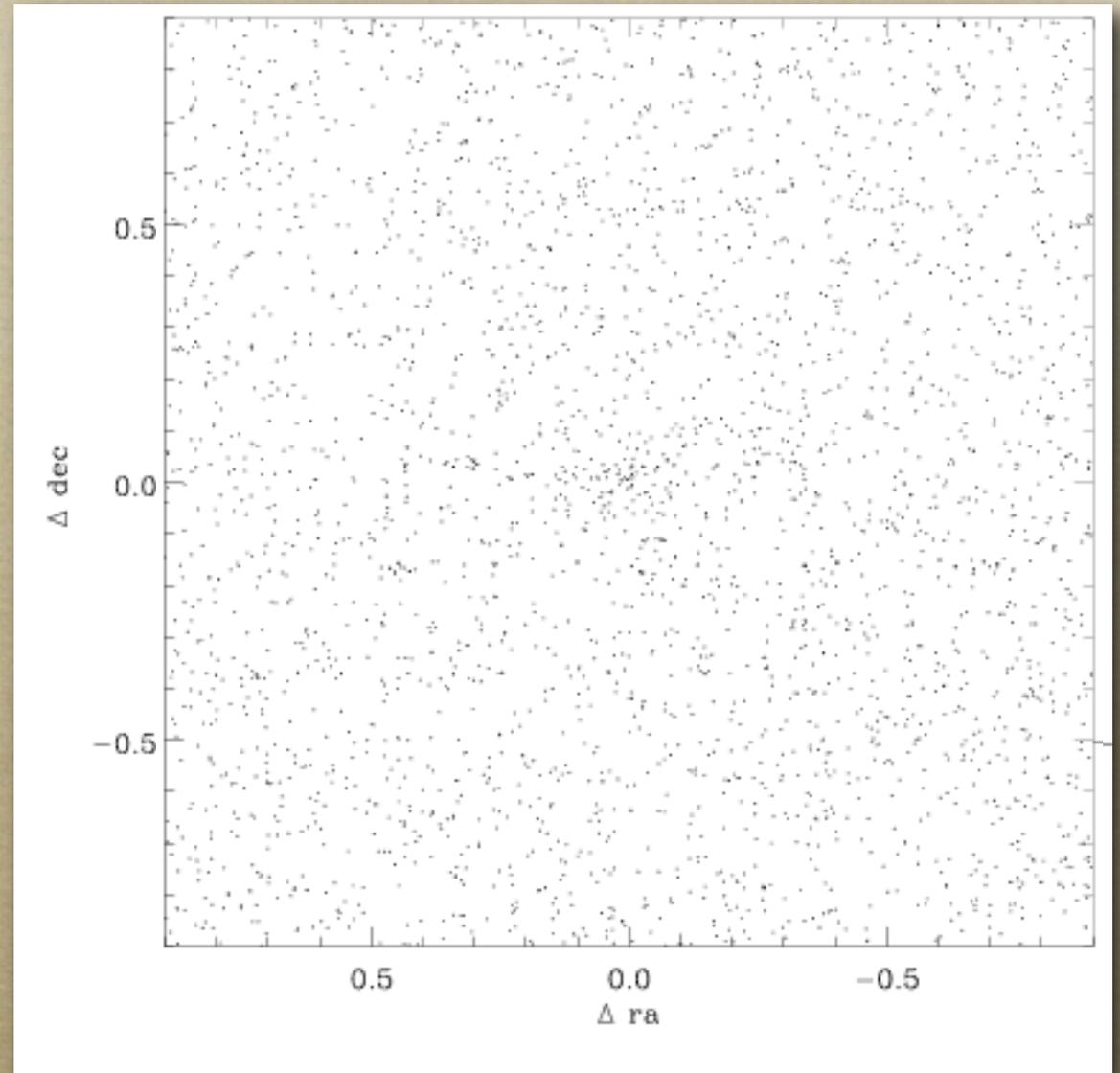


Finding the Milky Way Ultra-Faint Galaxies

Filtered CMD Stars

The ultra-faint galaxies are found via over-densities of resolved stars.

Milky Way stellar foreground overwhelms the dwarf galaxy.

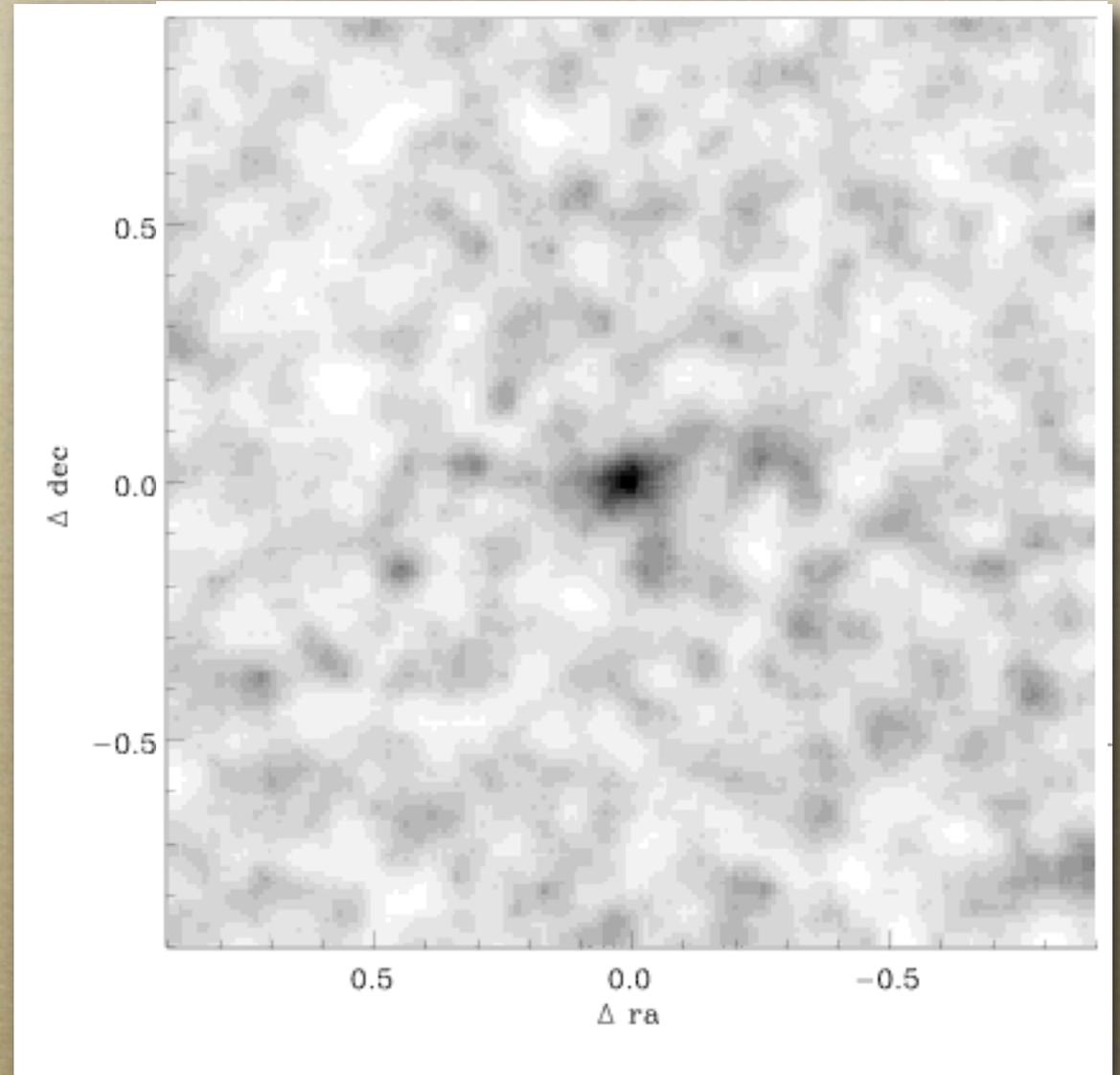


Finding the Milky Way Ultra-Faint Galaxies

Filtered+Smoothed

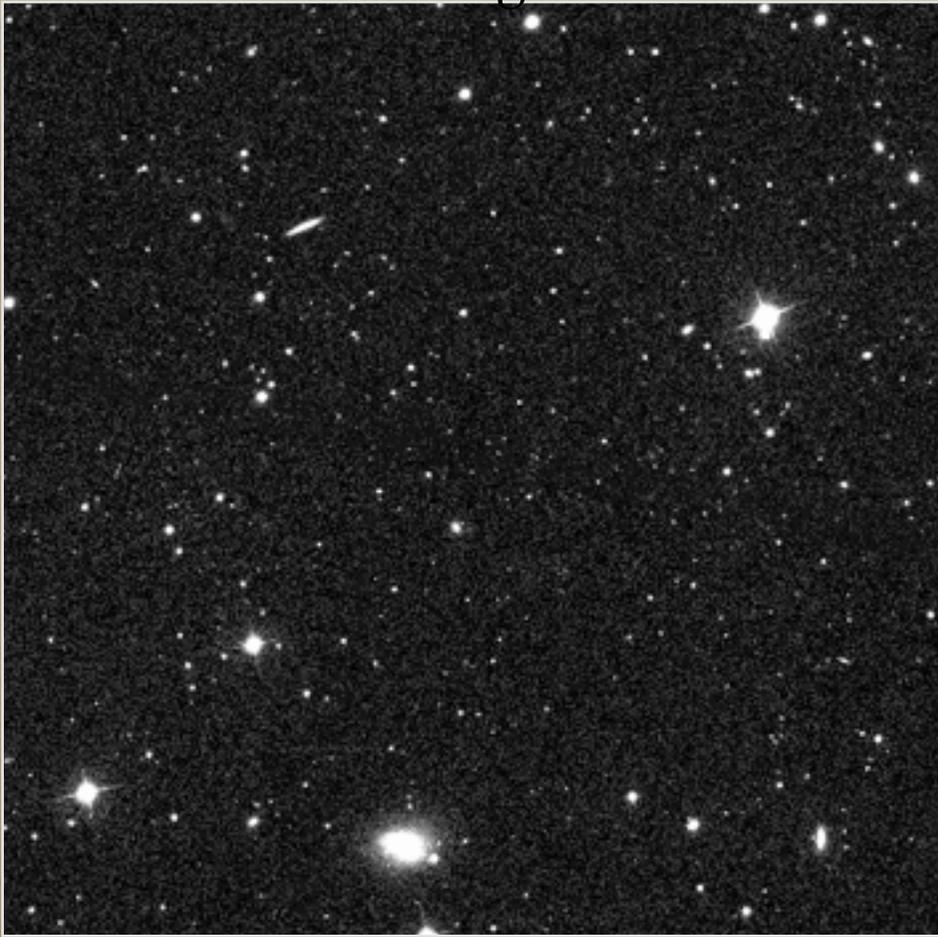
The ultra-faint galaxies are found via over-densities of resolved stars.

Milky Way stellar foreground overwhelms the dwarf galaxy.



Finding the Milky Way Ultra-Faint Galaxies

Raw Image

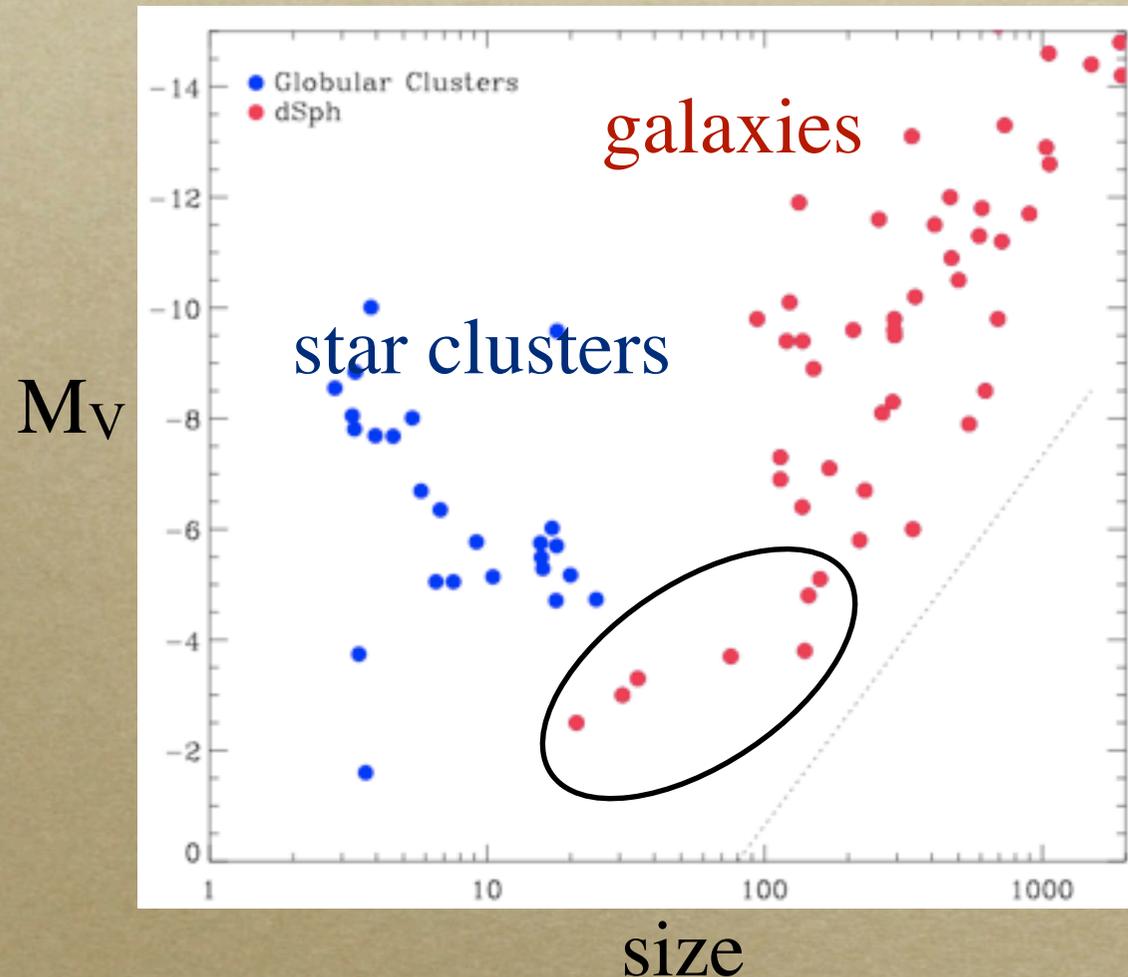


Member Stars only

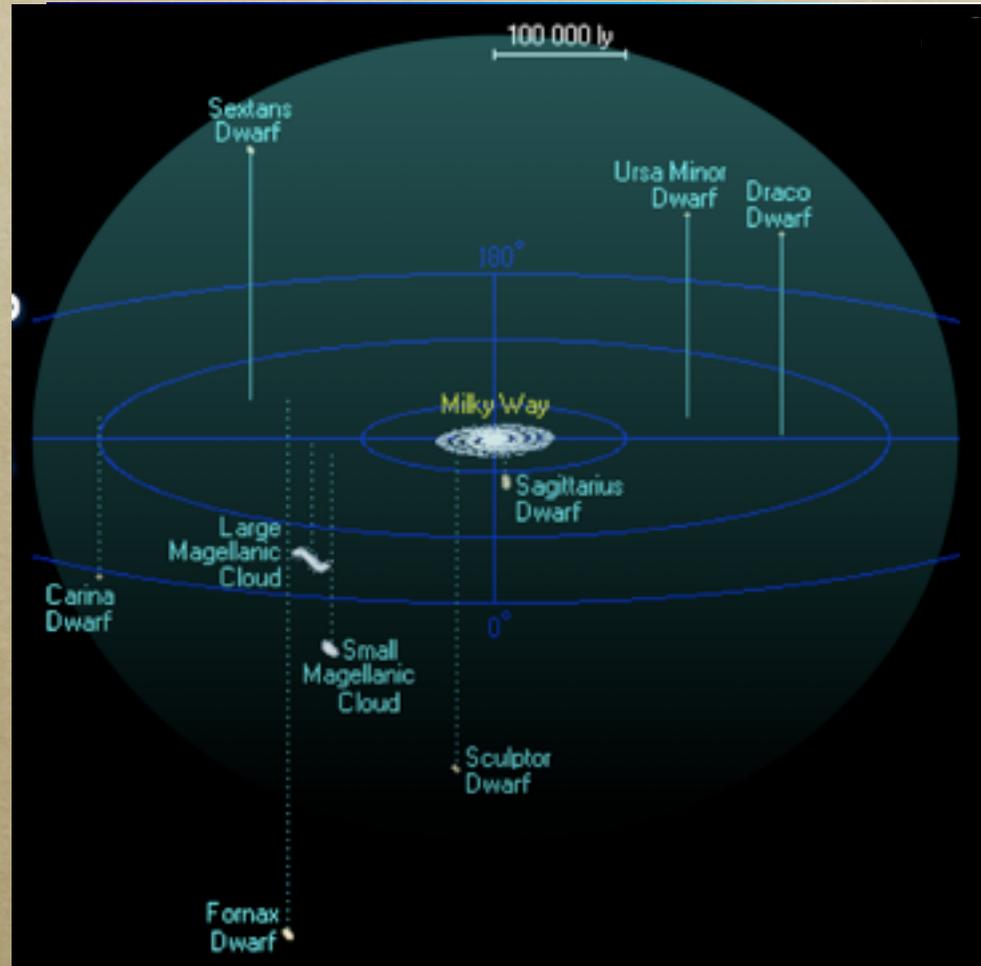


Finding the Milky Way Ultra-Faint Galaxies

The ultra-faint objects have similar total magnitudes to globular clusters, but much lower surface brightnesses.



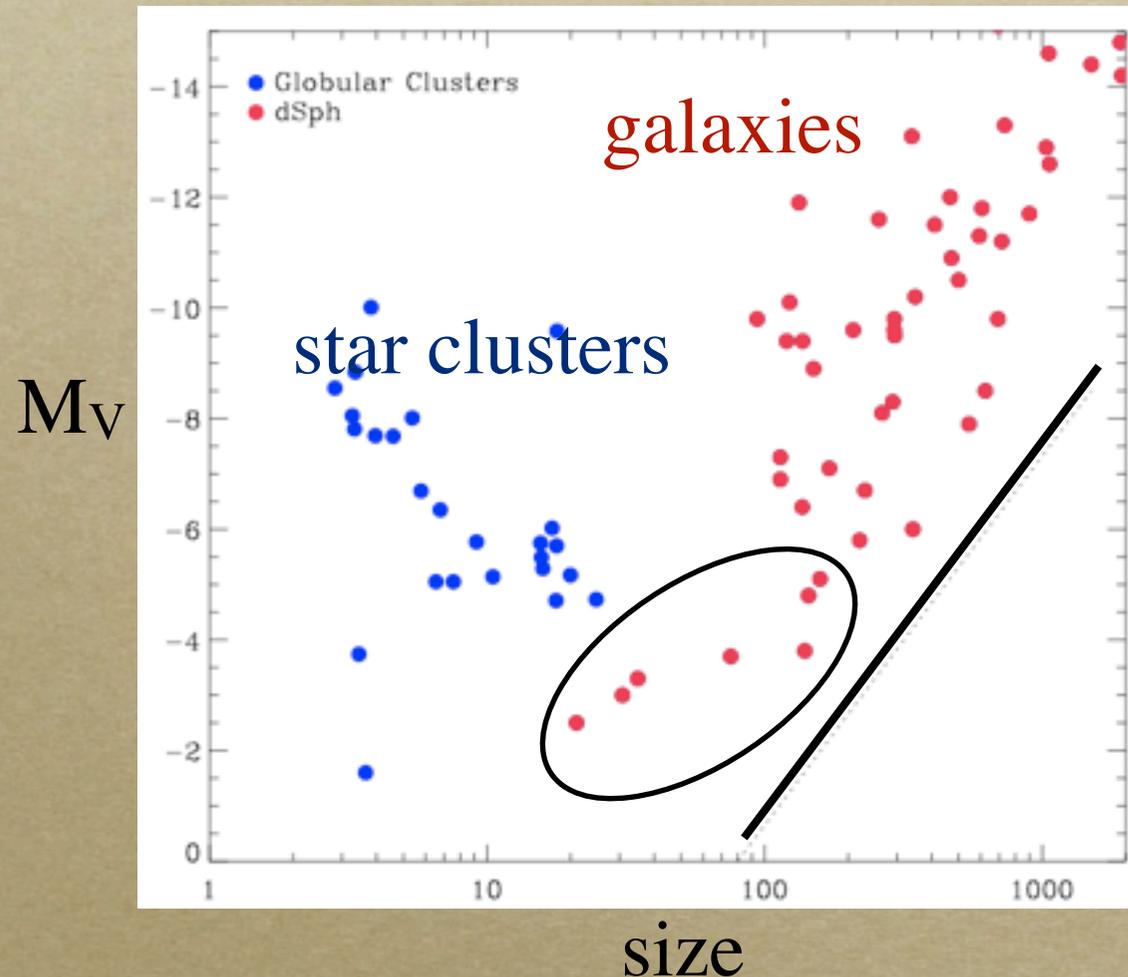
Are the Milky Way Ultra-Faints Galaxies?



Other possibilities include star clusters or tidal debris.

Finding the Milky Way Ultra-Faint Galaxies

The ultra-faint objects have similar total magnitudes to globular clusters, but much lower surface brightnesses.



Kinematics with Keck/DEIMOS



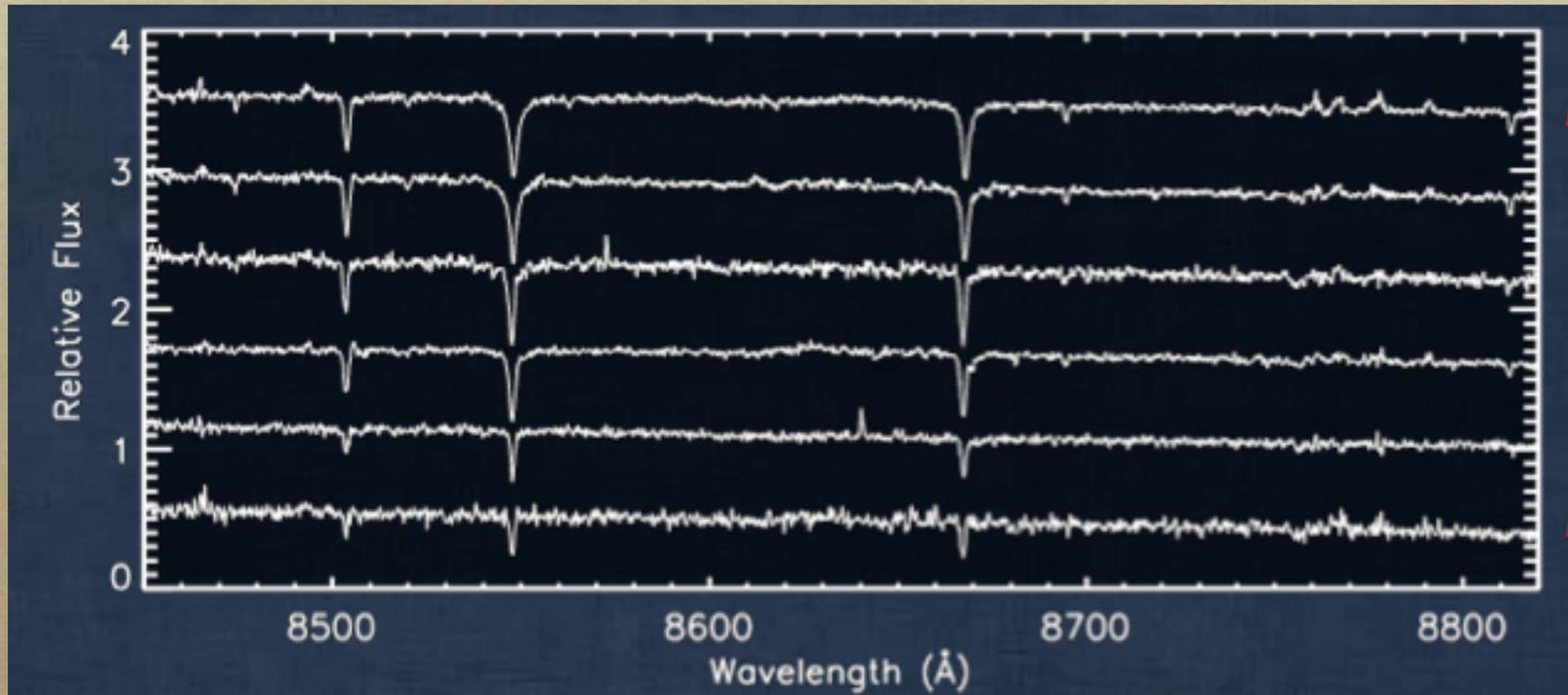
DEIMOS Multi-Object Spectrograph

-- 6500 to 9000Å

-- $0.33 \text{ \AA pixel}^{-1} \sim 12 \text{ km s}^{-1} \text{ pixel}^{-1}$

From stellar mass, internal
velocity dispersions
should be less than 5 km/s.

Kinematics with Keck/DEIMOS

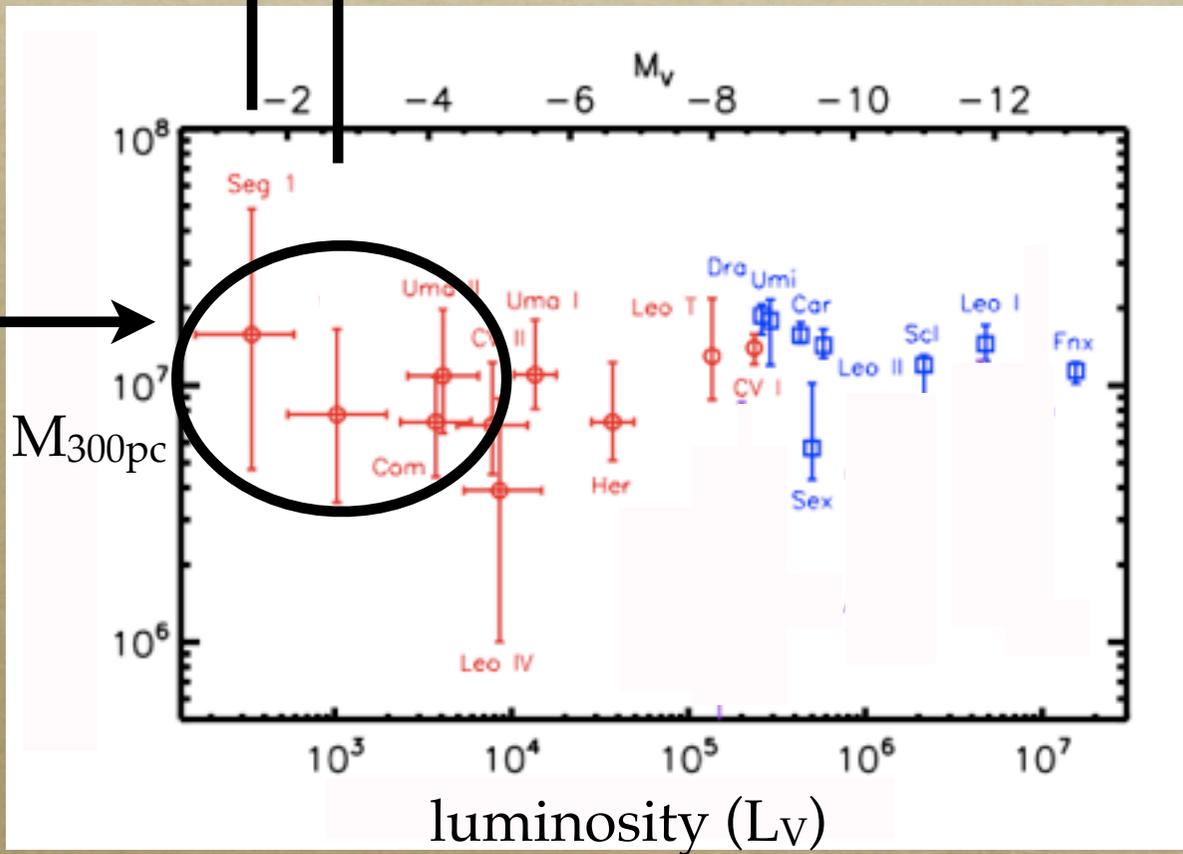


Measure velocities and metallicities of individual stars.

Kinematics of the Ultra-Faint Galaxies

Segue 1

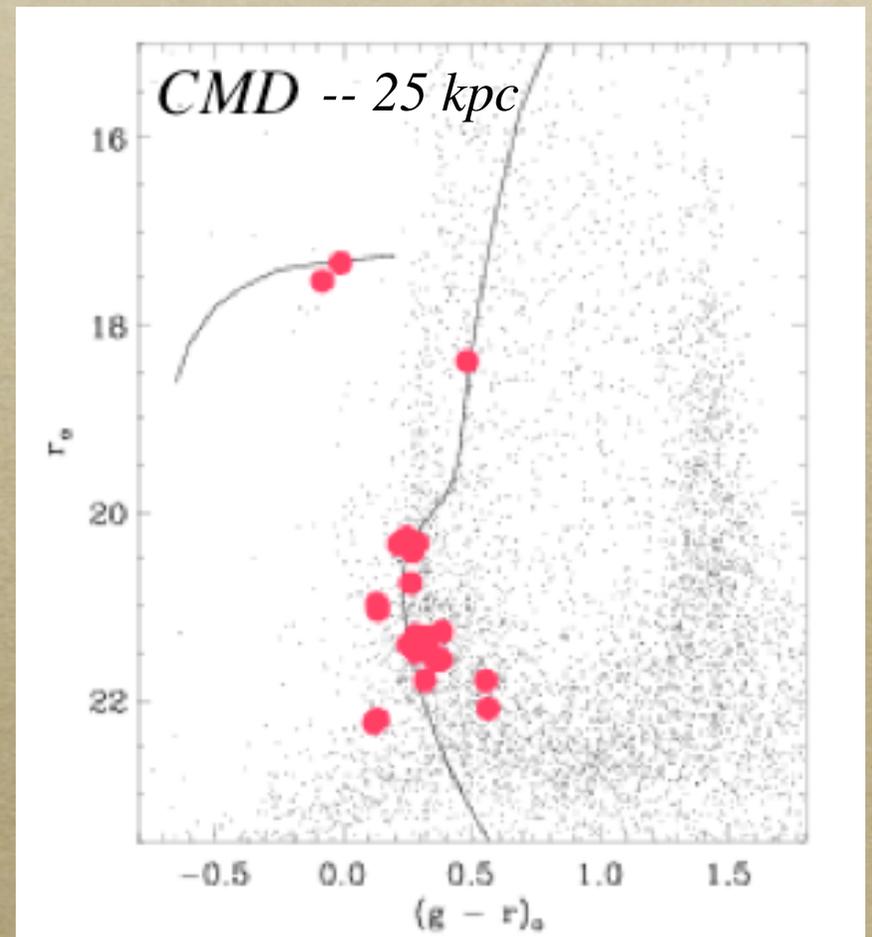
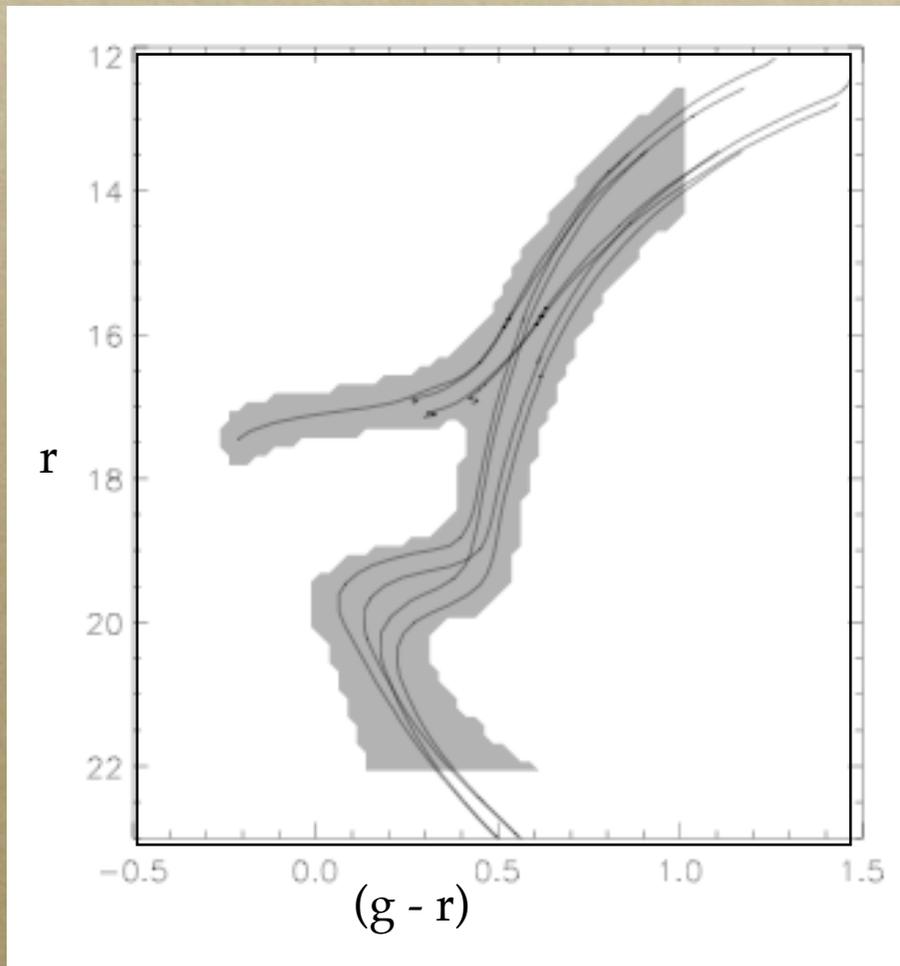
Willman 1



Strigari et al (2008): Plot mass within a fixed physical radius.

Faintest Satellites are also the Nearest

To SDSS limits, can detect faintest satellites out to 50 kpc.



You Call That A Galaxy??

- **Segue 1:** $d = 23$ kpc, $M_V = -1.5$
- **Ursa Major II:** $d = 30$ kpc, $M_V = -3.9$
- **Willman 1:** $d = 38$ kpc, $M_V = -2.7$
- **Bootes II:** $d = 42$ kpc, $M_V = -2.7$
- **Coma Berenices:** $d = 42$ kpc, $M_V = -3.8$

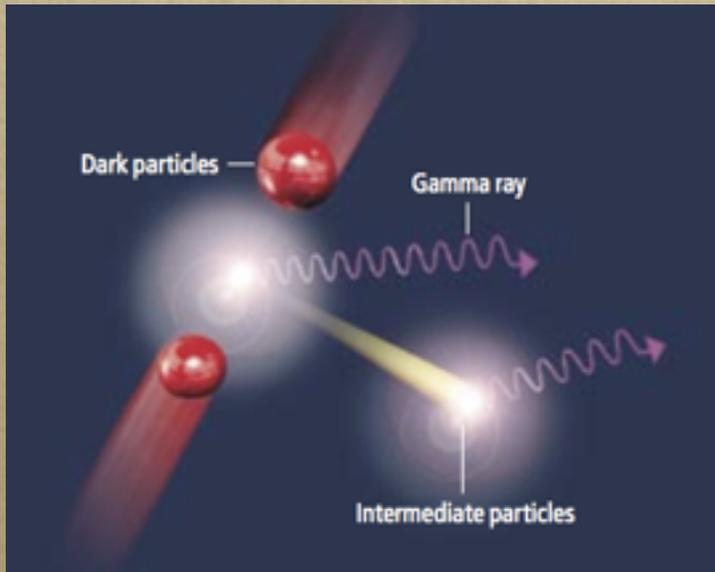
These satellites are most vulnerable to systematics..

1. Tides induced by proximity to Milky Way
2. Contamination from Milky Way stars
3. Inflated velocity dispersions due to binary stars.

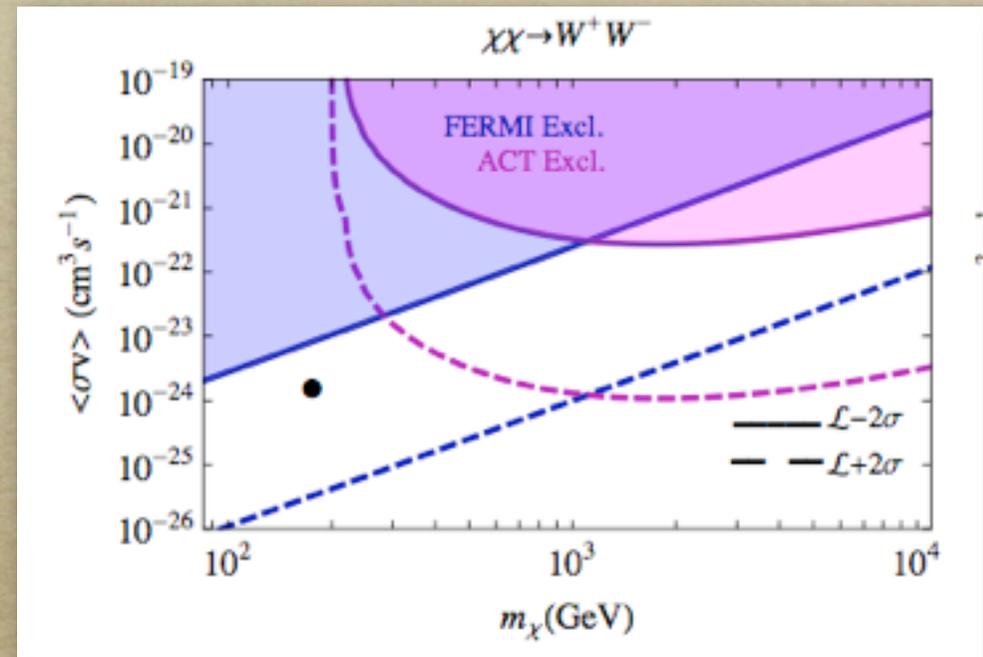
...but also the most interesting!

Indirect Dark Matter Detection

SUSY dark matter particles occasionally annihilate to produce observable γ -rays.



Non-detection of Segue 1 places strongest constraints on DM particle models



Essig et al. (2010)

The Case of Segue 1

Globular Cluster

CATS AND DOGS, HAIR AND A HERO: A QUINTET OF NEW MILKY WAY COMPANIONS¹

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ABSTRACT

We present five new satellites of the Milky Way discovered in Sloan Digital Sky Survey (SDSS) imaging data, four of which were followed up with either the Subaru or the Isaac Newton Telescopes. They include four probable new dwarf galaxies—one each in the constellations of Coma Berenices, Canes Venatici, Leo, and Hercules—together with one unusually extended globular cluster, Segue 1. We provide distances, absolute magnitudes, half-light radii, and color-

THE LEAST LUMINOUS GALAXY: SPECTROSCOPY OF THE MILKY WAY SATELLITE SEGUE 1

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Draft version September 16, 2008

ABSTRACT

We present Keck/DEIMOS spectroscopy of Segue 1, an ultra-low luminosity ($M_V = -1.5^{+0.6}_{-0.8}$) Milky Way satellite companion. While the combined size and luminosity of Segue 1 is consistent with either a globular cluster or a dwarf galaxy, we present spectroscopic evidence

Galaxy

The origin of Segue 1

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Accepted 2009 June 15. Received 2009 June 15; in original form 2009 January 15

ABSTRACT

We apply the optimal filter technique to Sloan Digital Sky Survey photometry around Segue 1. The outer parts of the cluster are distorted. There is strong evidence for $\sim 1^\circ$ of extra-tidal stars, extending both eastwards and southwestwards of the cluster.

Globular Cluster

Galaxy

A COMPLETE SPECTROSCOPIC SURVEY OF THE MILKY WAY SATELLITE SEGUE 1: THE DARKEST GALAXY*

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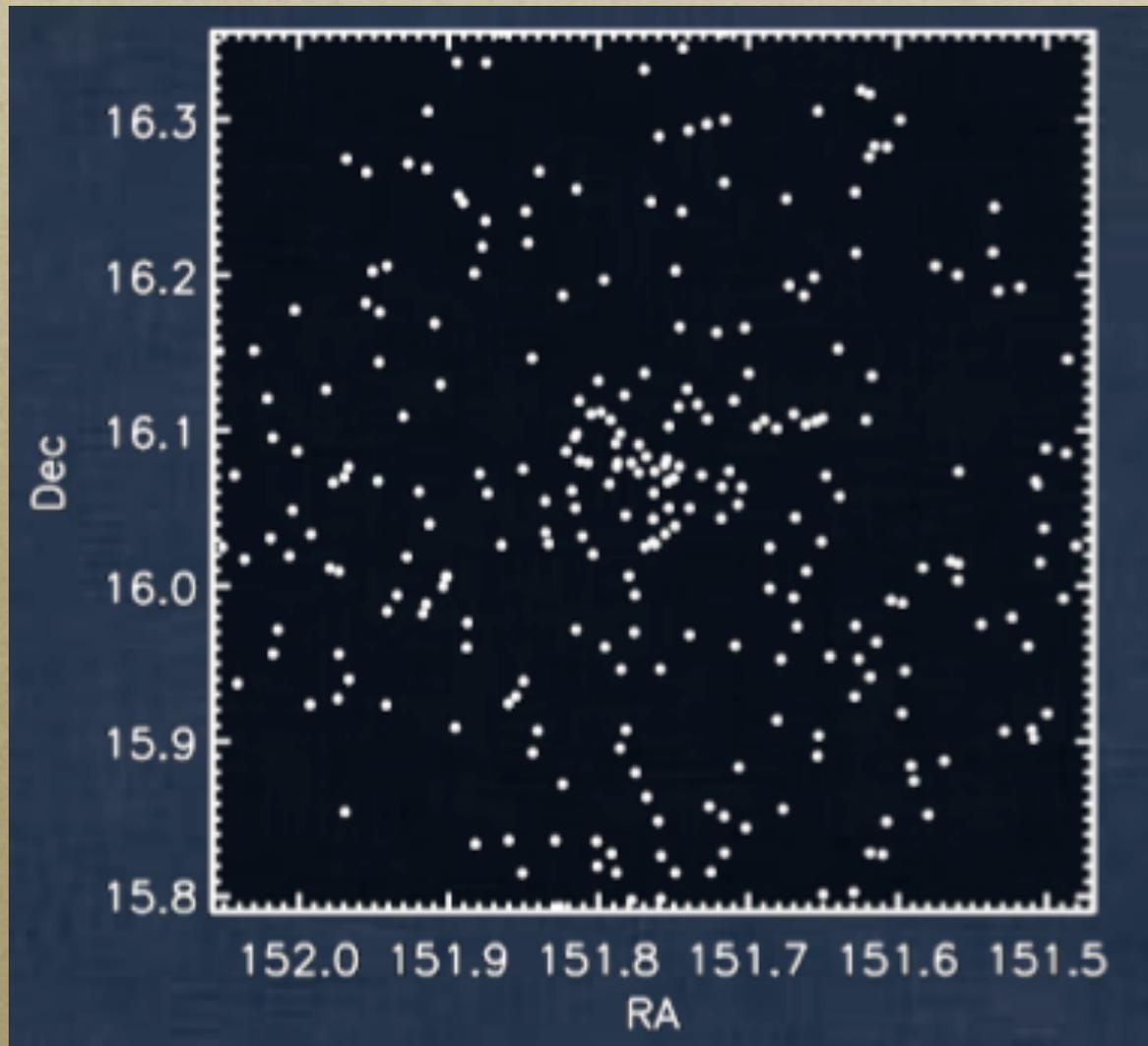
Submitted to *ApJ*

ABSTRACT

We present the results of a comprehensive Keck/DEIMOS spectroscopic survey of the ultra-faint Milky Way satellite galaxy Segue 1. We have obtained velocity measurements for 99.1% of the stars

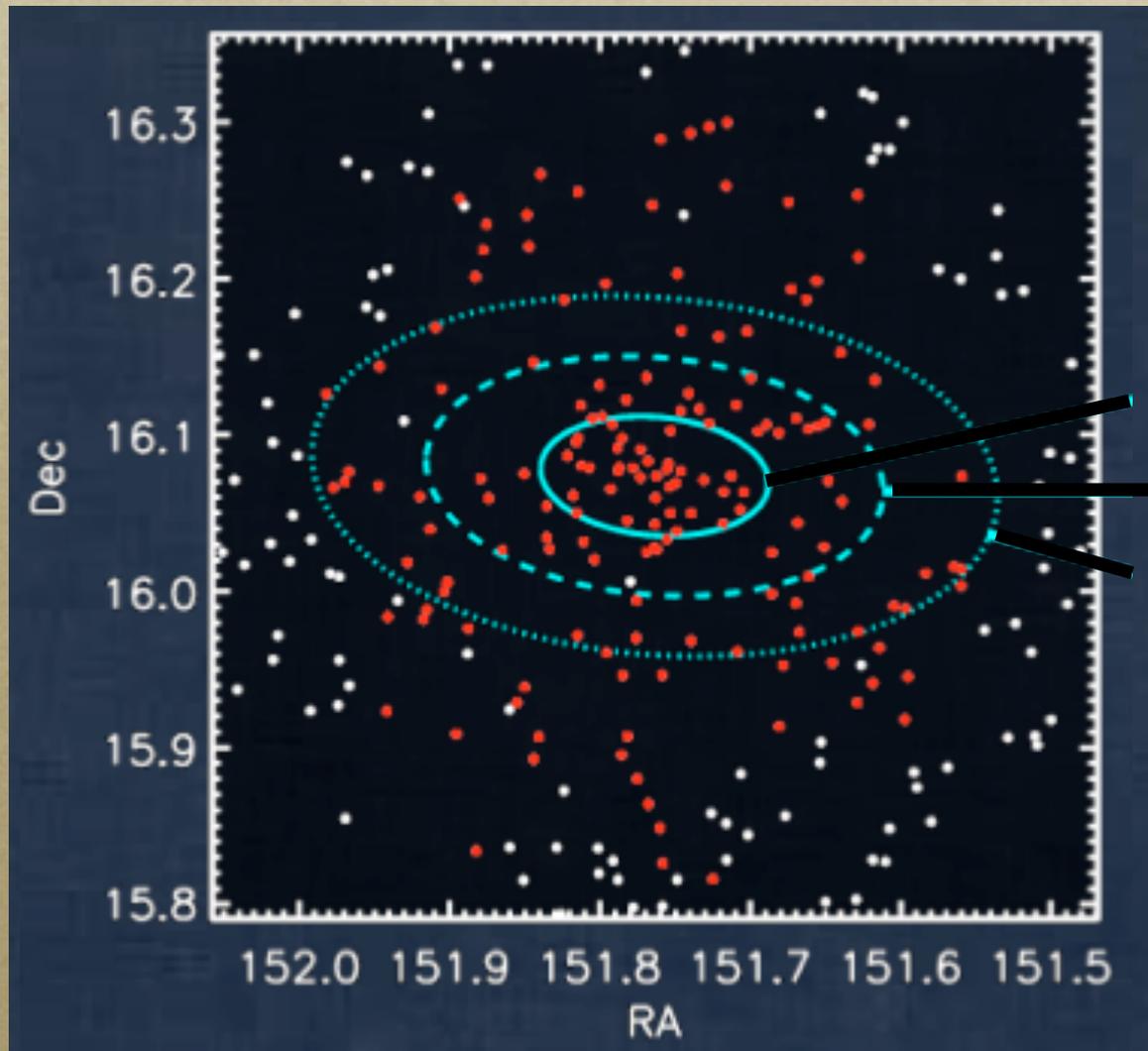
The Case of Segue 1

Keck/DEIMOS spectroscopy of (almost) every star out to 2 half-light radii.



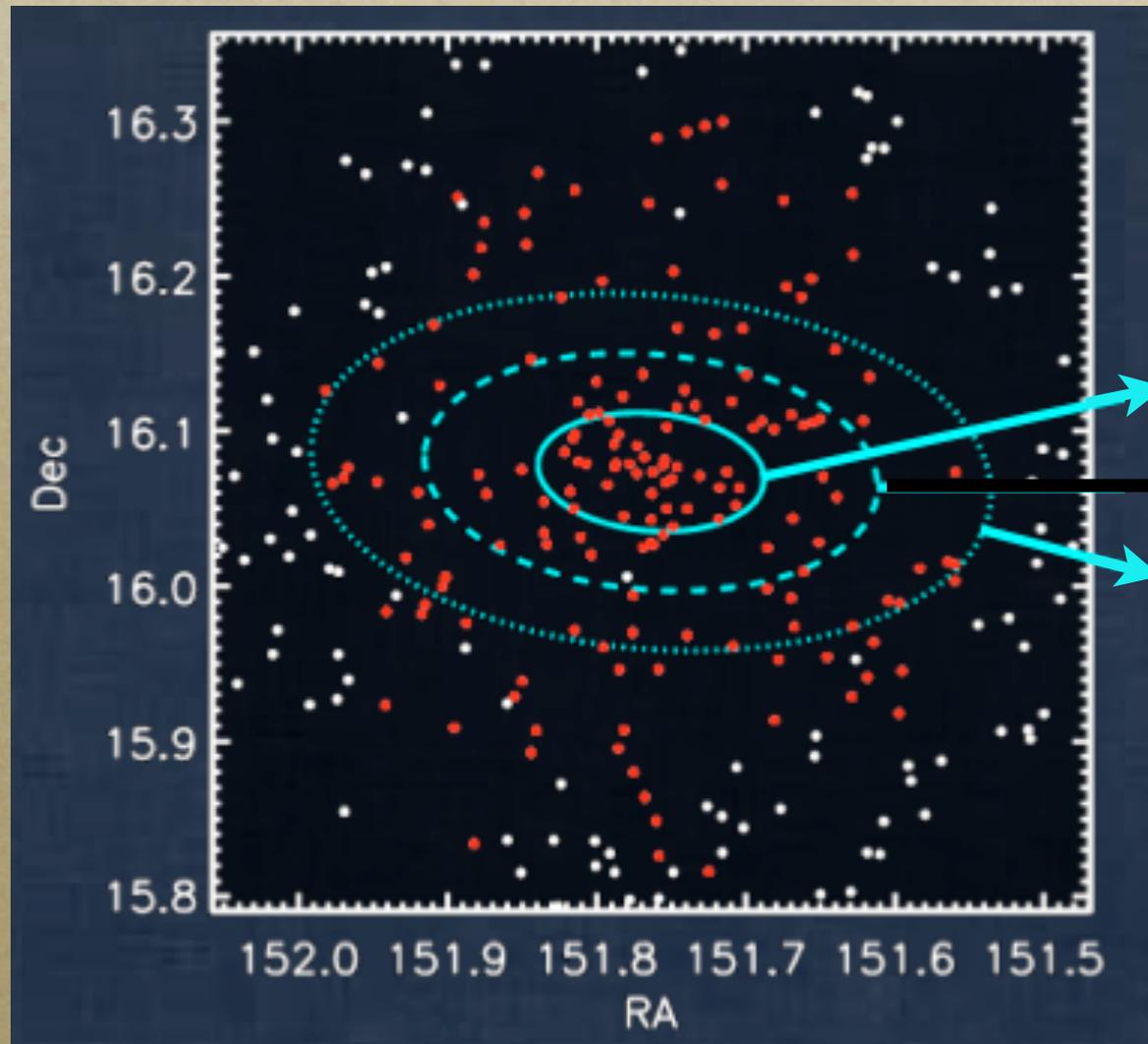
The Case of Segue 1

Keck/DEIMOS spectroscopy of (almost) every star out to 2 half-light radii.



The Case of Segue 1

Keck/DEIMOS spectroscopy of (almost) every star out to 2 half-light radii.



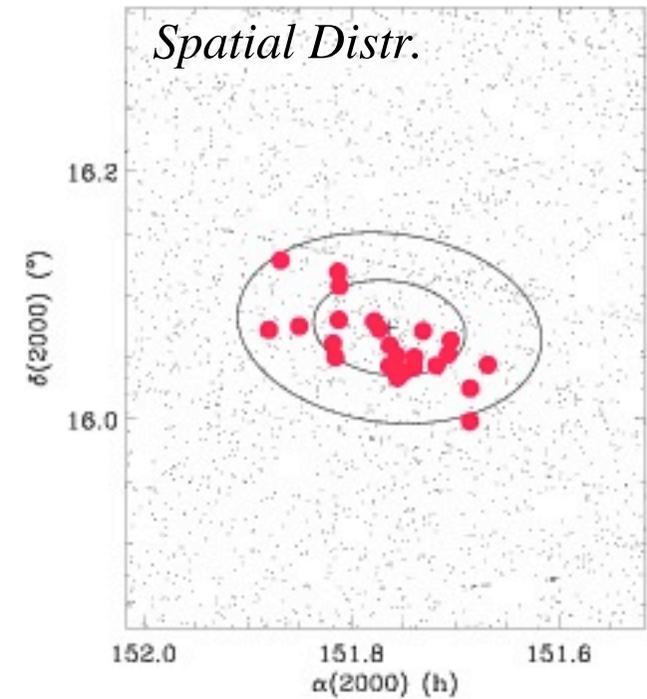
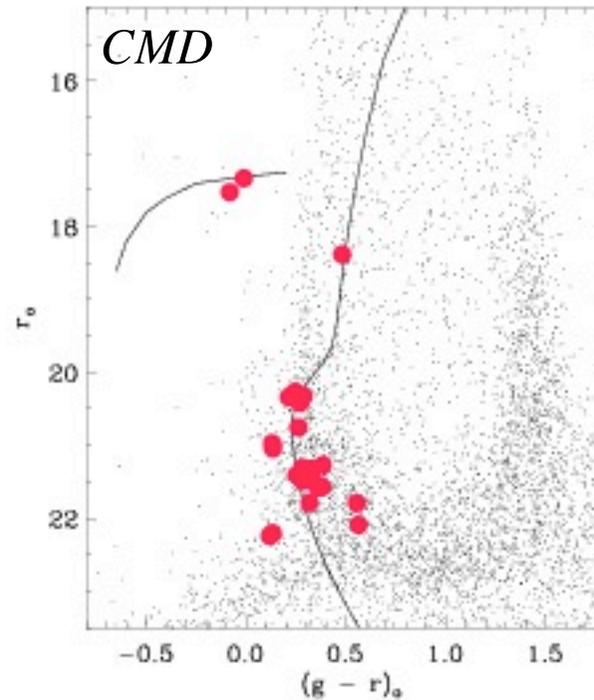
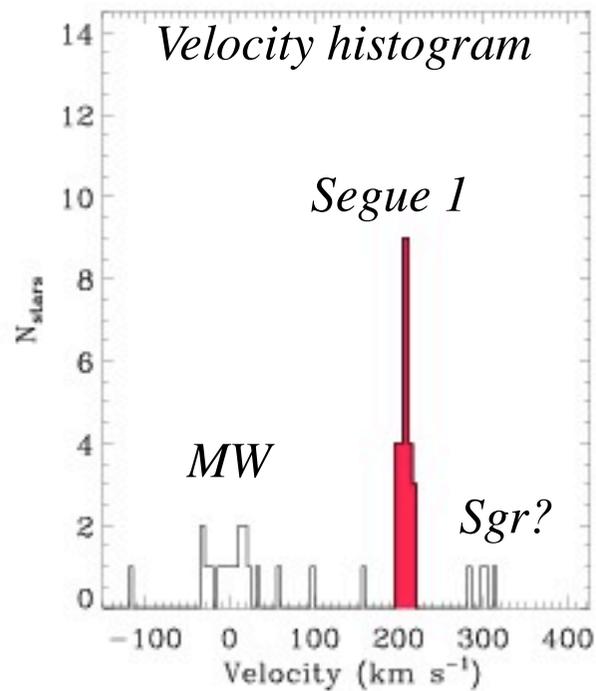
30 pc

90 pc

If no DM, tidal radius is 30 pc

Kinematics of Segue 1

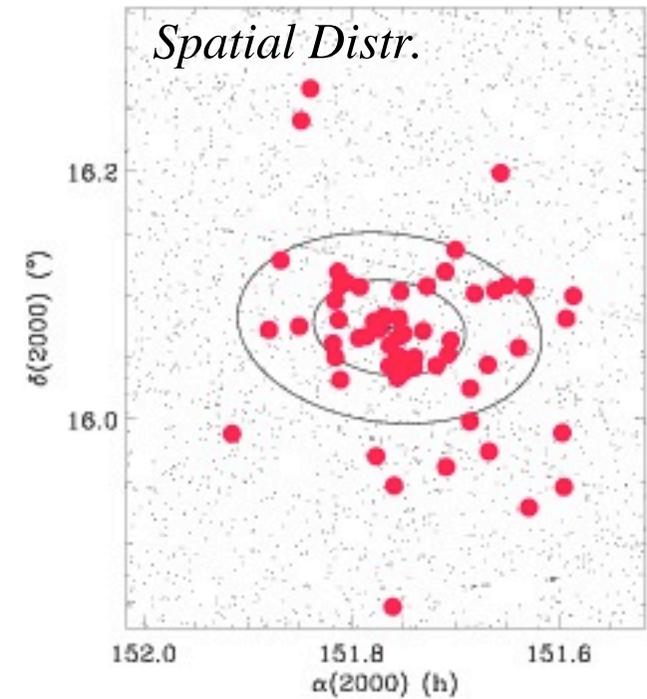
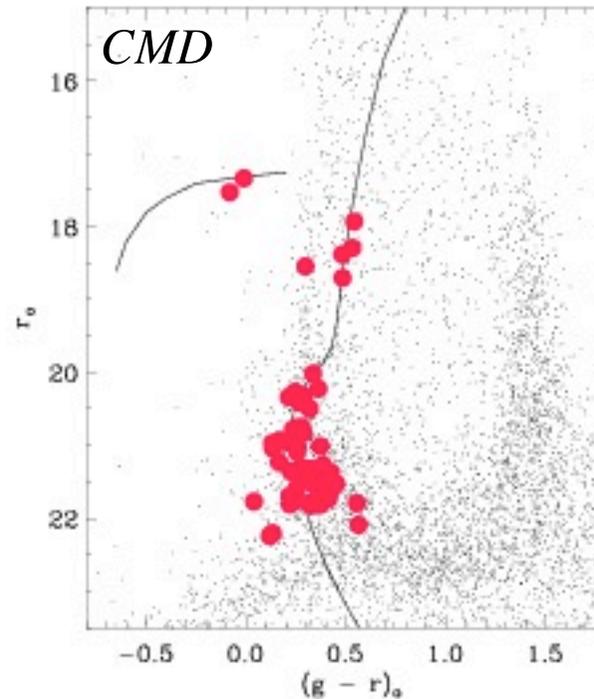
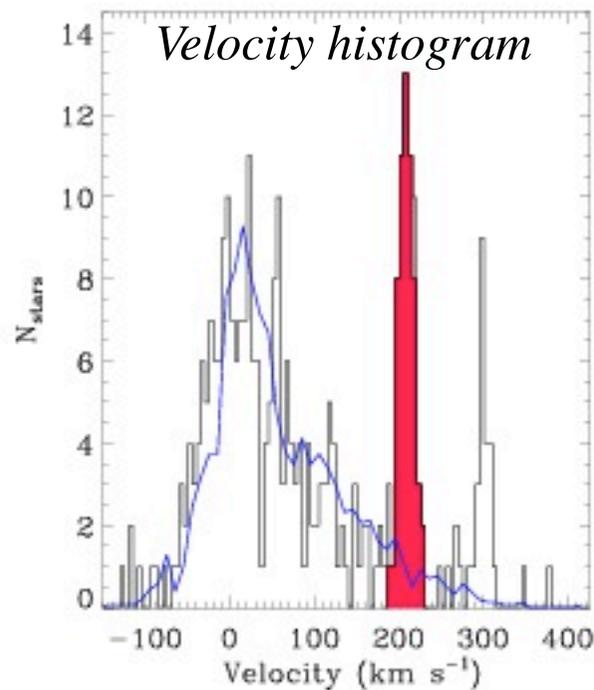
Geha et al (2009): 24 members $\sigma = 4.5 \pm 1$ km/s



If mass from stars only = 0.4 km/s

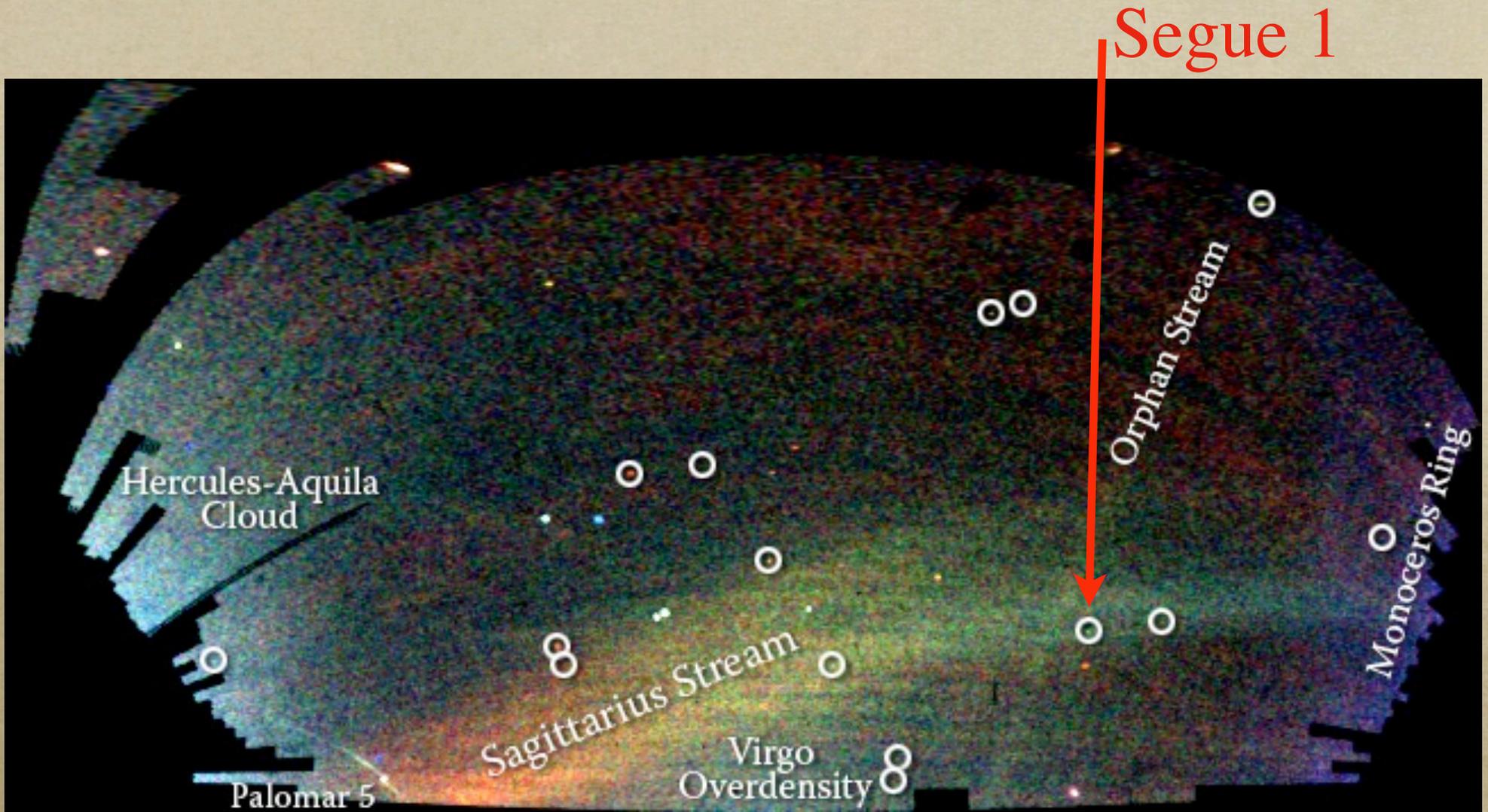
Kinematics of Segue 1

Simon, MG et al (2010): 71 members, $\sigma = 3.7 \pm 1$ km/s (binary corrected)



If mass from stars only = 0.4 km/s

Given measured dispersion:
 $10^5 M_{\text{sun}}$ and $M/L = 3400$



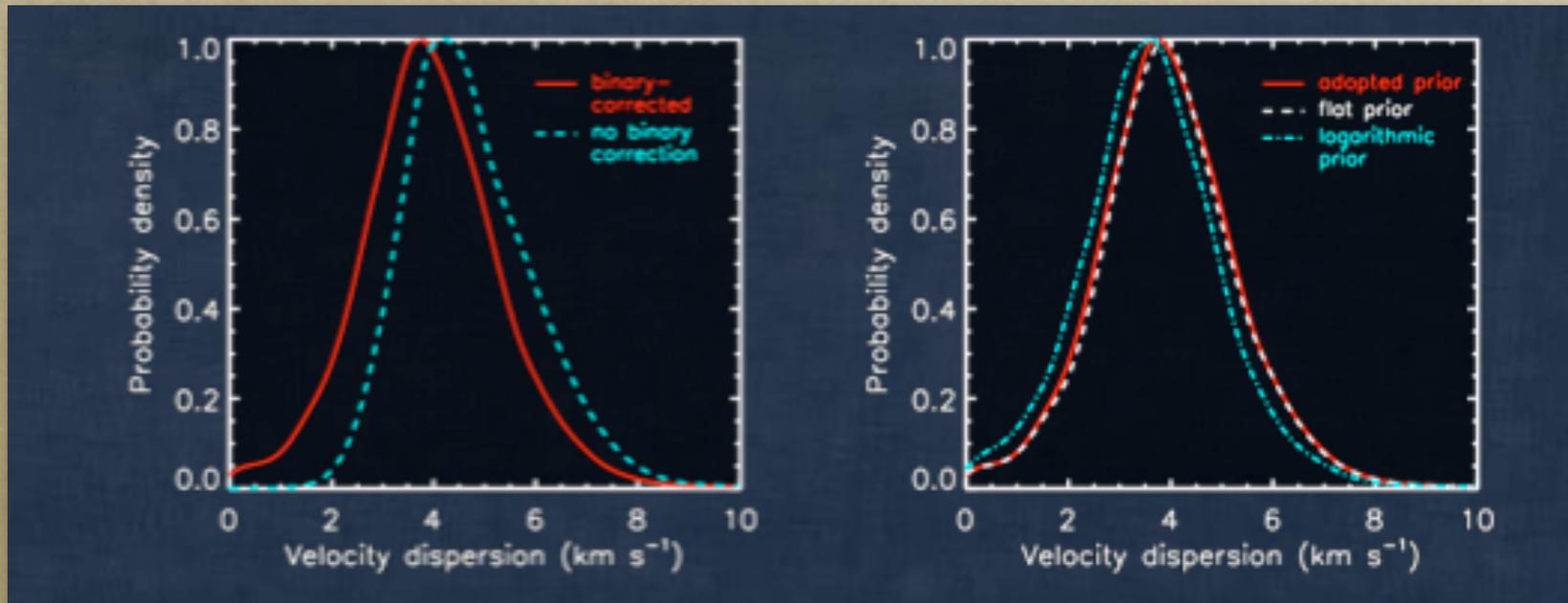
Background stellar streams are well separated in velocity space.

Kinematics of Segue 1

Unresolved binary stars can inflate the measured velocity dispersion.

Repeat velocity measurements over time can constrain contribution.

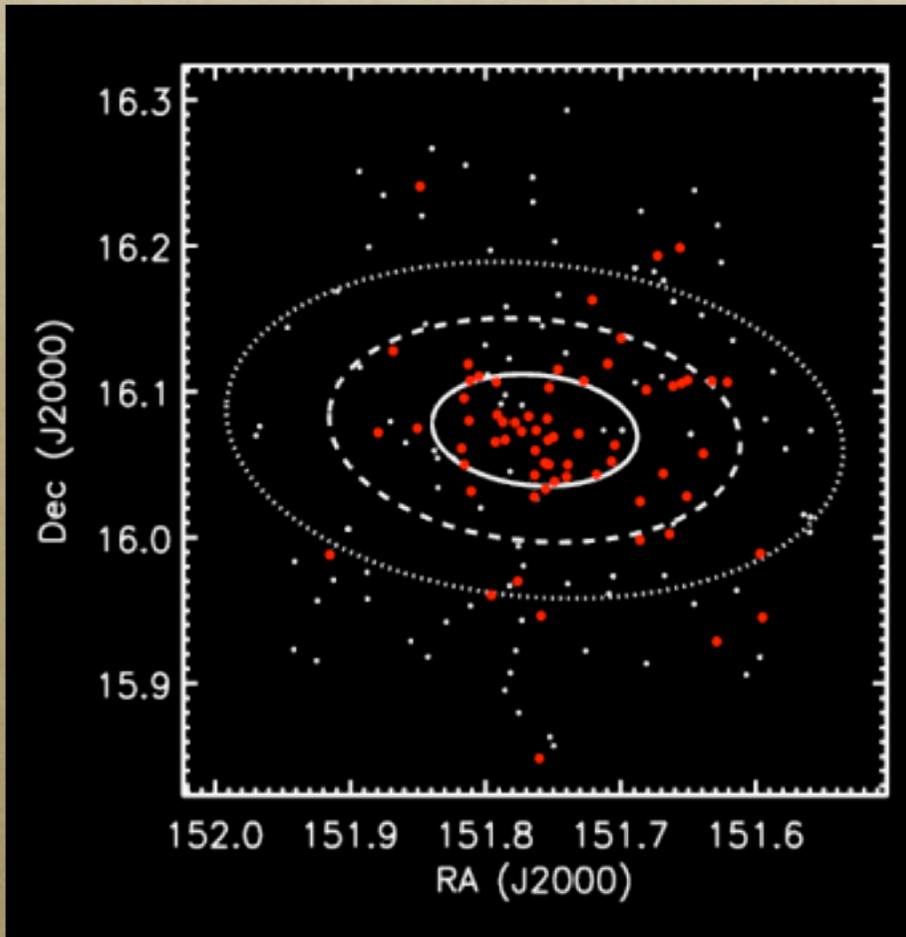
Martinez et al. (2010)



Binary stars contribute ~10% to velocity dispersion.

Kinematics of Segue 1

A complete sample of stars to 60pc: 71 members

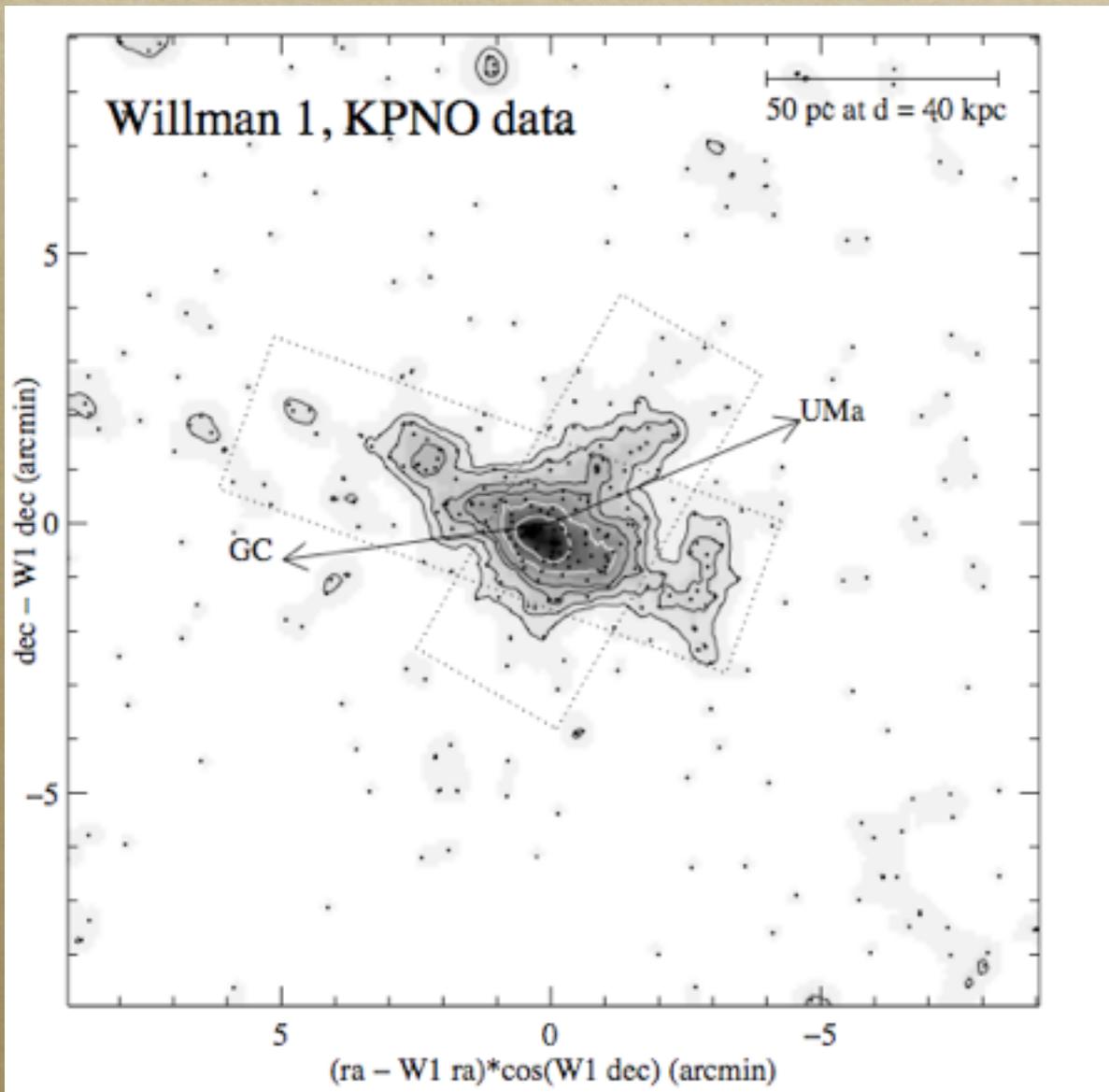


- Signs of tidal disruption?
 - Velocity gradient *no*
 - Excess of stars at large radii *no*
 - Velocity dispersion increasing with radius *no*

No evidence for tidal disruption in Segue 1.

Segue 1 is a dark matter dominated galaxy with mass $10^5 M_{\text{sun}}$ and $M/L = 3400$

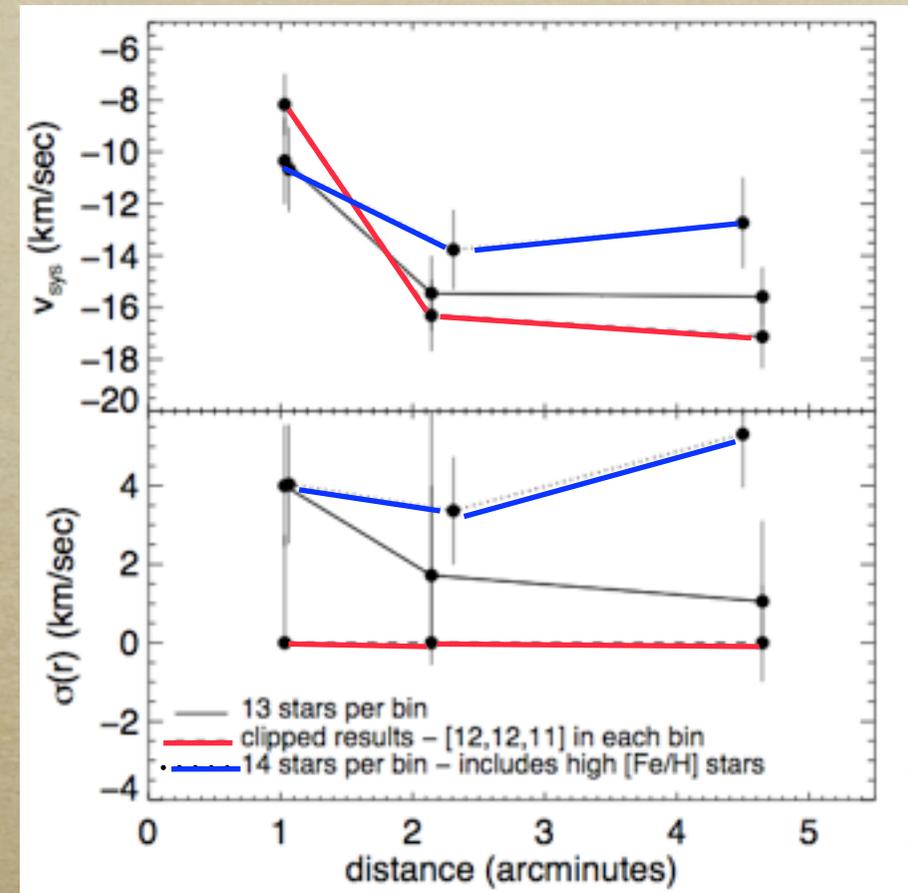
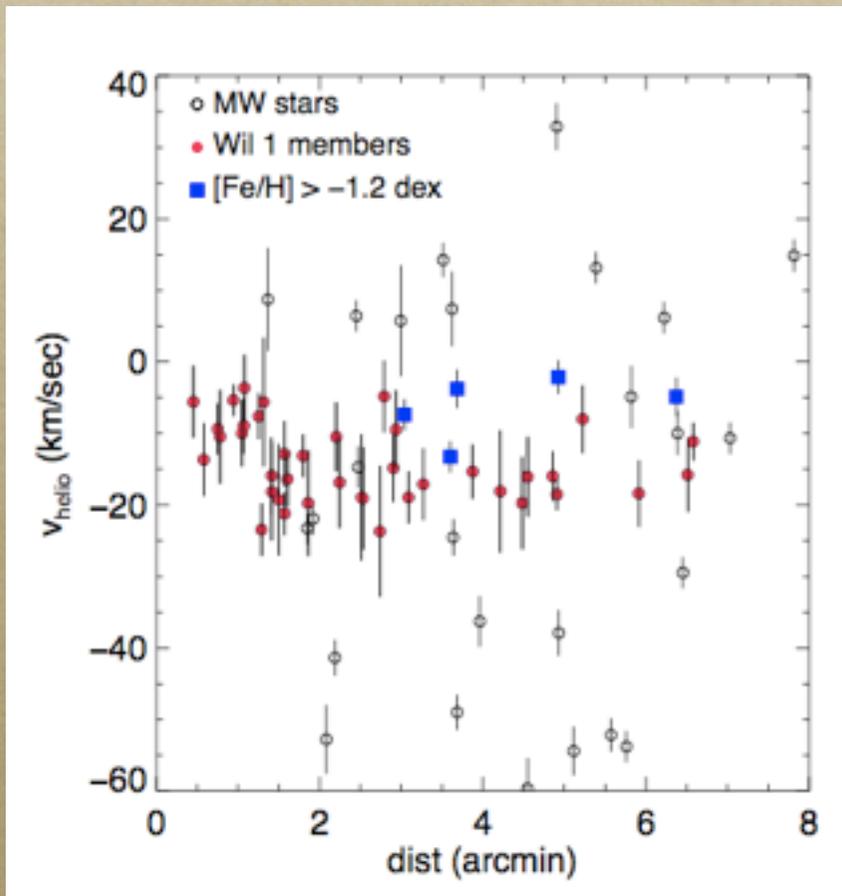
Willman 1: From prototype to “enigmatic halo object”



Willman 1 was first ultra-faint object discovered.

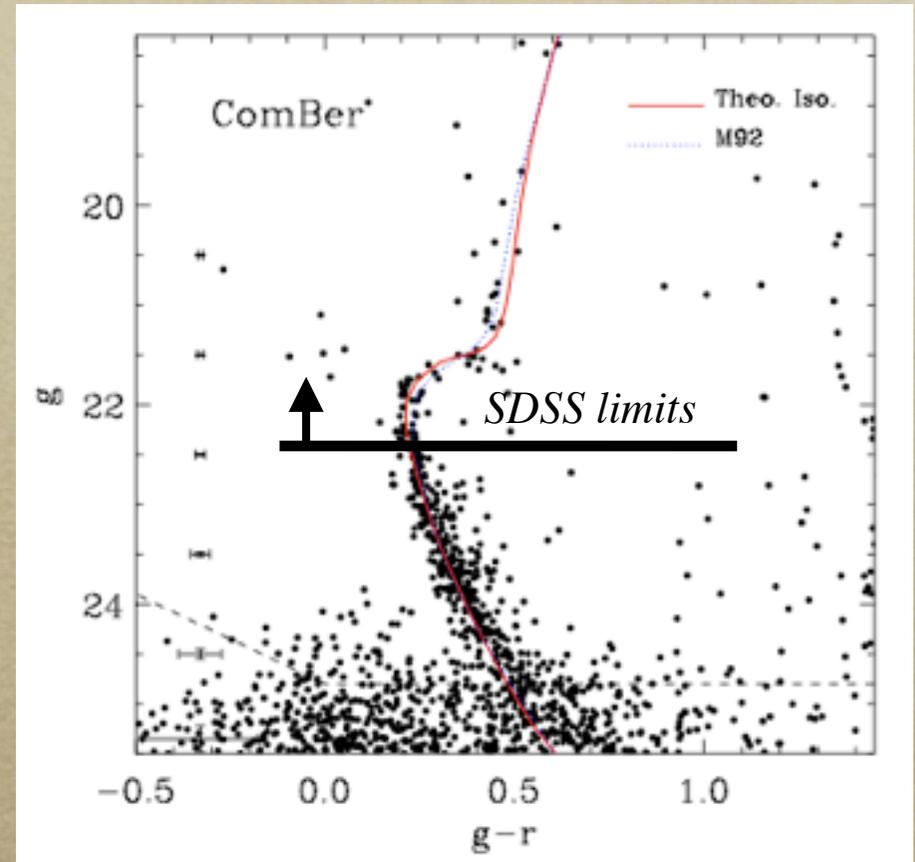
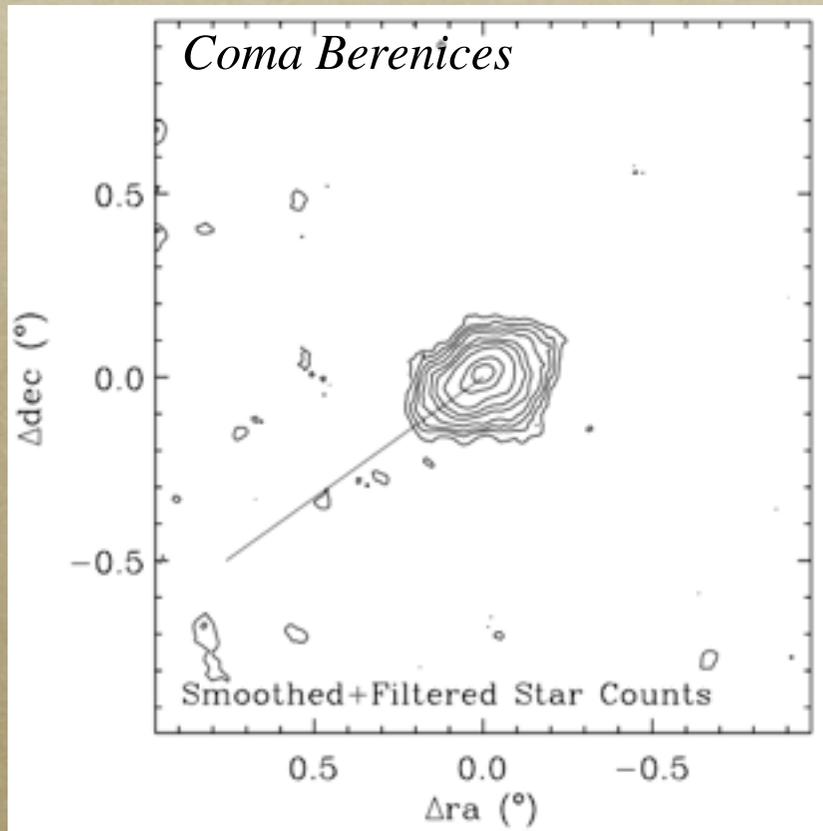
Photometry suggests multiple tidal tails.

Willman 1: From prototype to “enigmatic halo object”



Testing Tidal Stripping Another Way

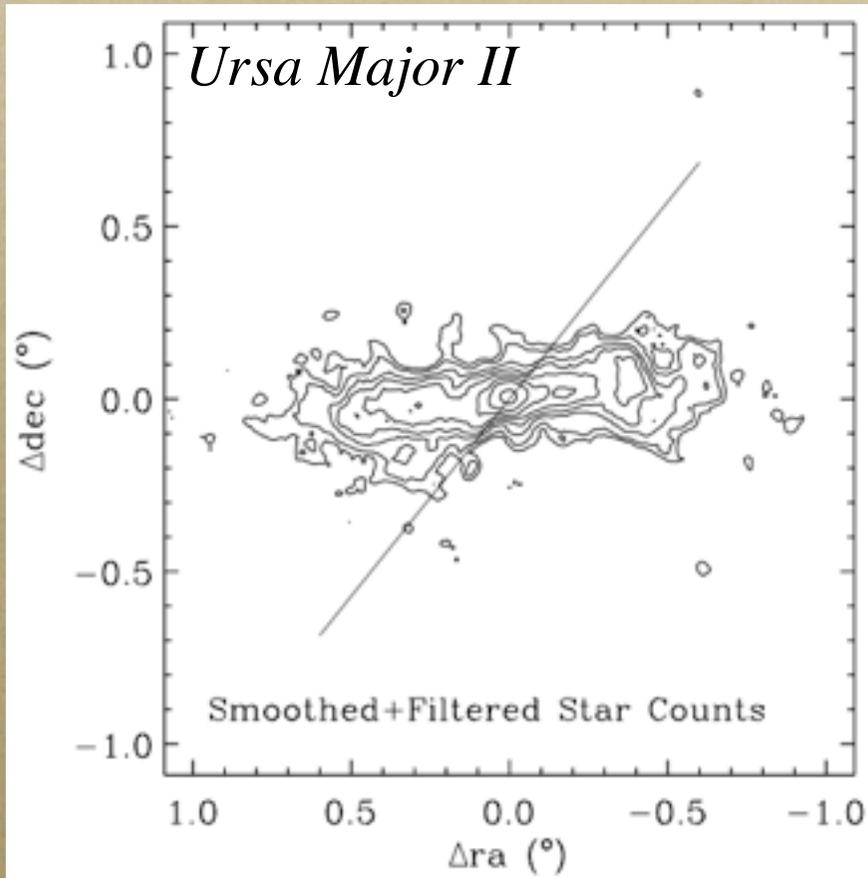
Munoz, MG & Willman (2009): Deep CFHT MegaCam imaging



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

Testing Tidal Stripping Another Way

Munoz, MG & Willman (2009): Deep CFHT MegaCam imaging

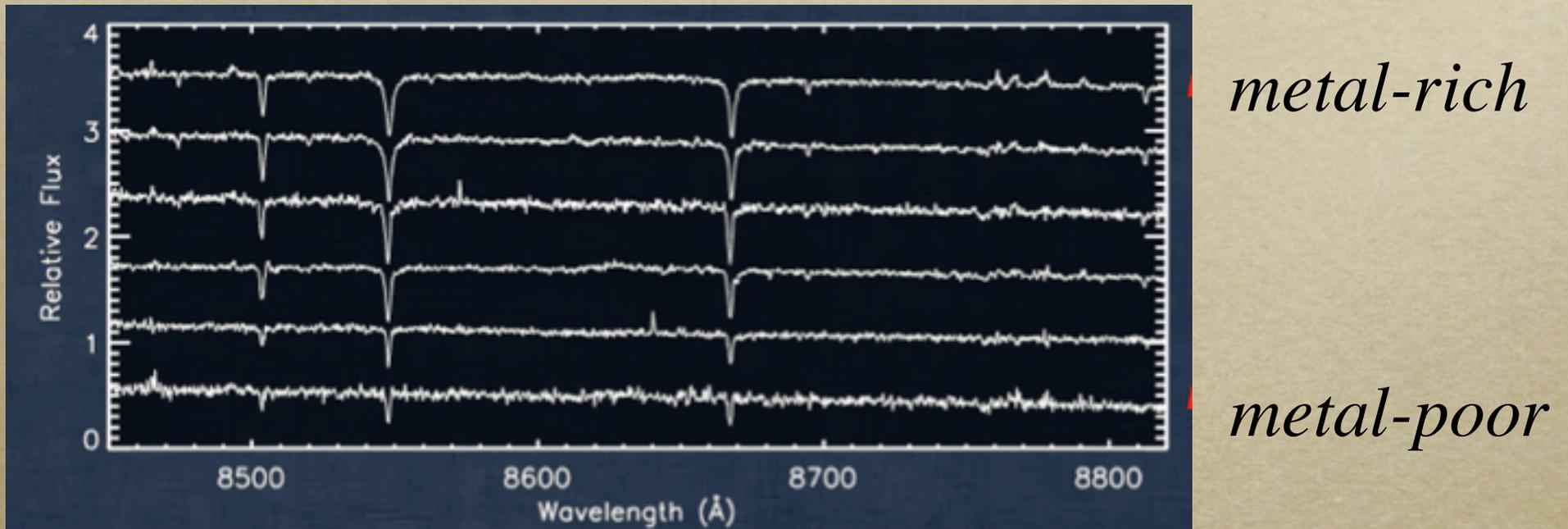


In contrast, UMaII does show evidence for tidal interactions.

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

Metallicity of the Ultra-Faint Galaxies

Spectra of five Segue 1 members



$[\text{Fe}/\text{H}] = -2.5$, internal spread of 1.5 dex.

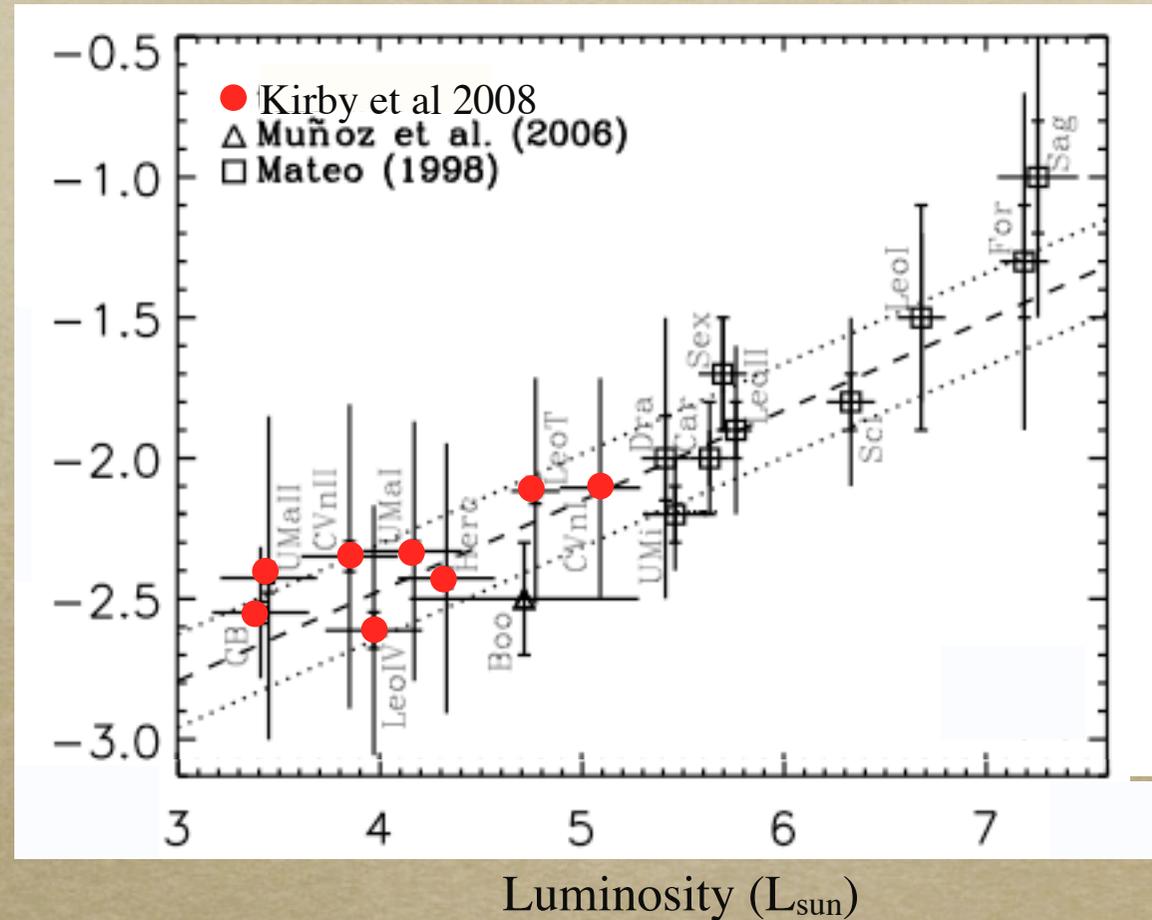
Metallicity of the Ultra-Faint Galaxies

[Fe/H] - L relationship is further evidence that ultra-faints are true galaxies.

The ultra-faint dSphs are most metal-poor stellar systems known.

Significantly larger internal abundances spreads as compared to globular star clusters.

[Fe/H]



Ultra-Faint Galaxy Round-up

Equilibrium galaxies
(good indirect DM targets)

Disrupting systems?
(not recommended)

Segue 1

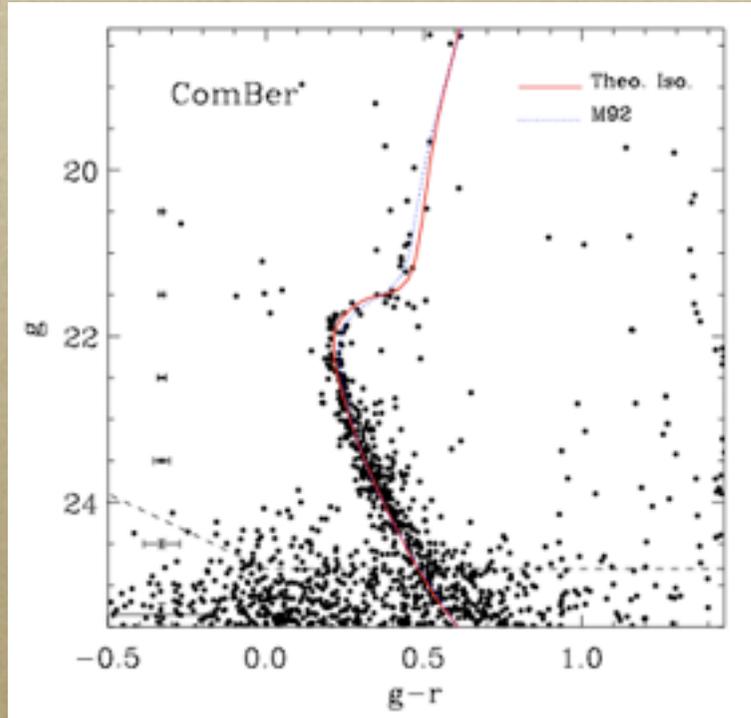
Willman 1

Coma Berenices

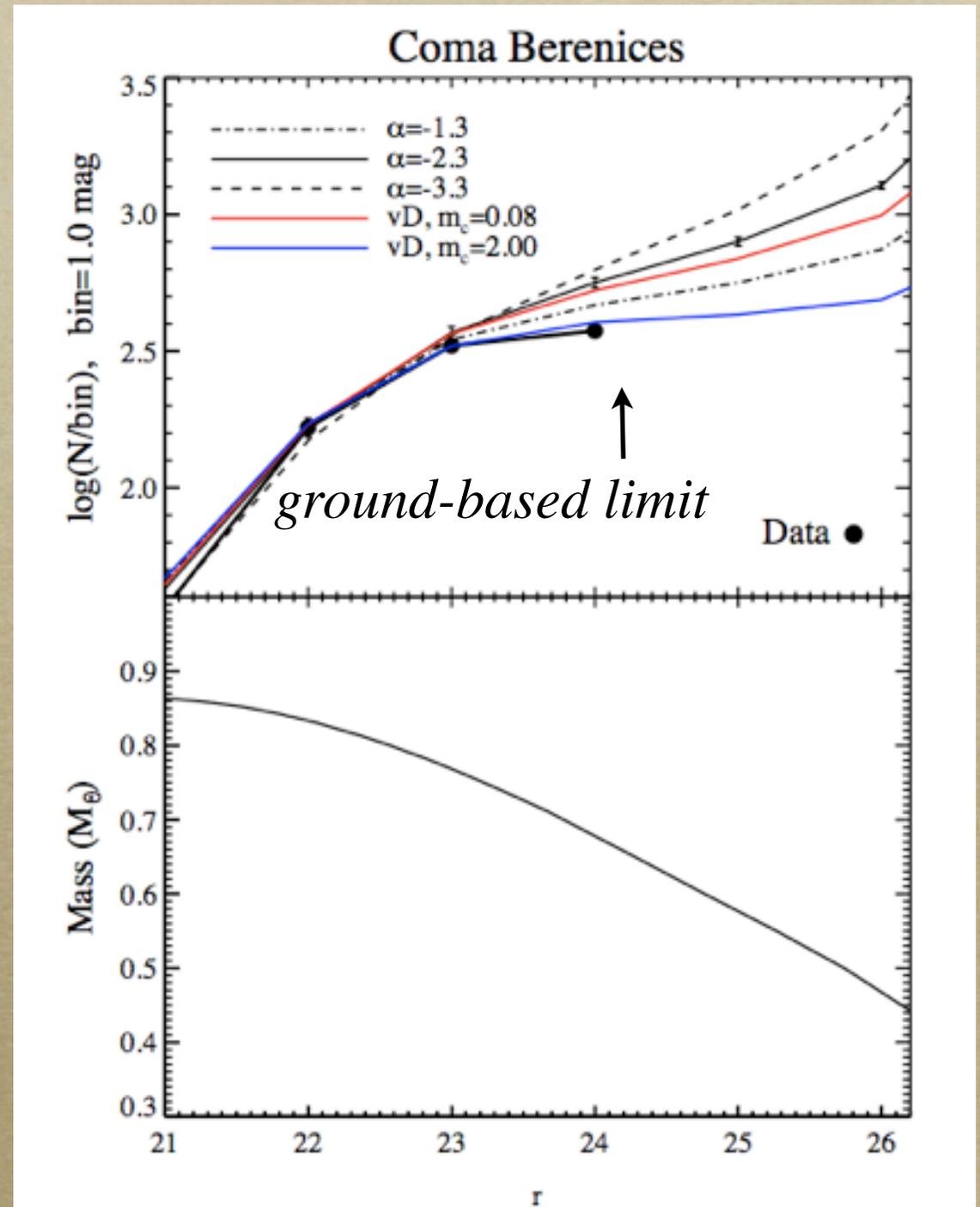
Ursa Major II

(Bootes II)

Stellar Populations + the IMF

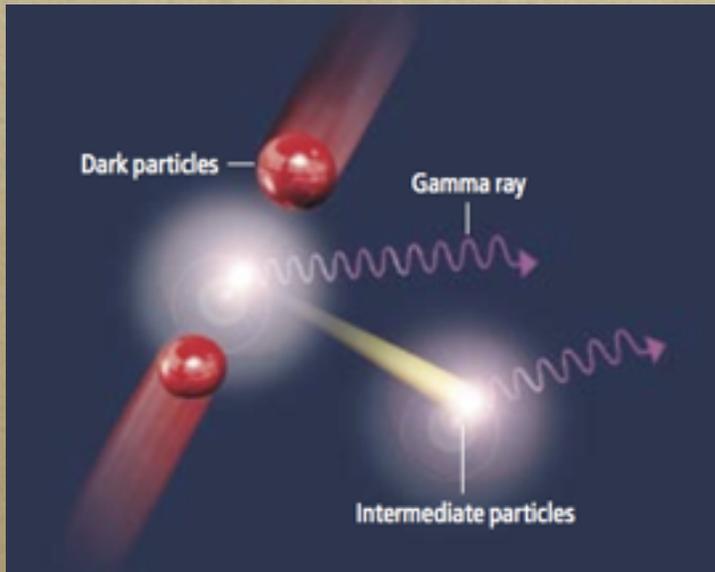


Stellar populations are old,
consistent with spectroscopic
metallicities.

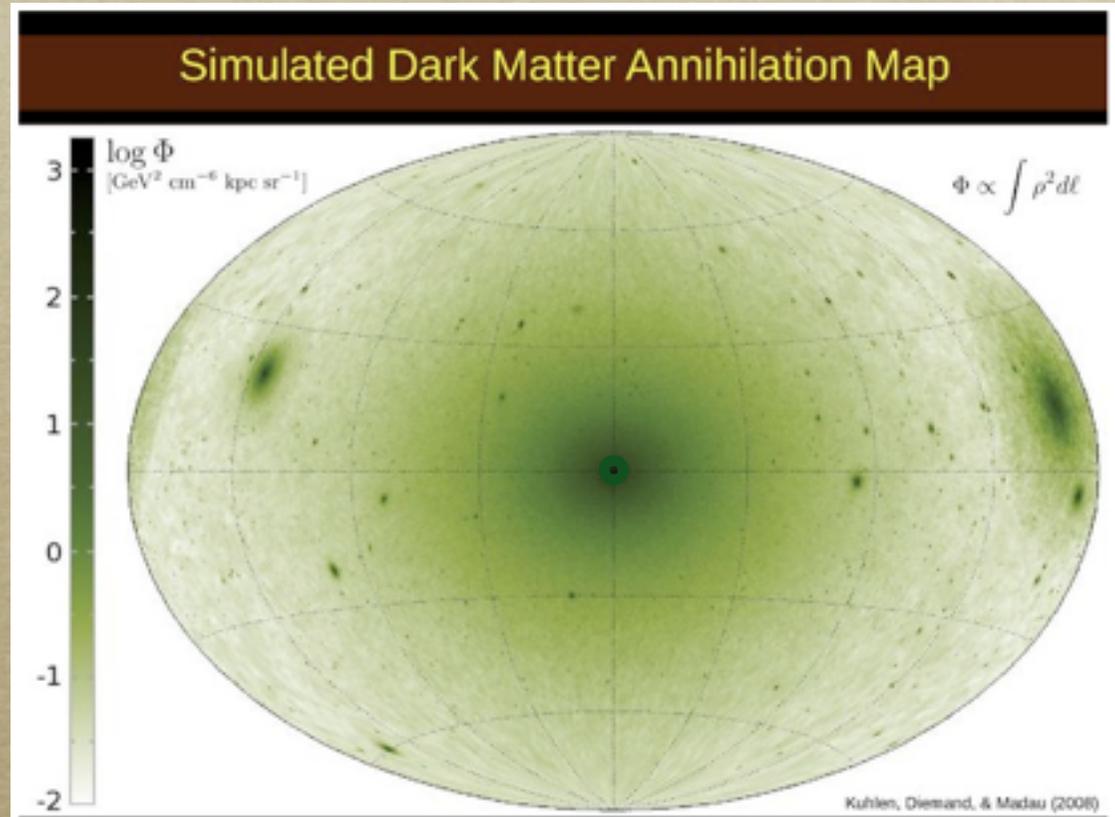


Indirect Dark Matter Detection

SUSY dark matter particles occasionally annihilate to produce observable γ -rays.



Ultra-faints are promising sites for detecting annihilation signal.



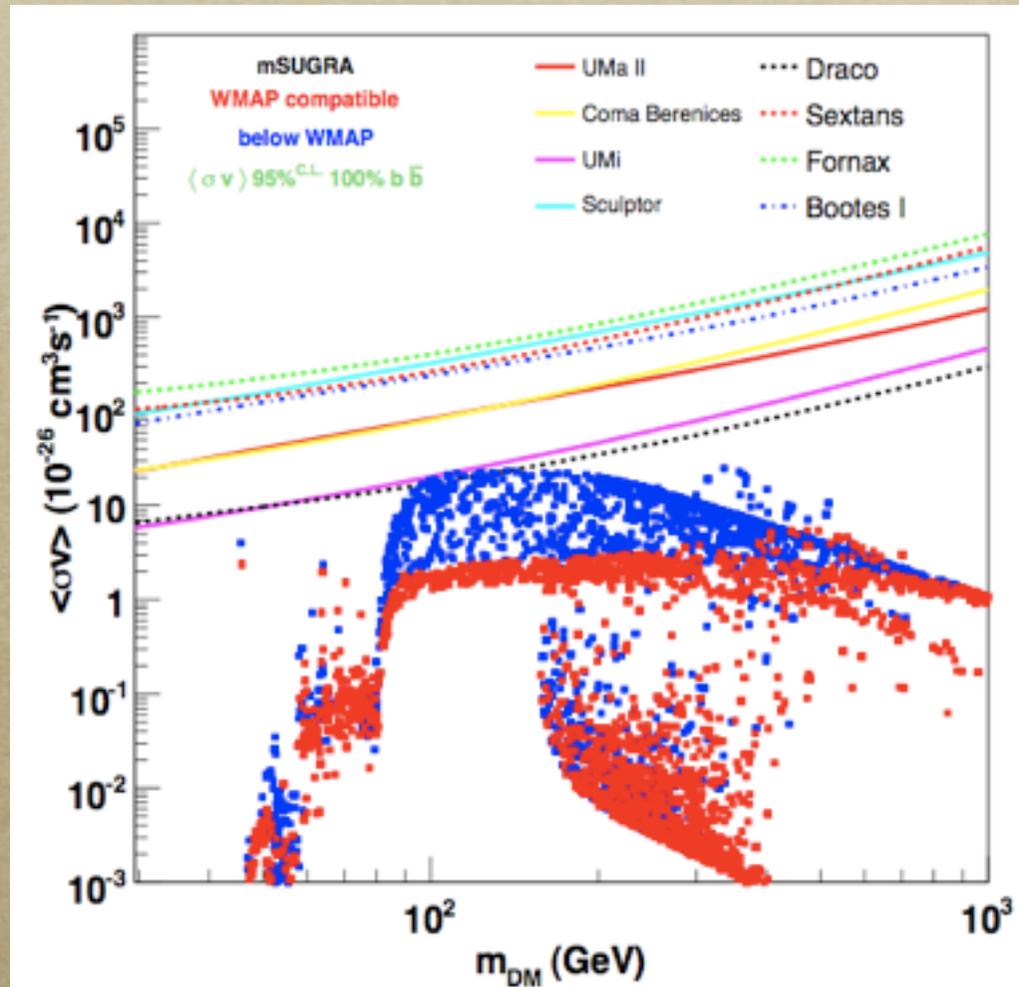
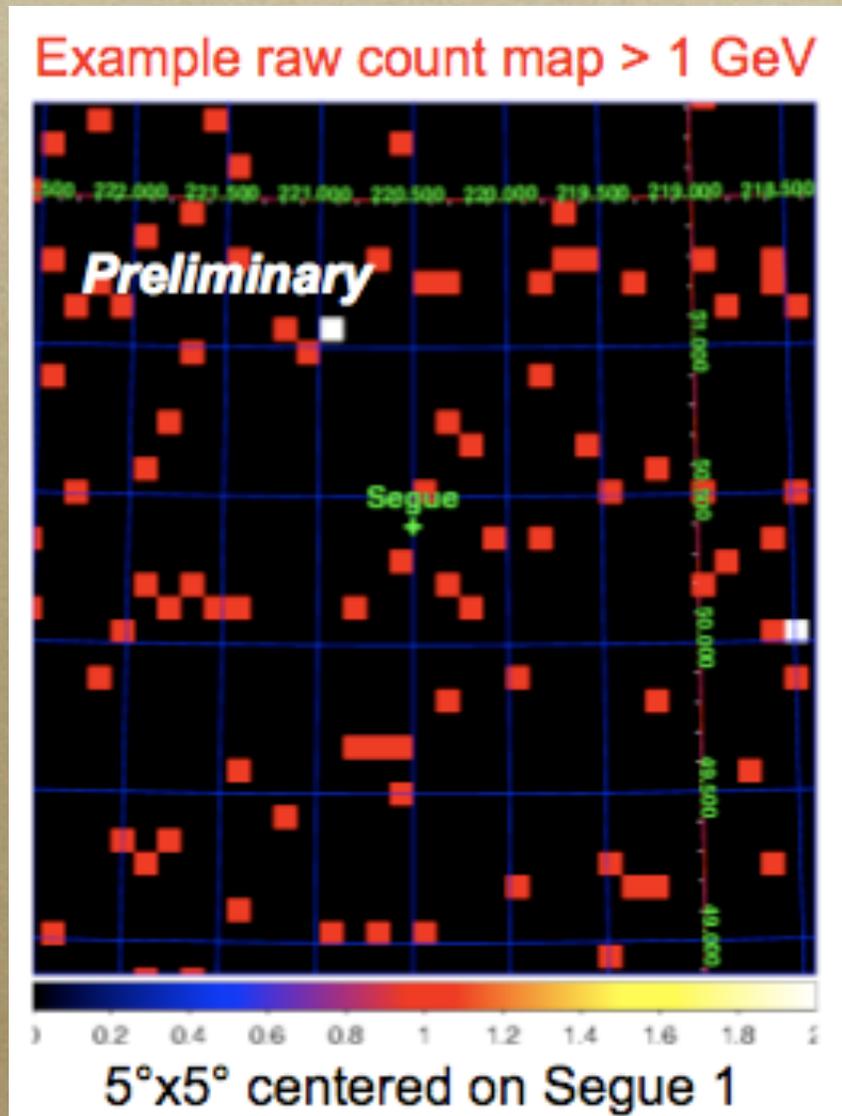
Kuhlen et al. (2008)

Essig, MG, et. al. (2010)

Indirect Dark Matter Detection

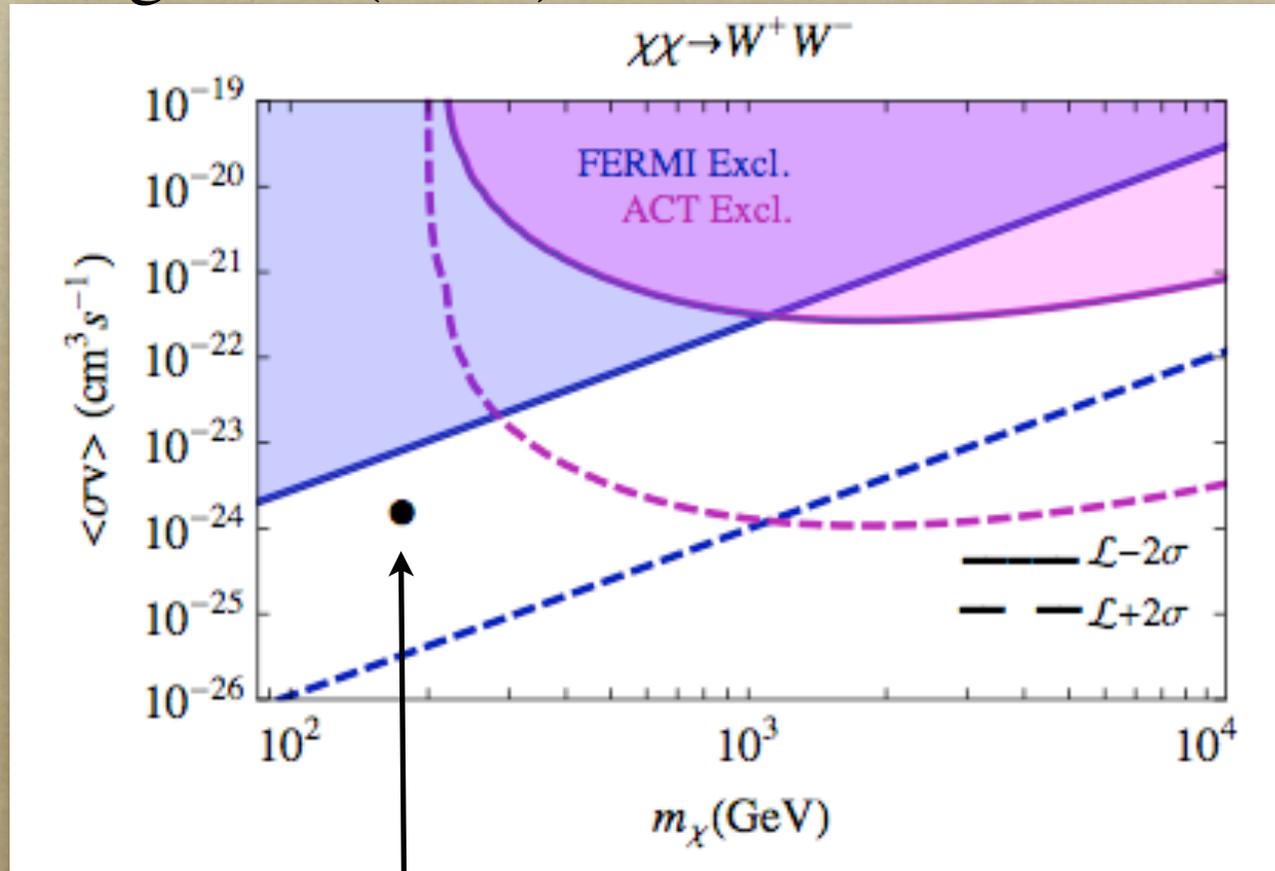
No satellites detected in
9-month Fermi data.

Abdo et al 2010



Indirect Dark Matter Detection

Essig et al. (2010)



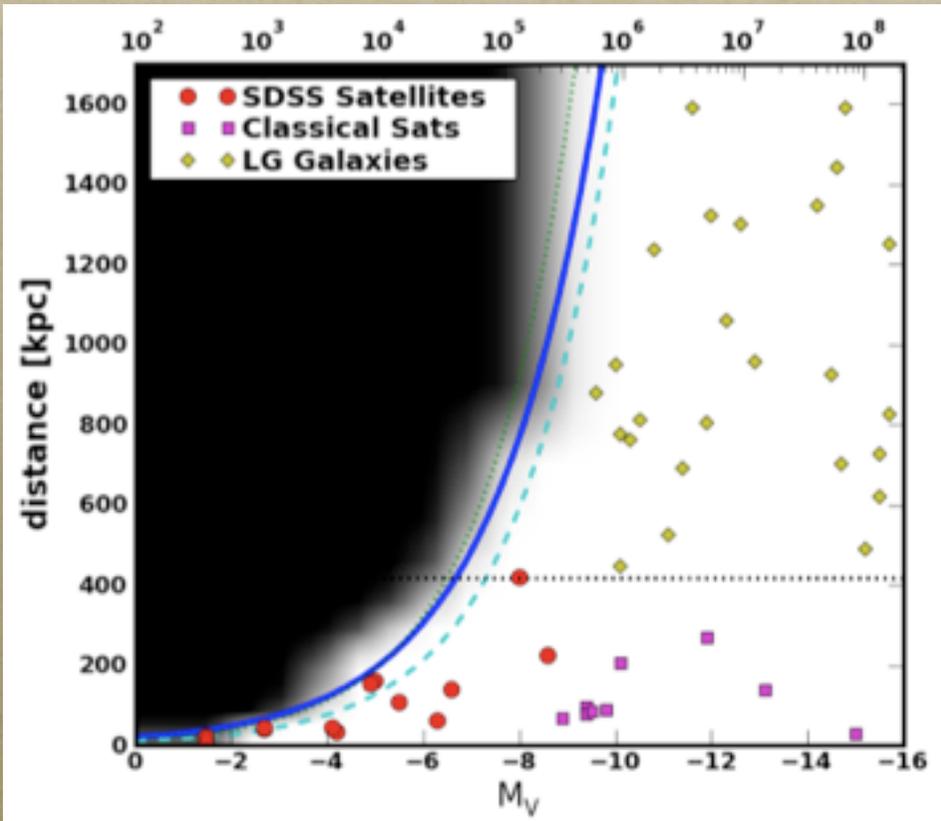
Segue 1 mass +
Fermi upper limits

Segue 1 mass +
MAGIC upper limits

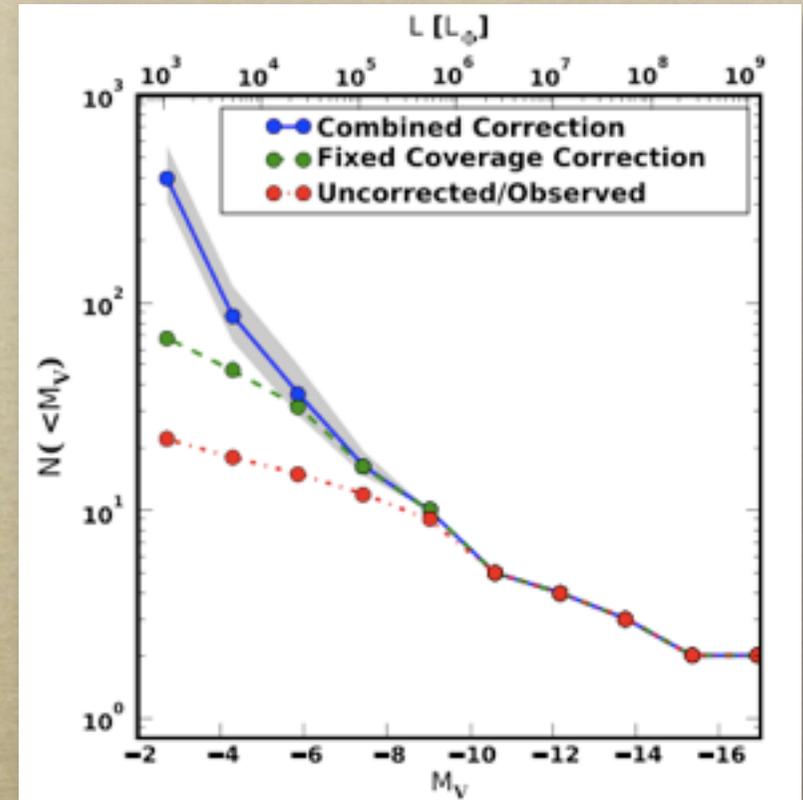
wino-like neutralino which can
explain Pamela results.

Finding New Milky Way Satellites

Tollerud et al. (2008)



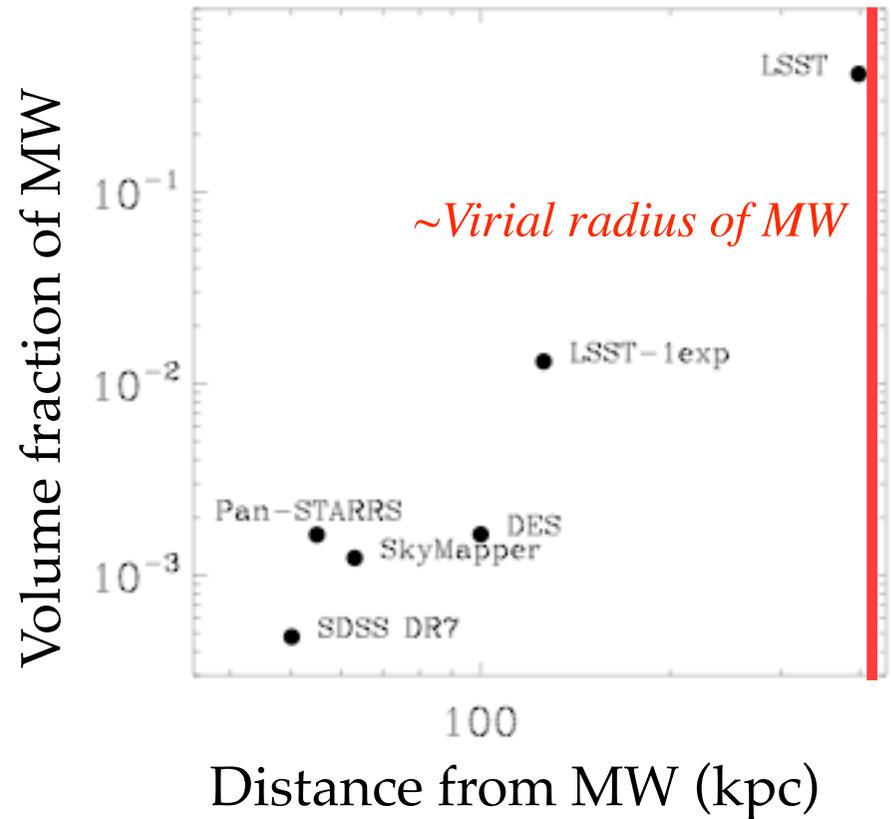
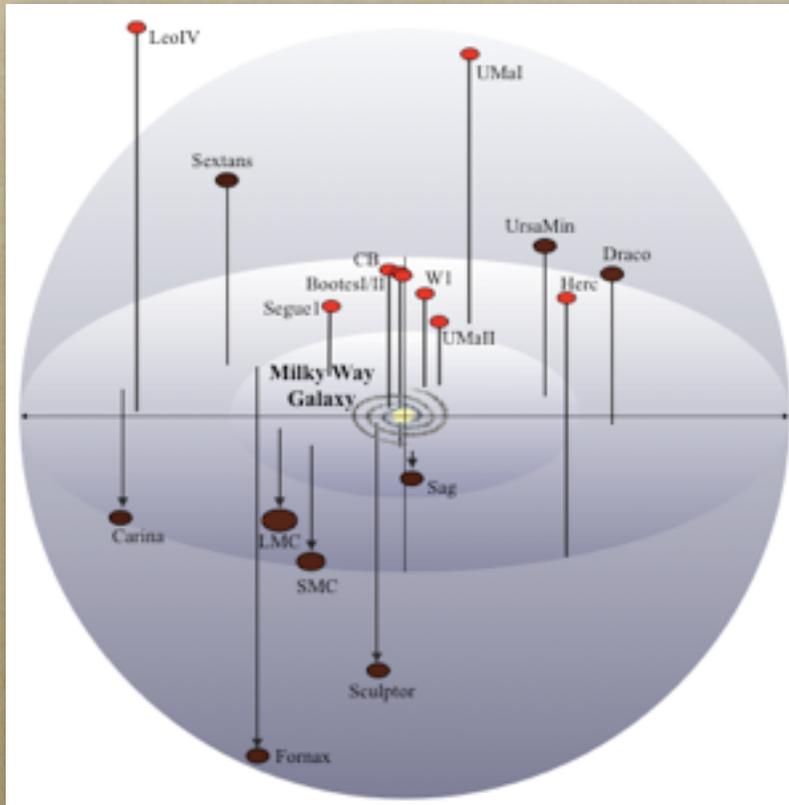
M_V



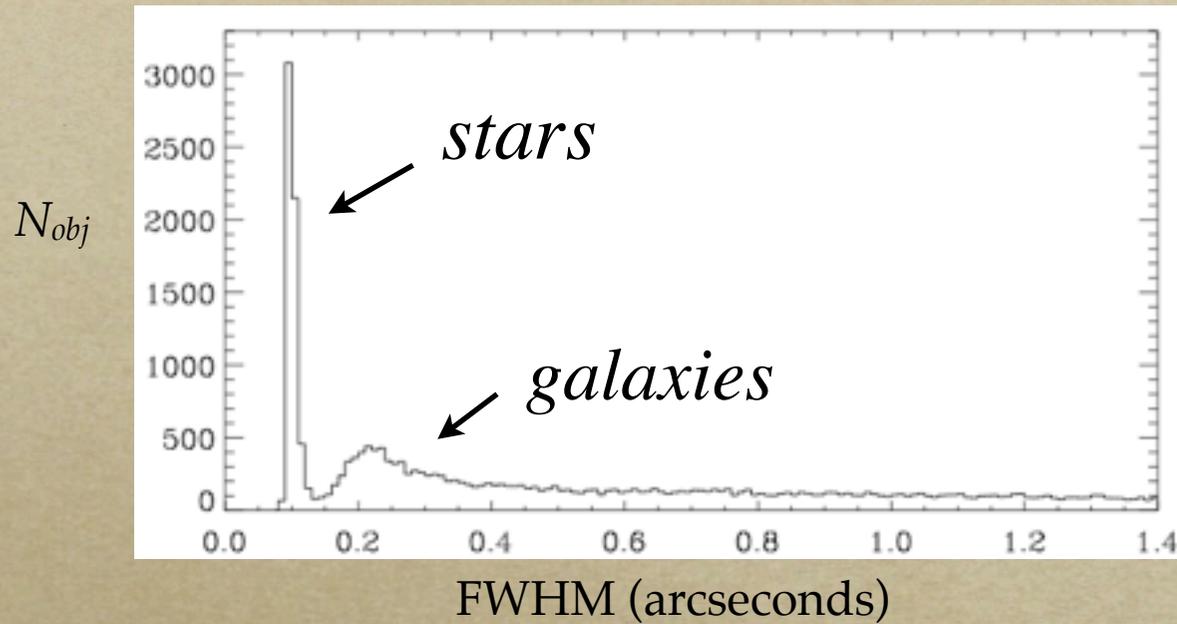
Predictions suggest at most 1 dwarf galaxy per 100 square degrees

Finding New Milky Way Satellites

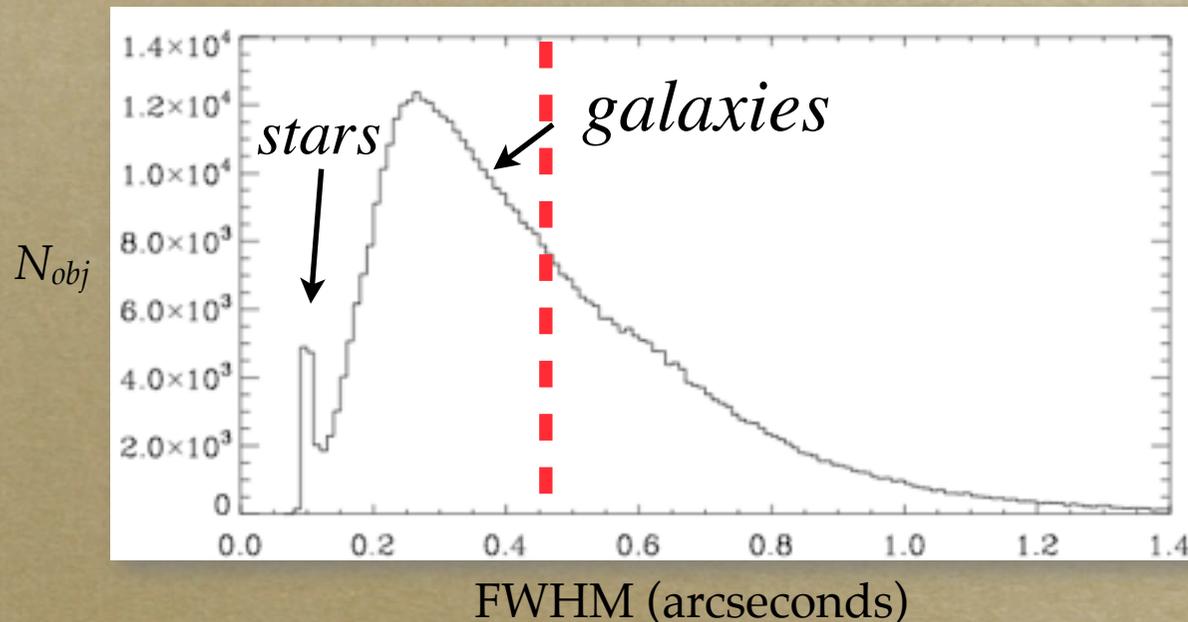
Want to match number and radial distribution of satellites in Milky Way.



Finding New Milky Way Satellites

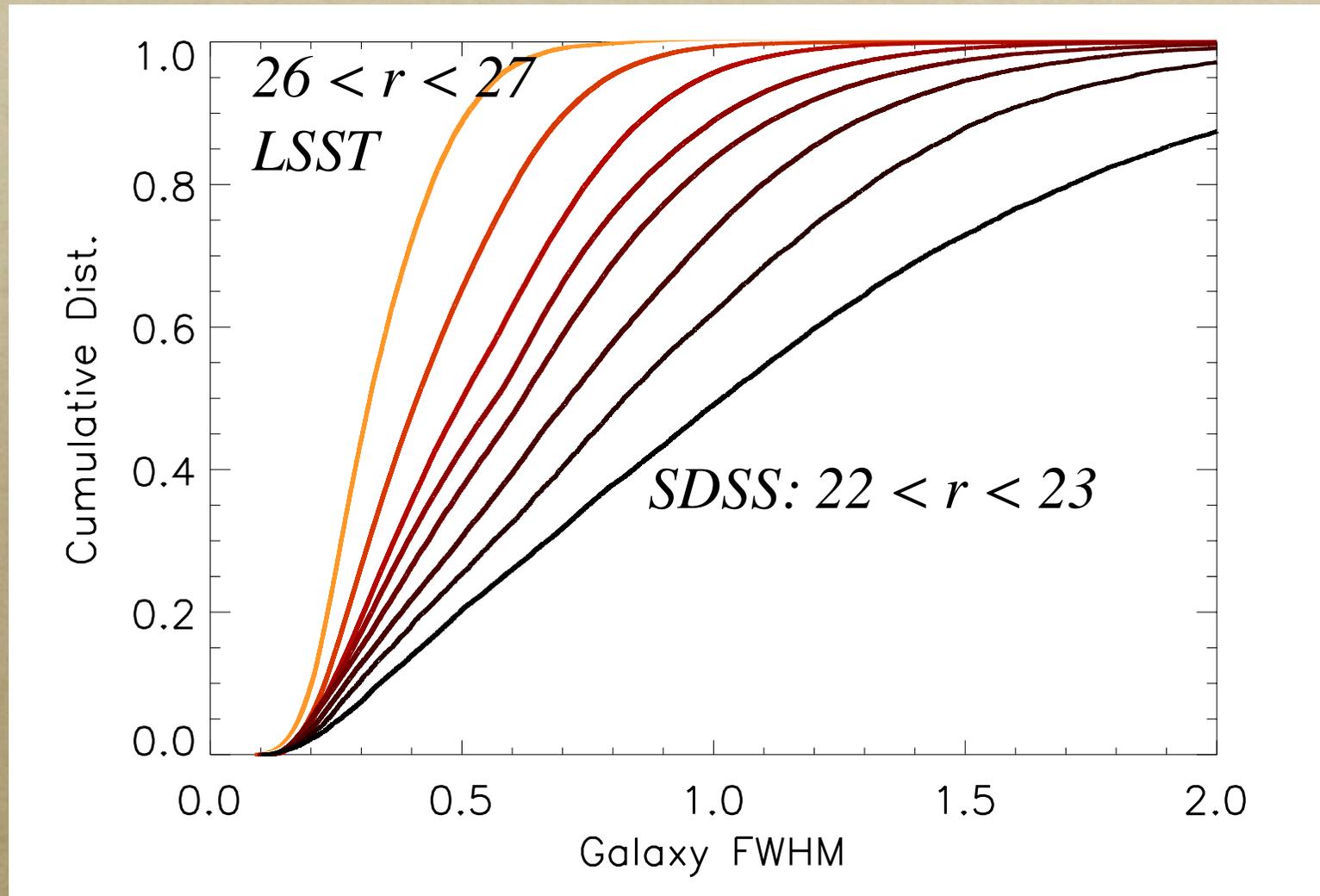


SDSS depths
 $r < 23$



LSST depths
 $26 > r > 25$

Finding New Milky Way Satellites

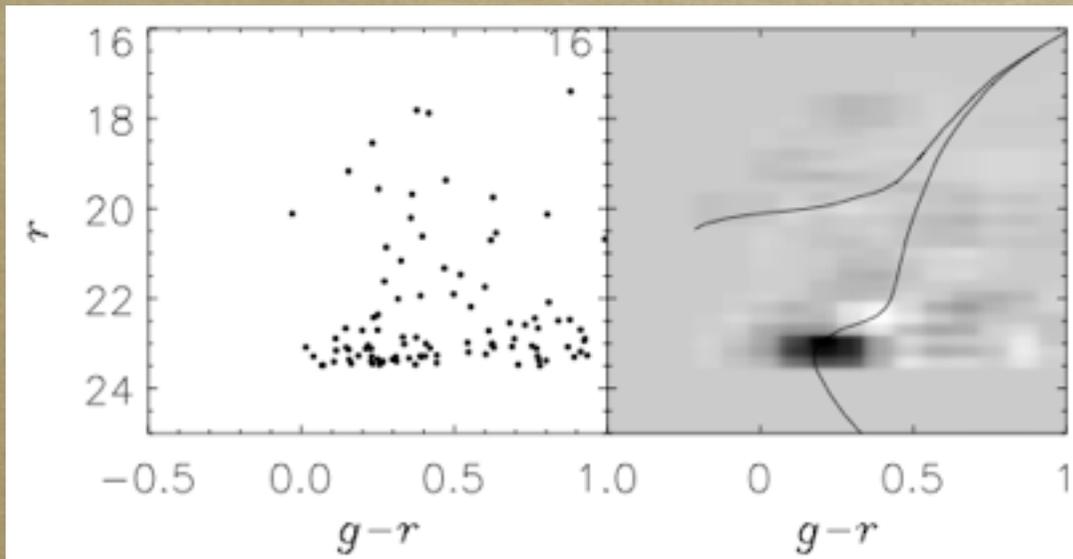
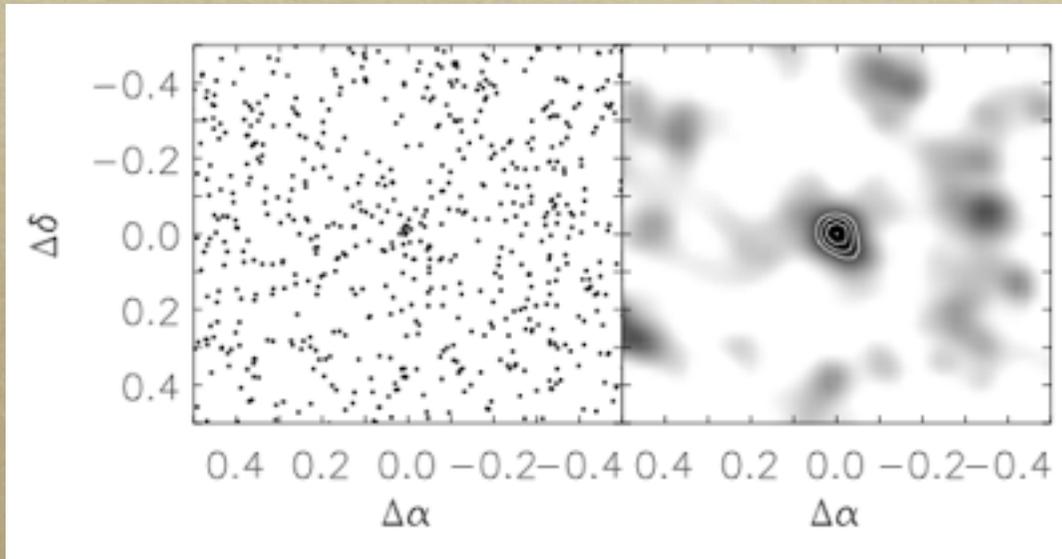


plot from R. Fadely

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Completed search of RCS2/CFHLS survey:
800 sq degrees, $r \sim 24$

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Complete census of Milky Way satellite population will be challenging!

Conclusions

The ultra-faint dwarfs are extreme in every sense:

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

The ultra-faint dwarfs are good probes of dark matter:

- Luminosity/mass function constraints (the missing satellite problem)
- Good targets for indirect dark matter detection experiments (Fermi, ACTs)

