The Darkest Galaxies

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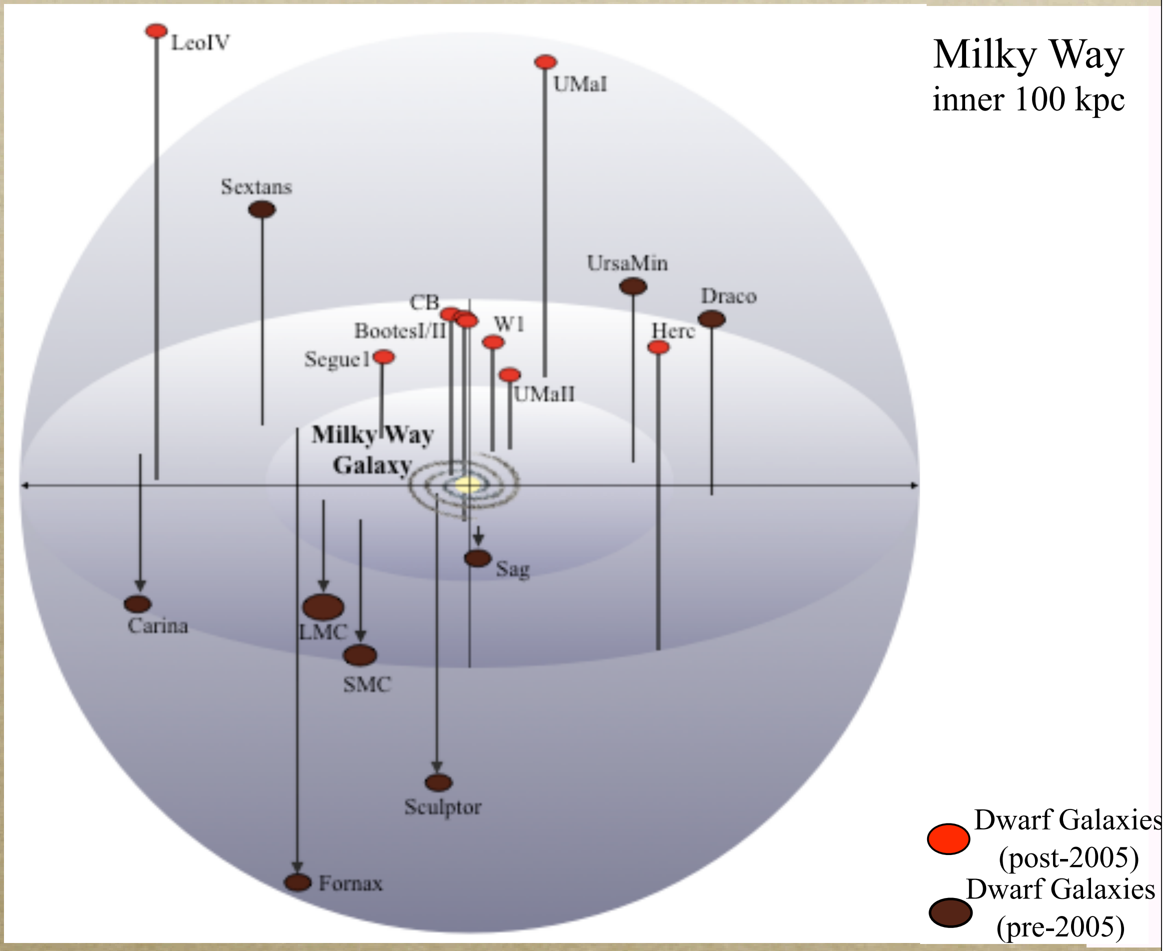
- Louie Strigari (Stanford)
- James Bullock (UCI)
- Manoj Kaplinghat (UCI)
- Joe Wolf (UCI)


Milky Way
inner 100 kpc

Introduction to Dwarf Galaxies

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

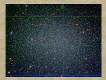
Dwarfs with gas

Dwarfs without gas

$M_V = -16$

SDSS dwarf

$M_V = -12$



Leo I

Leo T

$M_V = -6$

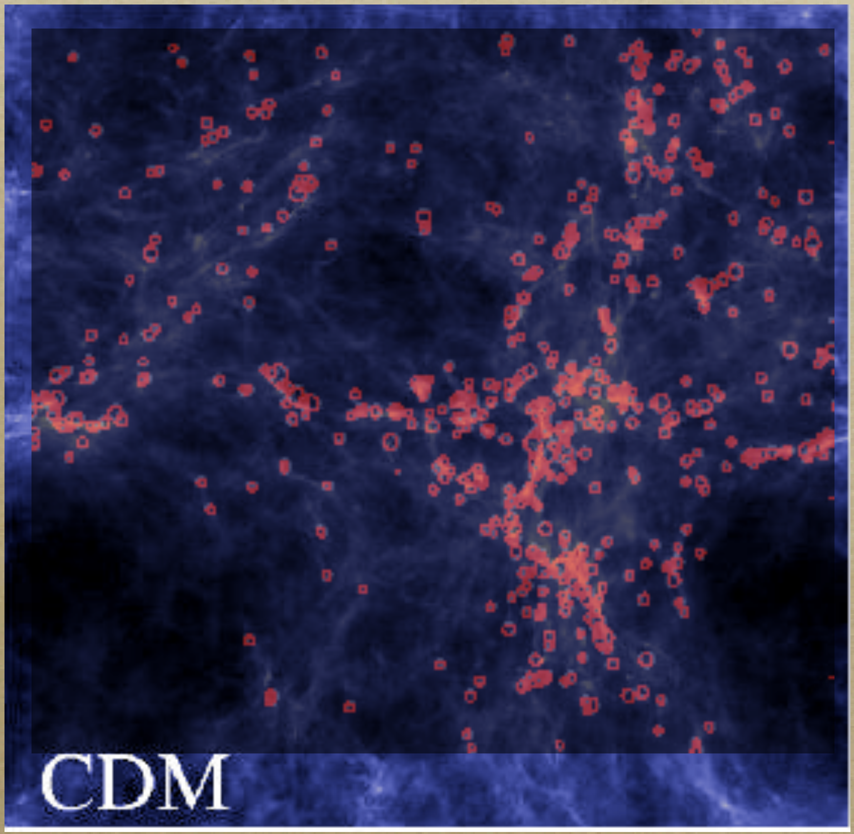
UMa I

Dwarf Galaxies as Probes of Dark Matter

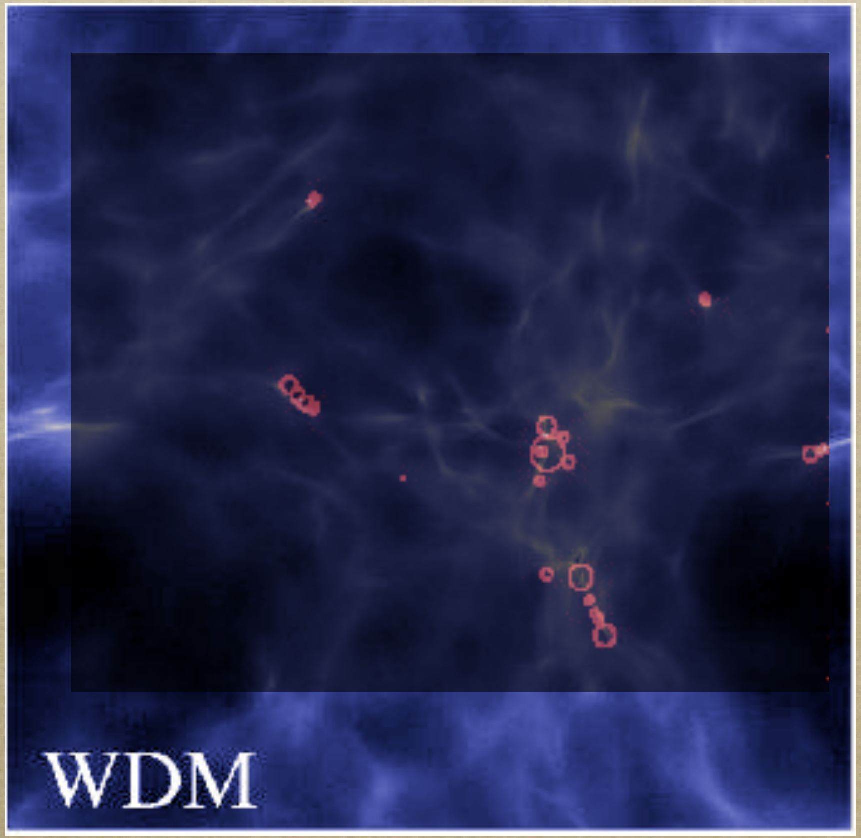
In hierarchical galaxy formation, low mass objects collapse first and merge to create larger structures.

○ = *objects* > $10^5 M_{sun}$

Gas distribution 1Mpc box @ z=17 **(*Yoshida et al.* 2003)**



Cold Dark Matter simulation

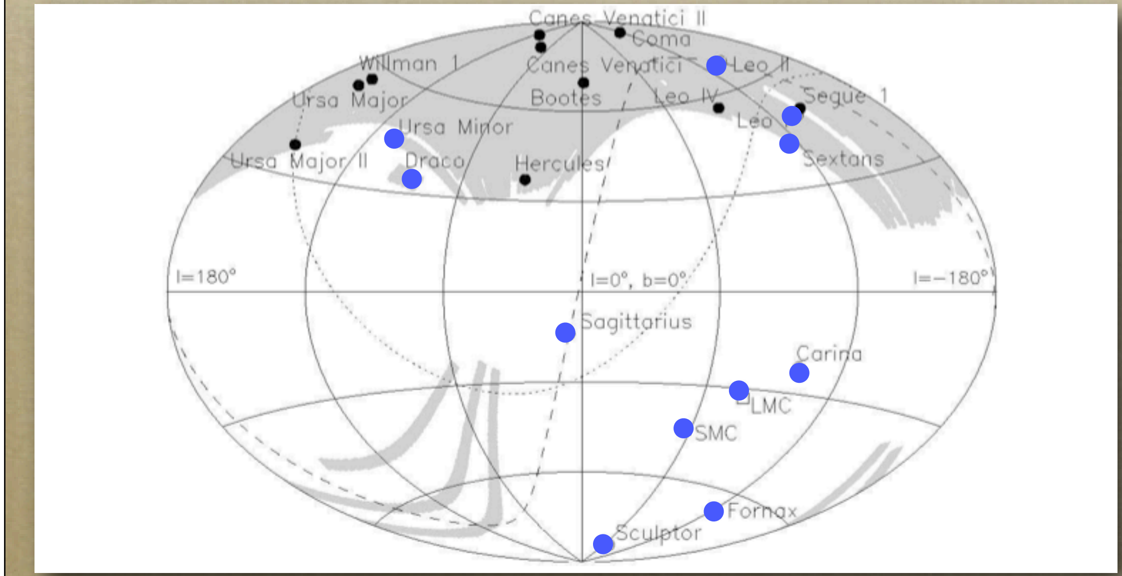


Warm Dark Matter (m_x = 10 KeV)

● The number of low mass objects provide strong constraints on cosmology. ●

The Milky Way Satellite Census

▨ *Sloan Digital Sky Survey (SDSS) coverage*



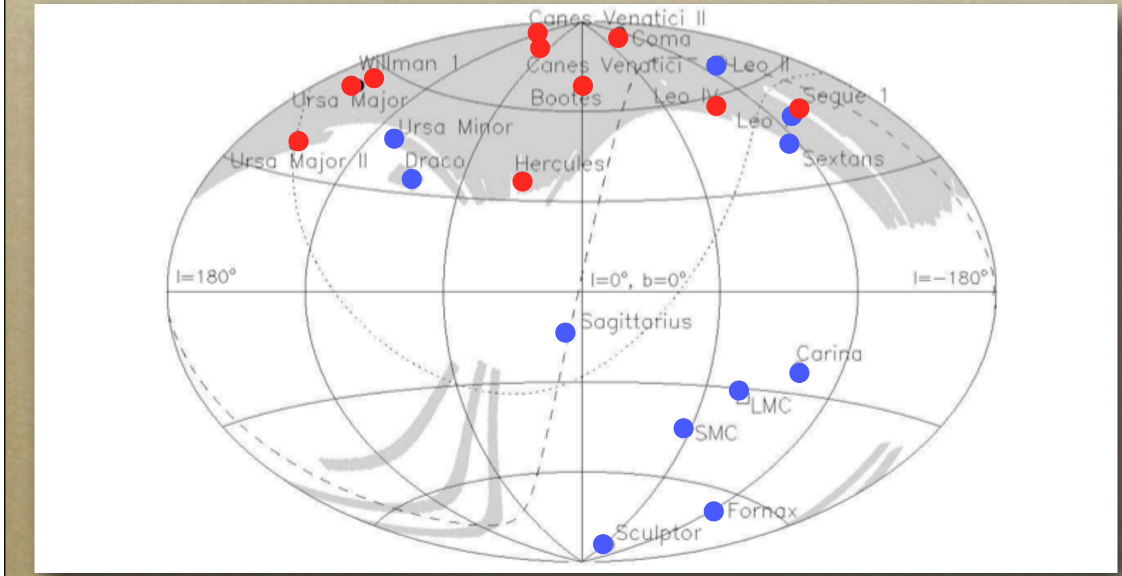
Name	**Year Discovered**
LMC	*B.C*
SMC	*B.C*
Sculptor	*1937*
Fornax	*1938*
Leo II	*1950*
Leo I	*1950*
Ursa Minor	*1954*
Draco	*1954*
Carina	*1977*
Sextans	*1990*
Sagittarius	*1994*

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

Name	Year Discovered
LMC	*B.C*
SMC	*B.C*
Sculptor	*1937*
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Leo II	*1950*
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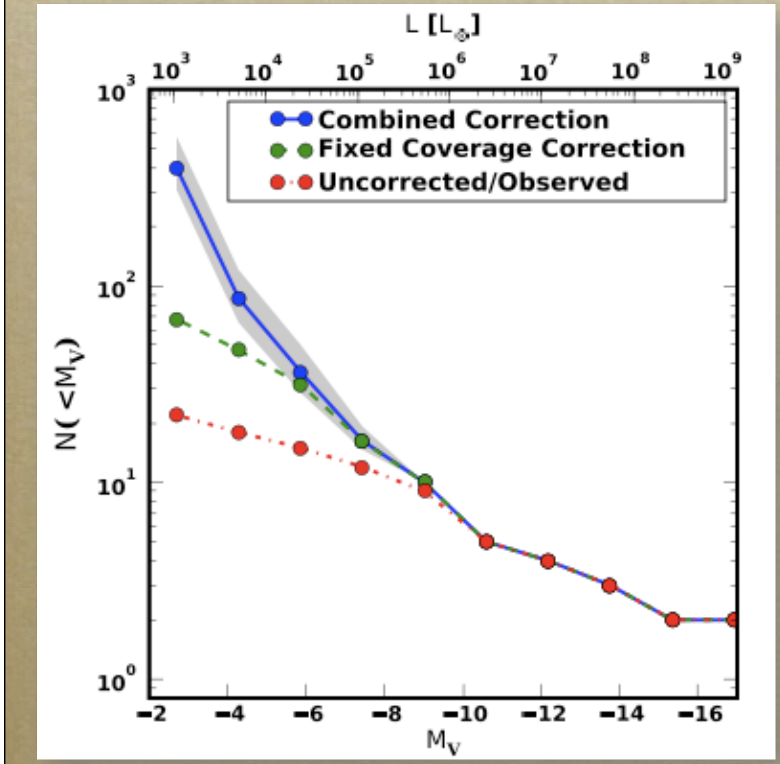
Draco	*1954*
Carina	*1977*
Sextans	*1990*
Sagittarius	*1994*
Ursa Major I	***2005***
Willman I	***2005***
Ursa Major II	***2006***
Bootes I	***2006***
Canes Venatici I	***2006***
Canes Venatici II	***2006***
Coma Berencies	***2006***
Segue I	***2006***
Leo IV	***2006***
Hercules	***2006***
Leo T	***2007***
Bootes II	***2007***
Leo V	***2008***
Segue II	***2009***

Willman et al (2005a,b) Zucker et al (2006a,b), Belokurov et al (2006a,b,2009), Irwin et al (2007),Walsh et al. (2007)

The Milky Way Satellite Census



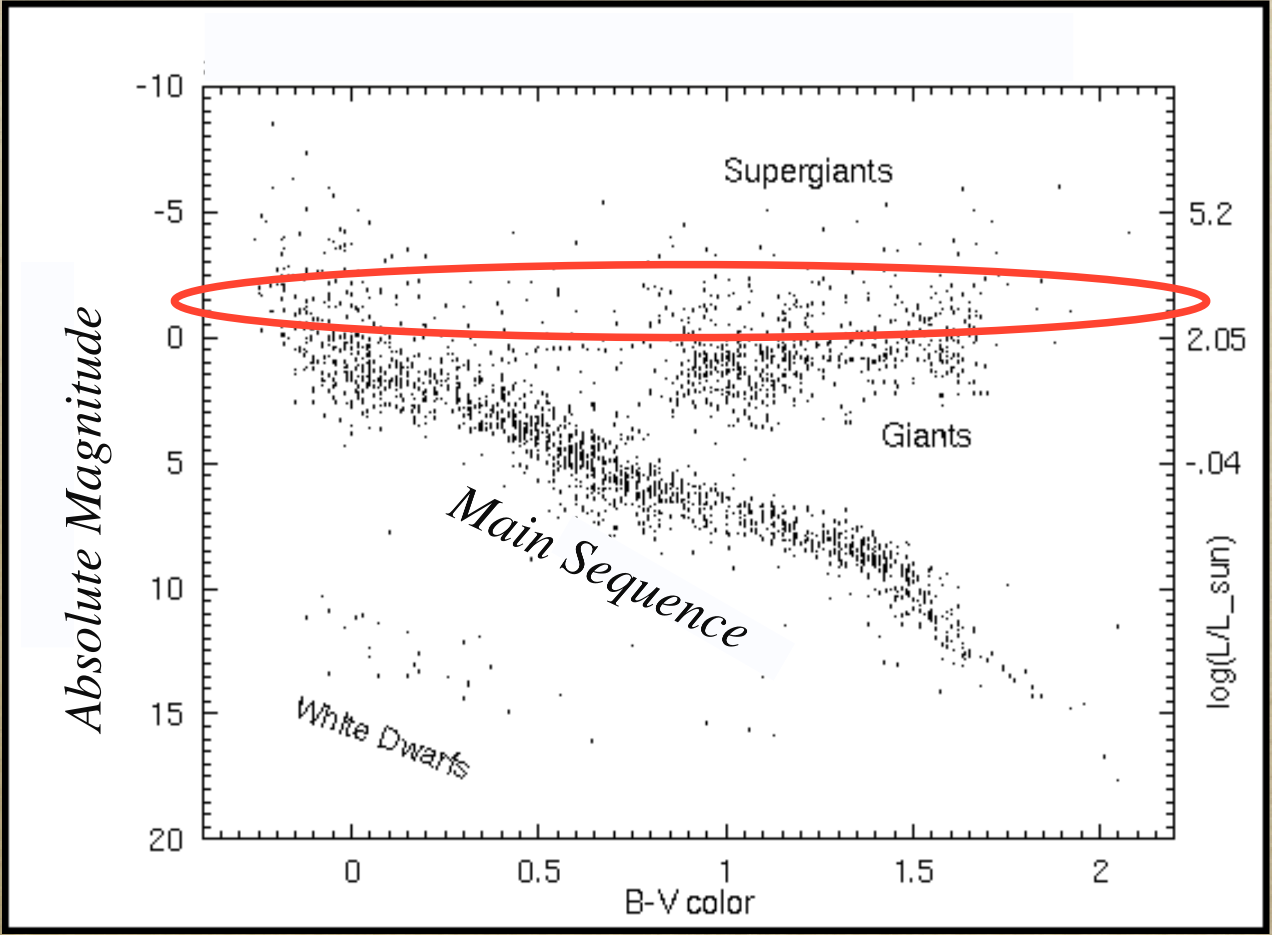
Tollerud et al. (2008)

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 ΛCDM
      “the missing satellite issue”
c) ***Particle Physics***:
   Indirect dark matter detection

SIDE NOTE: These objects are faint!

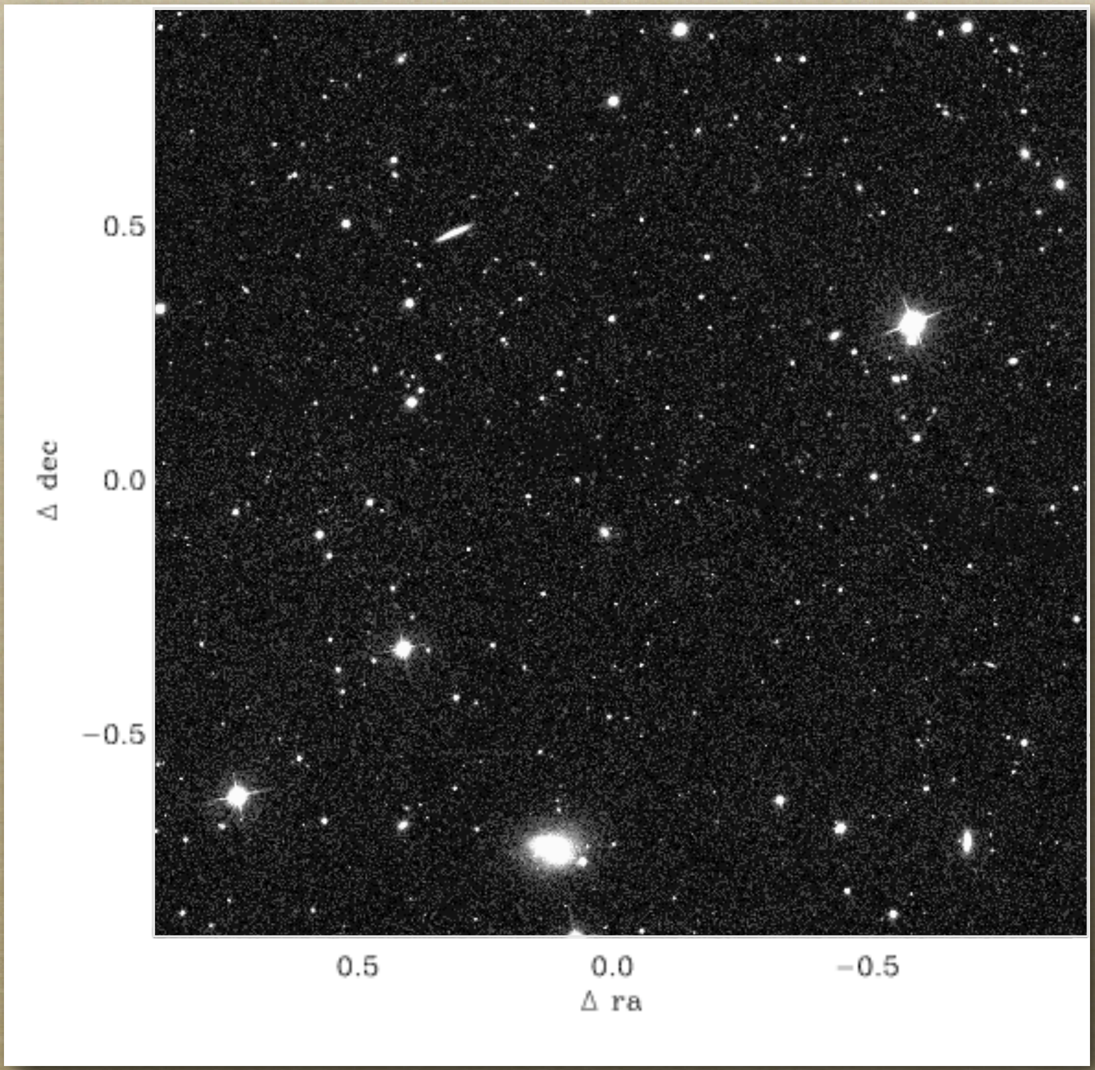


The total luminosity of Segue 1 ($M_V \sim -1.5$) is less than a SINGLE luminous star.

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

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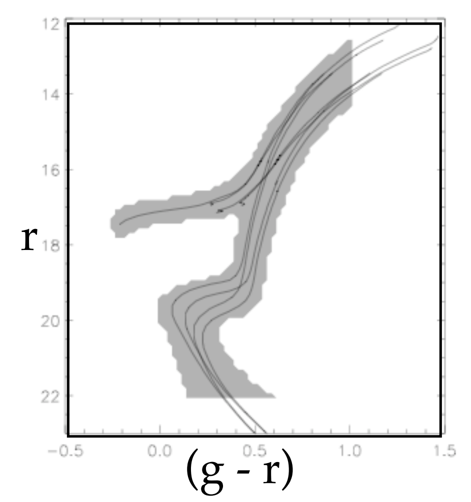
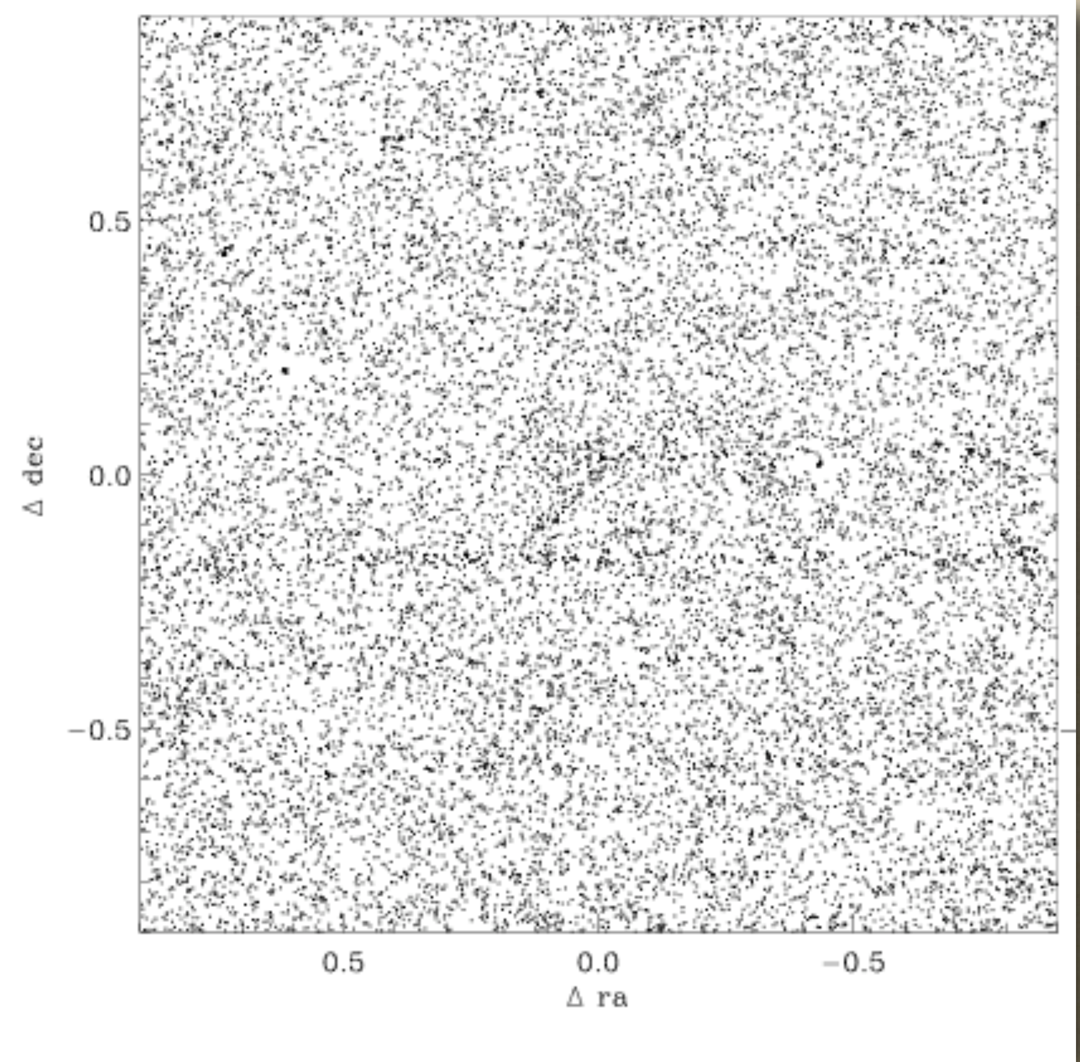
Milky Way stellar foreground overwhelms the dwarf galaxy.

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



Full Star Counts



Finding the Milky Way Ultra-Faint Galaxies

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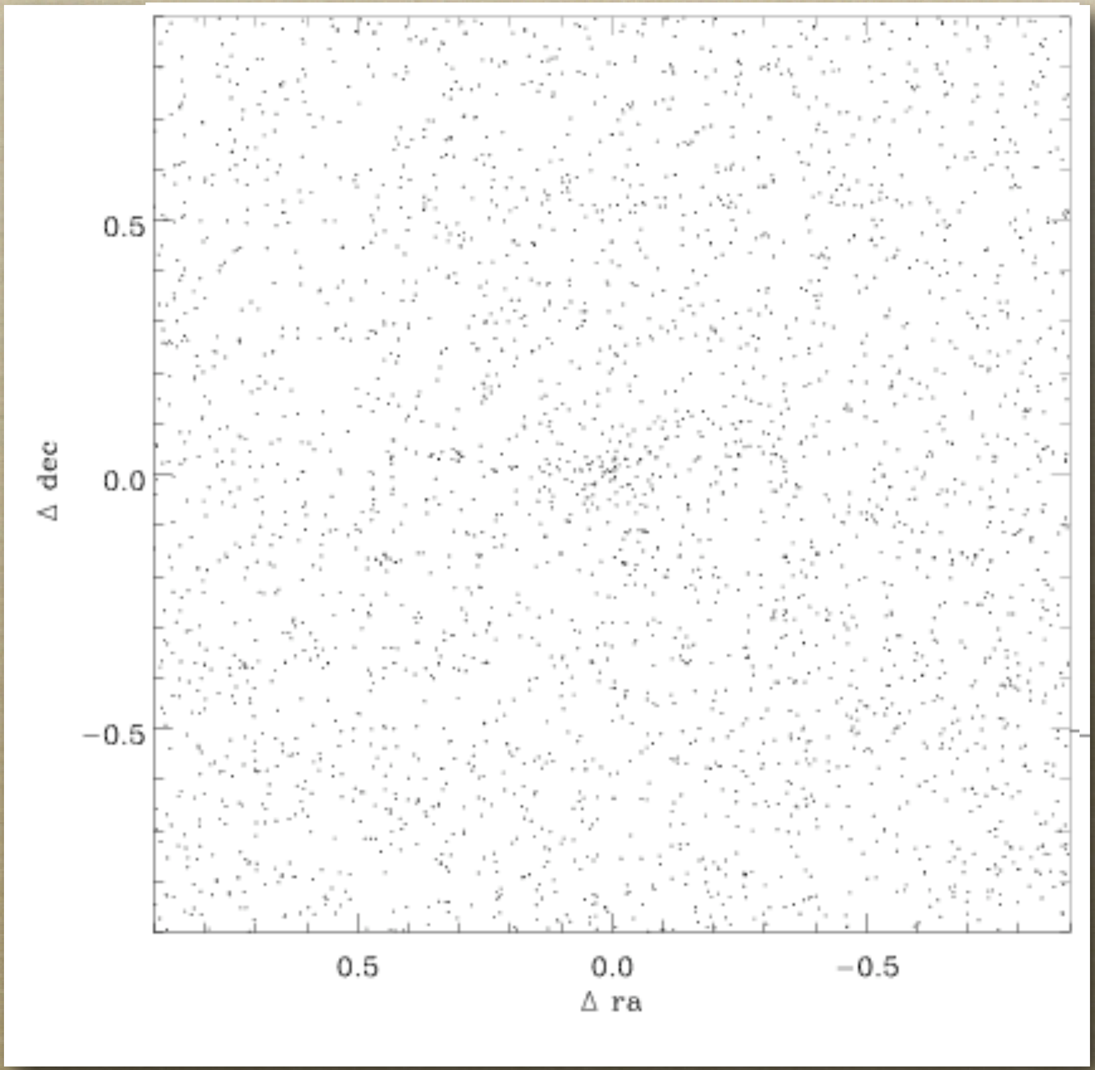
Filtered CMD Stars



Finding the Milky Way Ultra-Faint Galaxies

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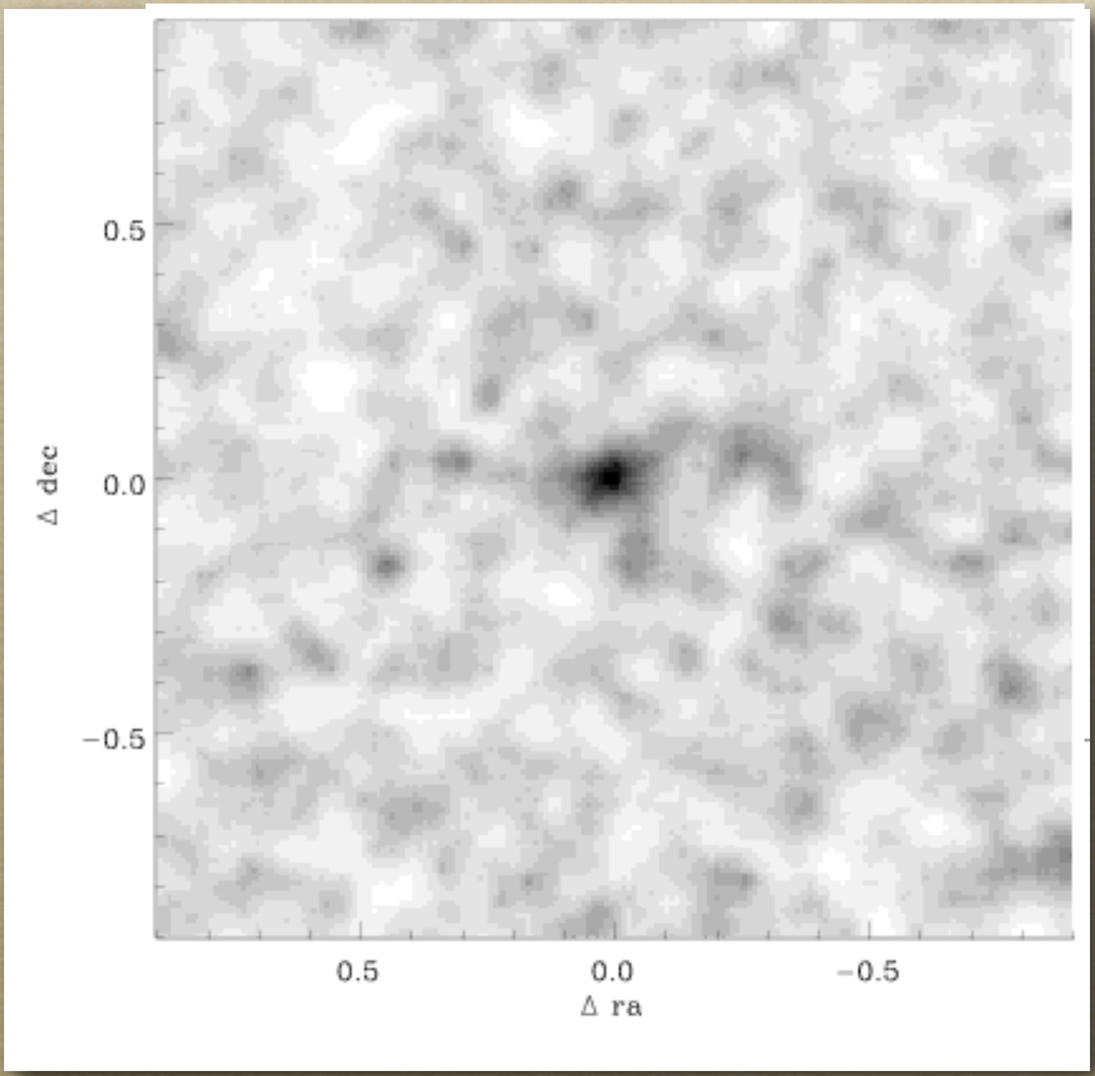
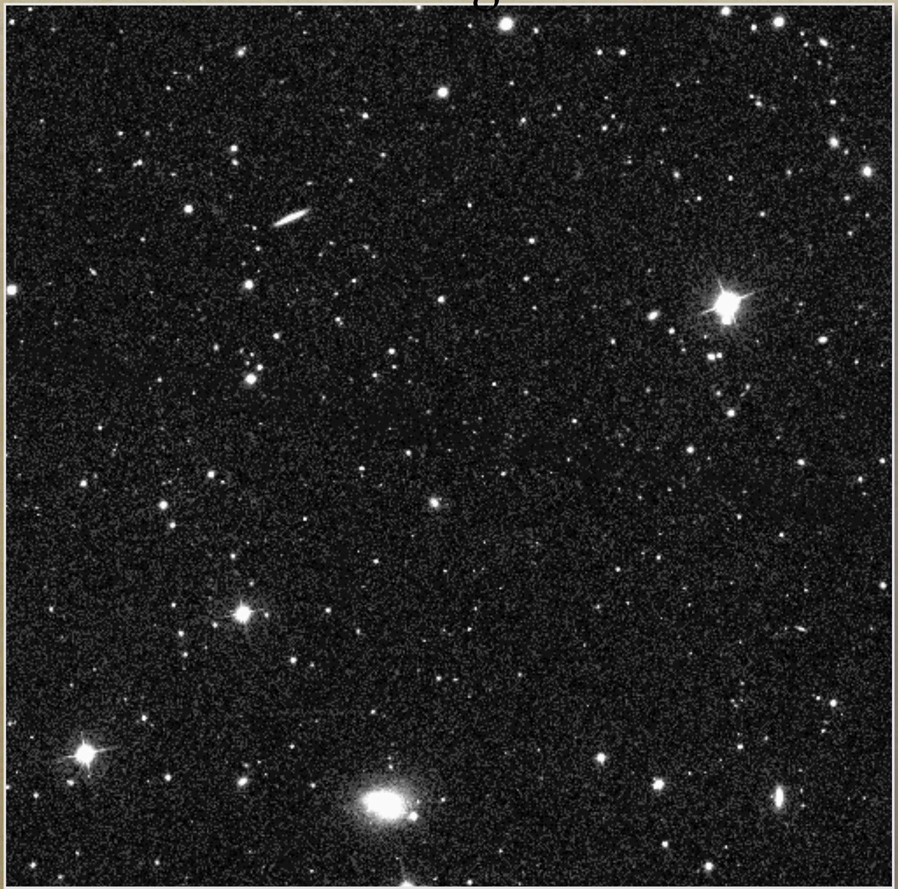
Milky Way stellar foreground overwhelms the dwarf galaxy.

Filtered+Smoothed



Finding the Milky Way Ultra-Faint Galaxies

Raw Image

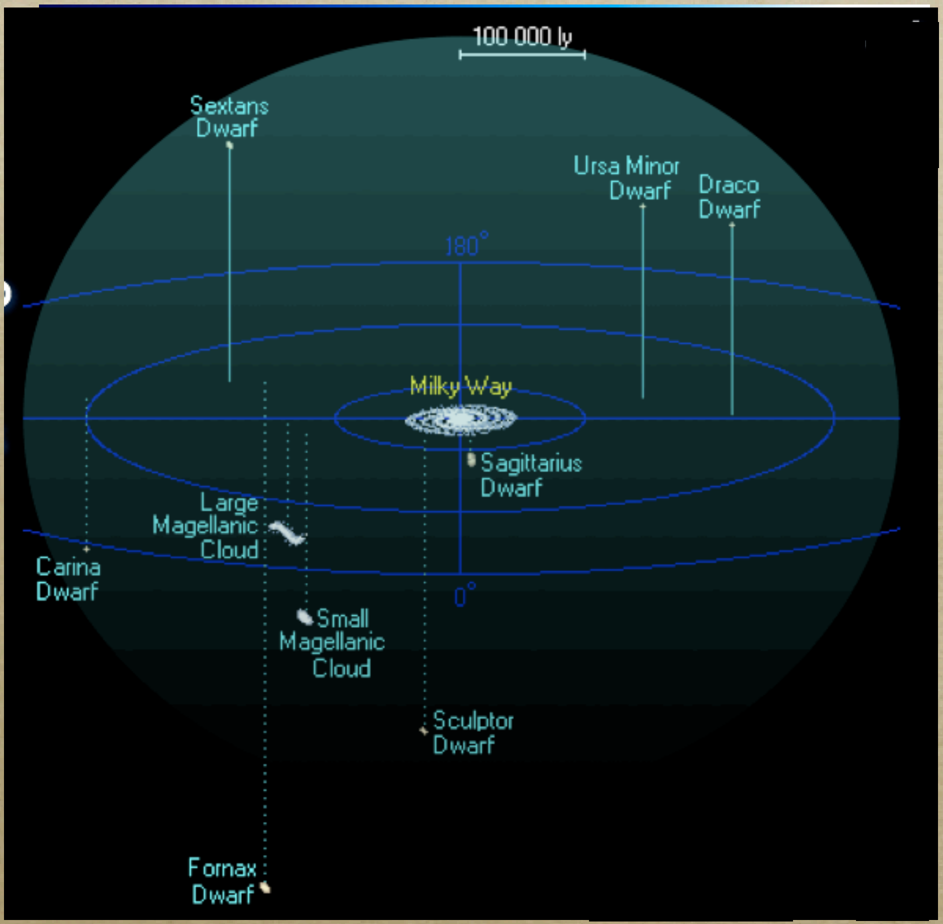


Member Stars only

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

=> *biases remain in size and surface brightness* <=

Are the Milky Way Ultra-Faints Galaxies?

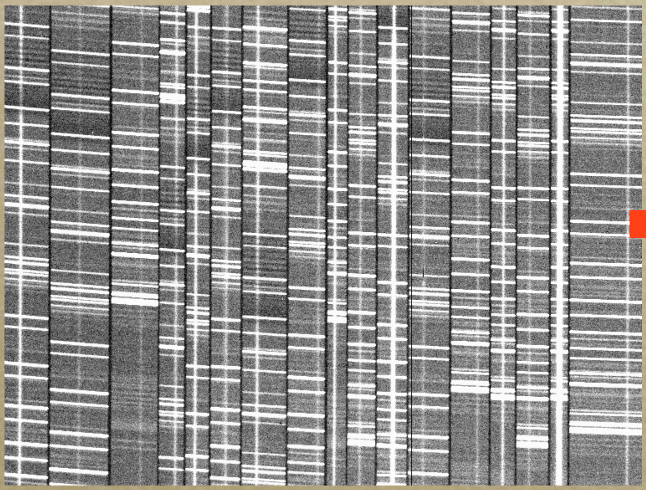


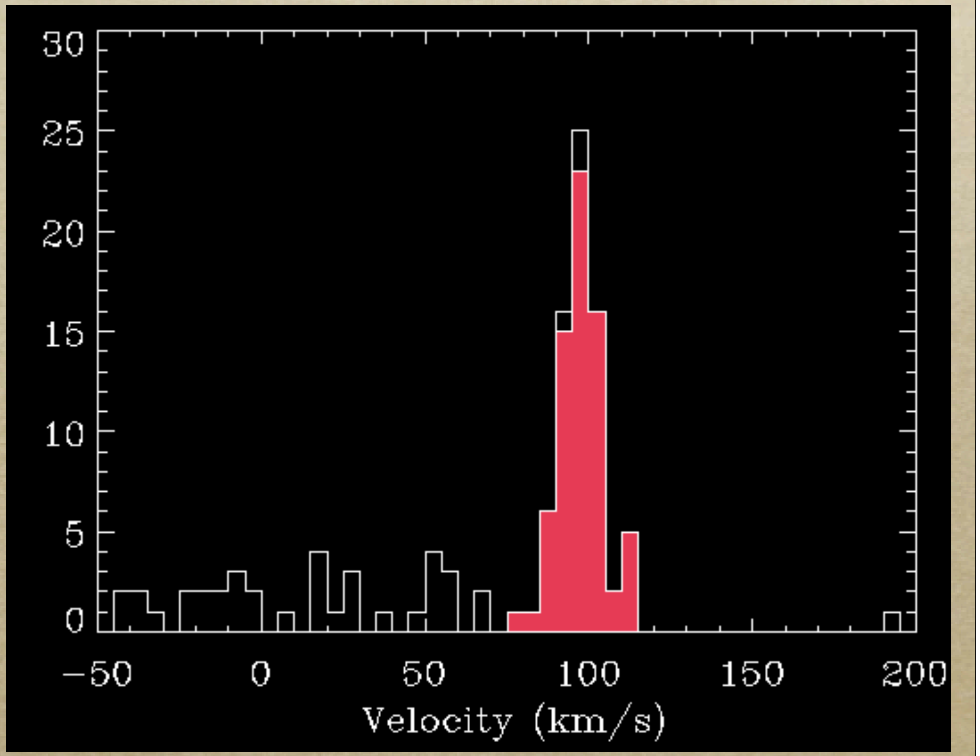
Are the new objects dwarf galaxies?
or odd globular clusters?
or intersecting tidal streams?
...

→ To answer this question, both kinematics and chemical abundances required.

Kinematics with Keck/DEIMOS

DEIMOS Multi-Object Spectrograph
-- 6500 to 9000Å
-- 0.33 Å pixel^{-1} ~ 12 km s^{-1} pixel^{-1}

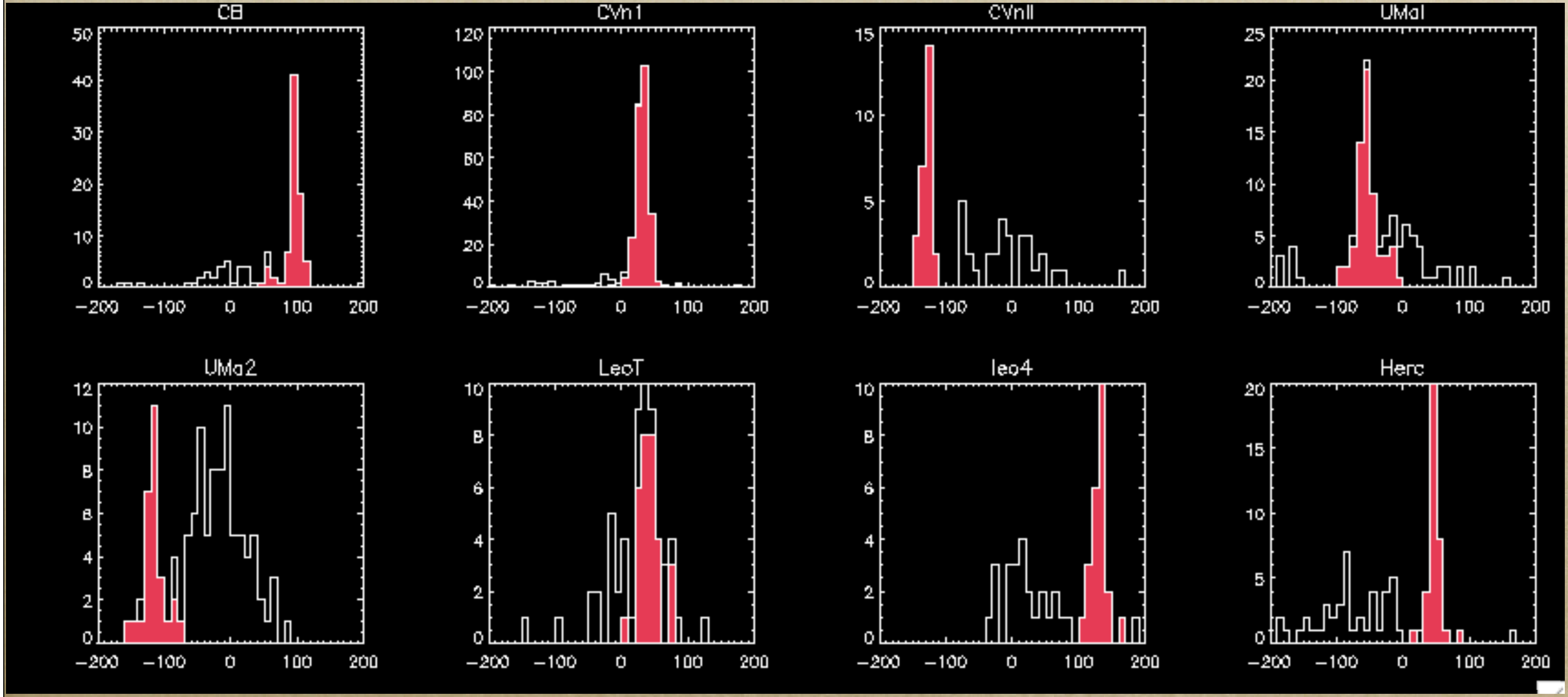




Measure internal velocity dispersion and estimate mass of each object.

Kinematics of the Ultra-Faint Galaxies

Keck + DEIMOS data

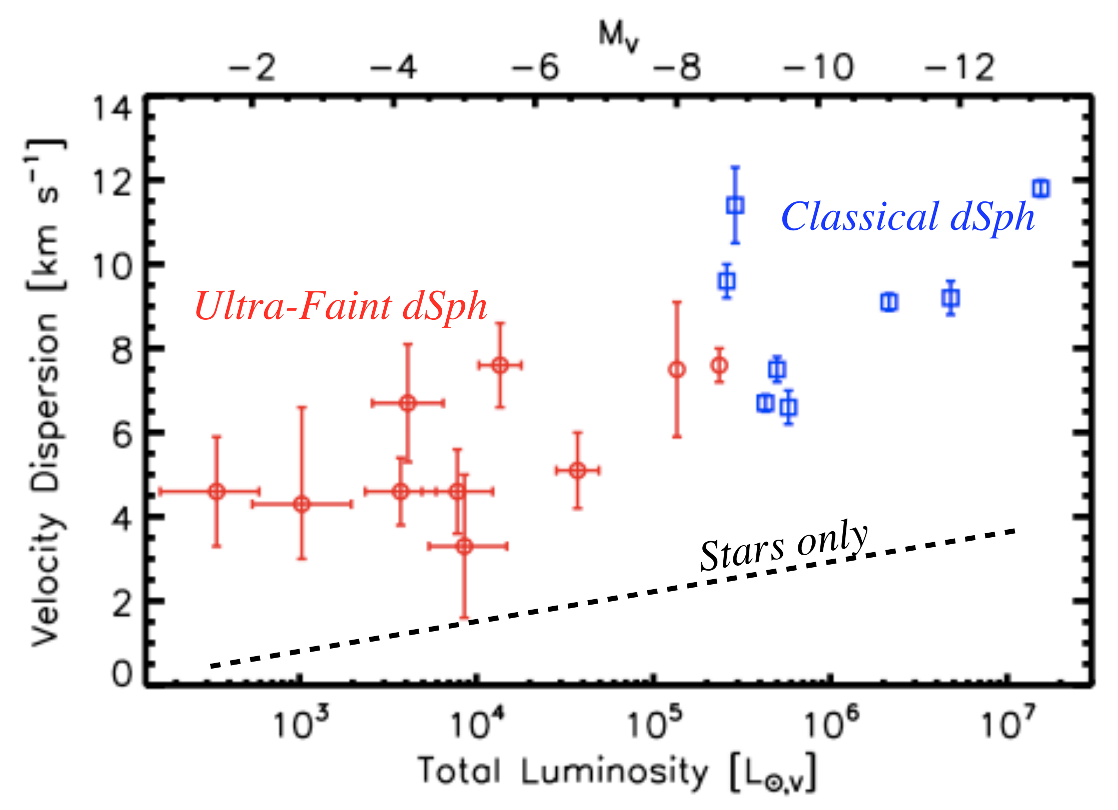


***Velocity* (*km s*$^{-1}$)**

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

Simon & Geha 2007
Martin et al 2007
Munoz et al. 2006

Kinematics of the Ultra-Faint Galaxies



10^5 decrease in luminosity

vs.

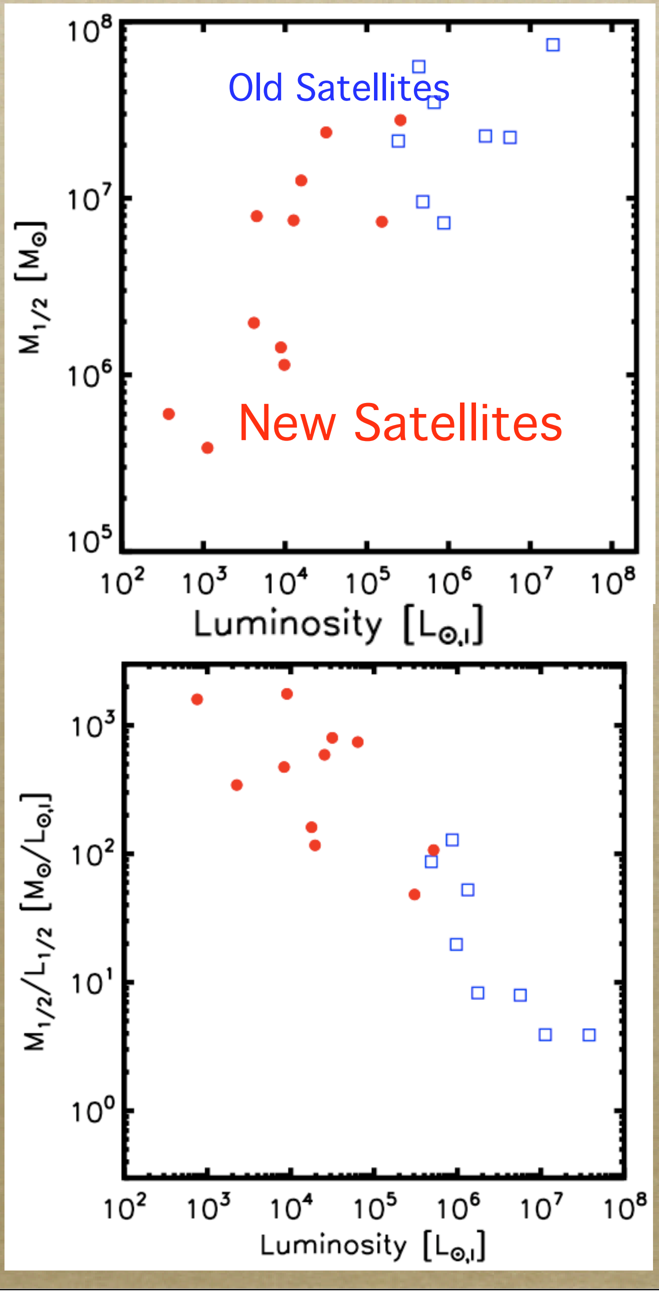
~2 decrease in velocity dispersion.

Assuming simplest model where mass follows light:

$100 < M/L_V < 1000$

Plot from J. Wolf

Kinematics of the Ultra-Faint Galaxies



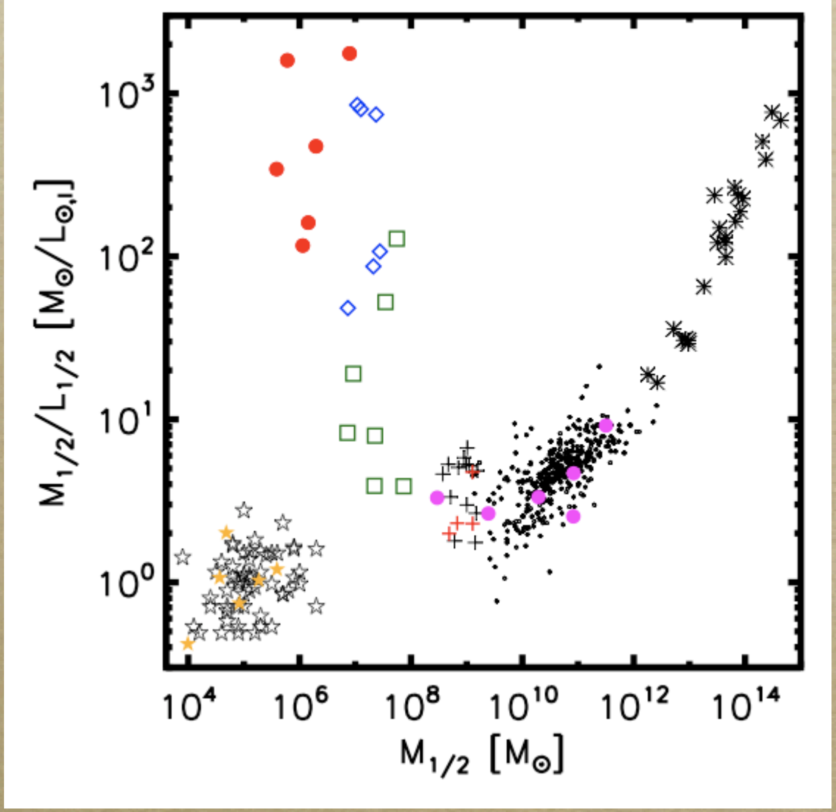
Wolf et al. (2009): Determine masses inside half-light radius $M_{1/2}$. Reduces degeneracy between anisotropy and density profile.

Mass-to-light increases with decreasing luminosity.

Kinematics of the Ultra-Faint Galaxies

Wolf et al. (2009)

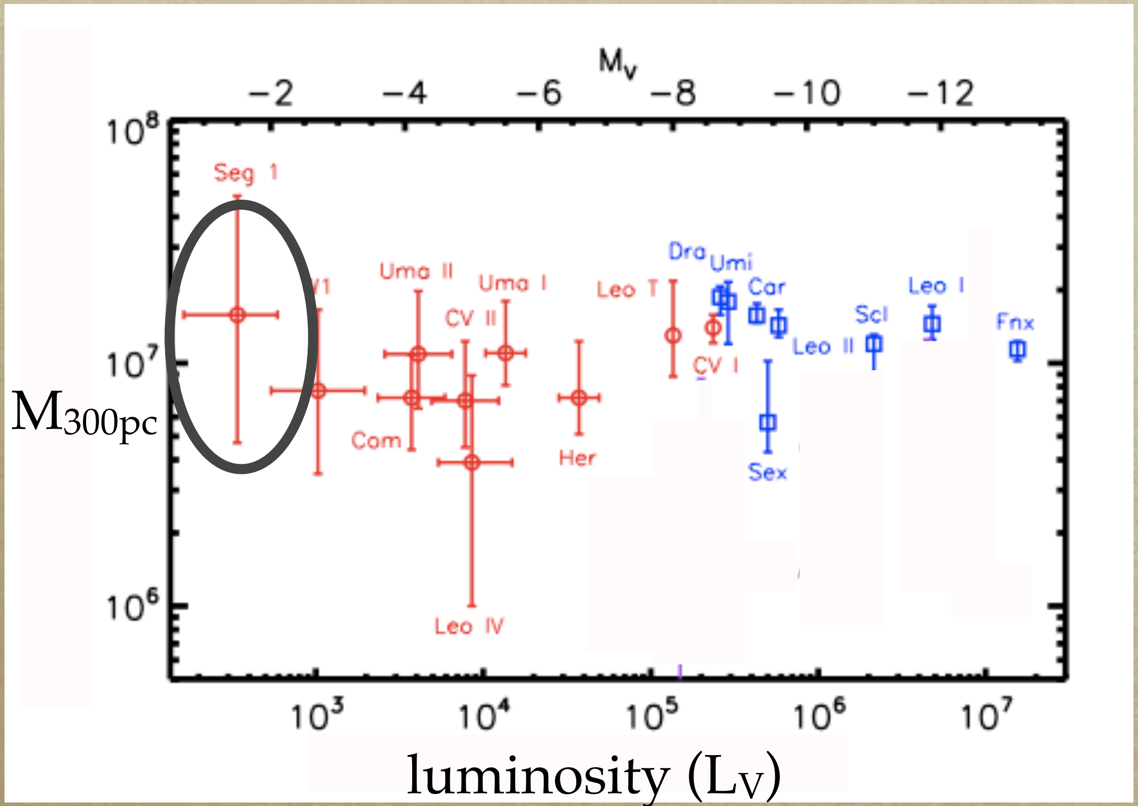
M/L



Mass

Ultra-faint galaxies are most dark matter dominated stellar systems known!

Kinematics of the Ultra-Faint Galaxies



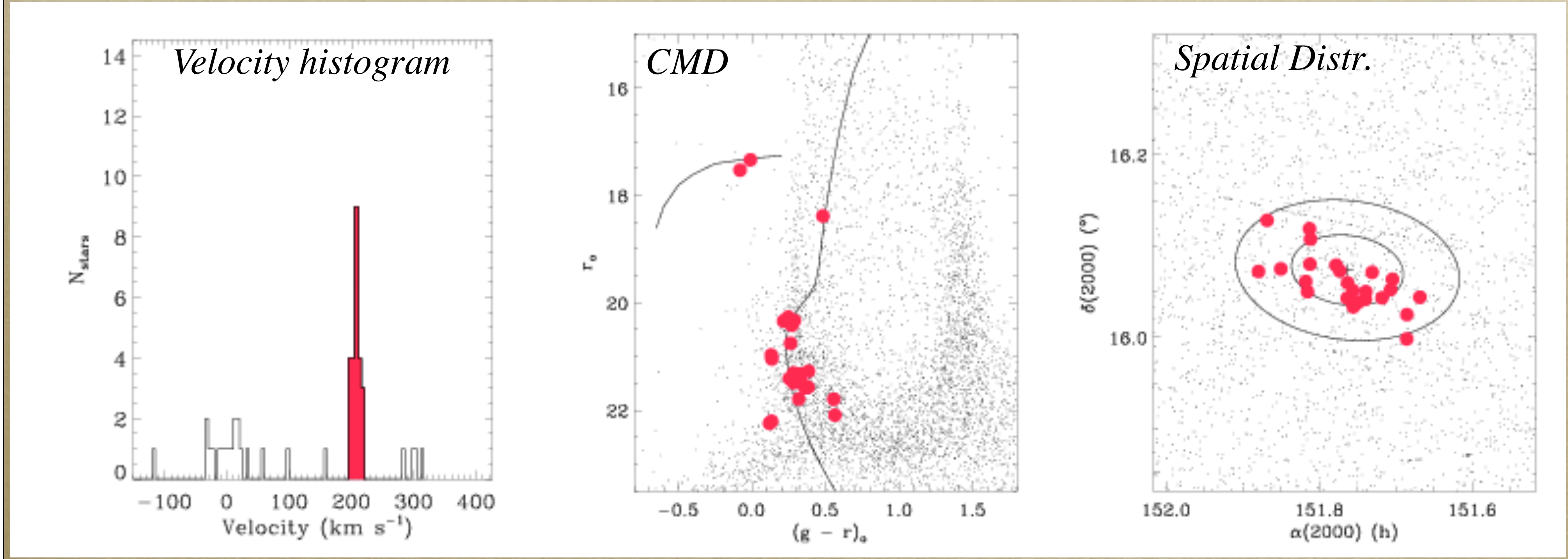
Strigari et al (2008): Plot mass within a fixed physical radius.

Within 300pc, masses are similar across all Milky Way dSphs.

Kinematics of Segue 1

$M_V \sim -1.5$
$L_V \sim 340\ L_{sun}$

April 2009: A complete sample of stars $r < 22$ within 60pc = 2 r_{eff}



If mass from stars only = 0.4 km/s
Measured = 4.5± 1 km/s

$M \sim 10^5\ M_{sun}$
$M_{300pc} \sim 10^7\ M_{sun}$

Geha et al (2009)

Kinematics of Segue 1

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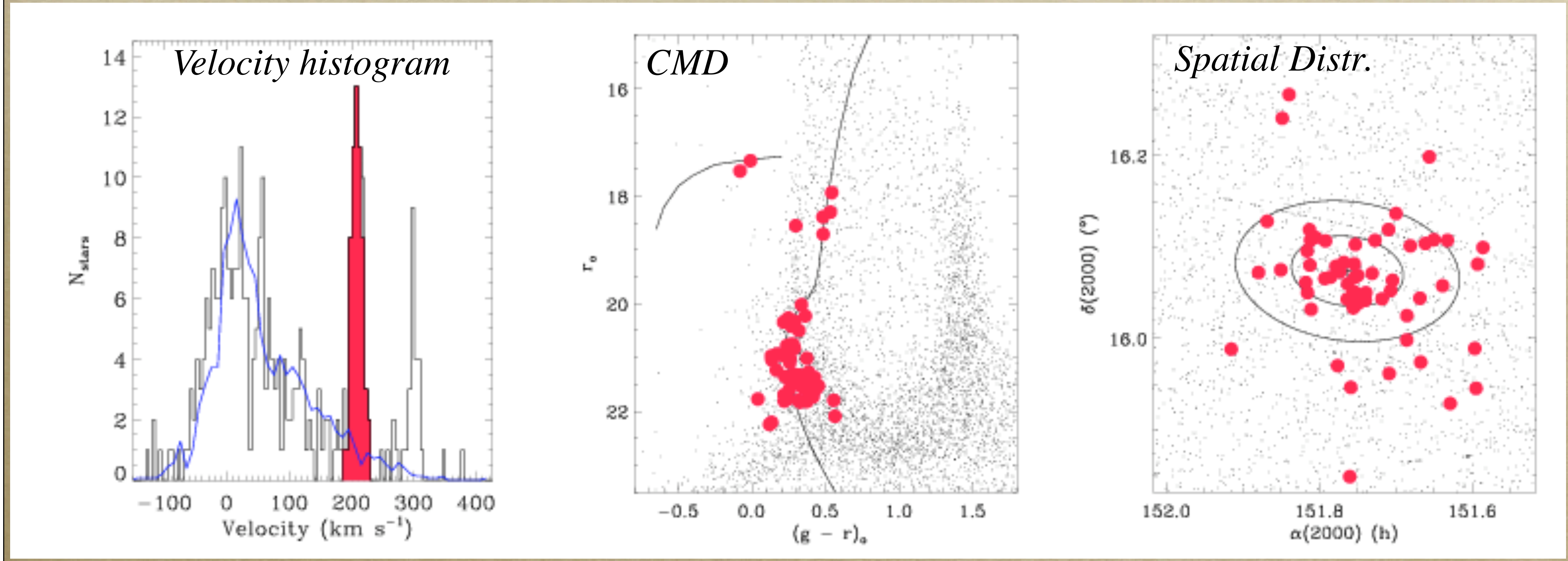

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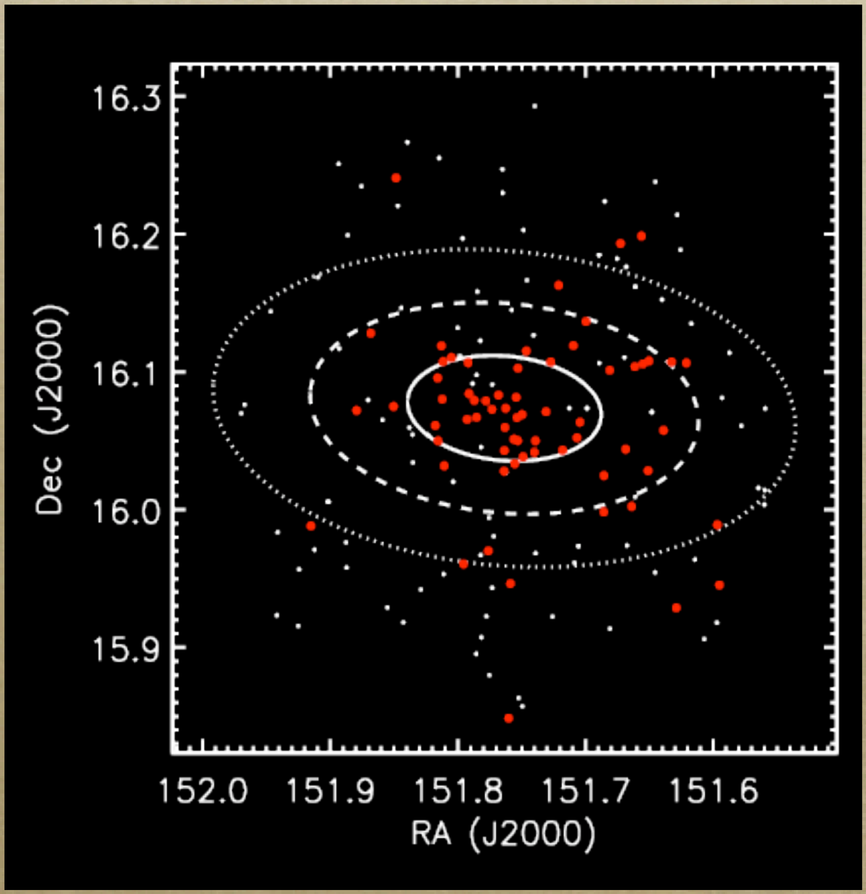
$M \sim 10^5\ M_{sun}$
$M_{300pc} \sim 10^7\ M_{sun}$

Simon et al (2009, in prep)

Kinematics of Segue 1

A complete sample of stars to 60pc: 65 members



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

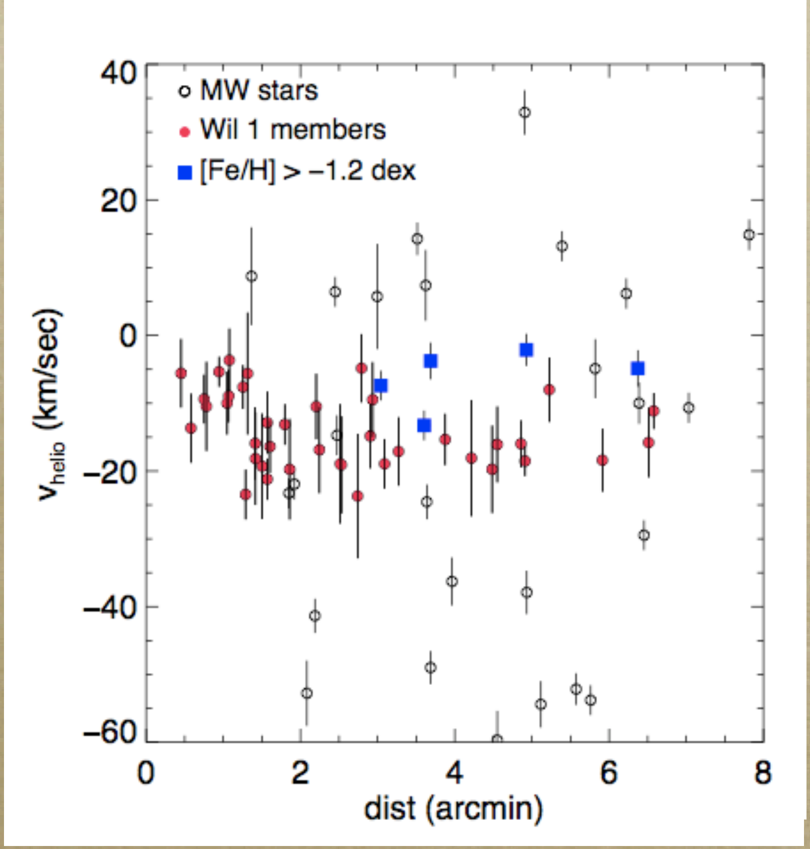
No evidence for tidal disruption in Segue 1.

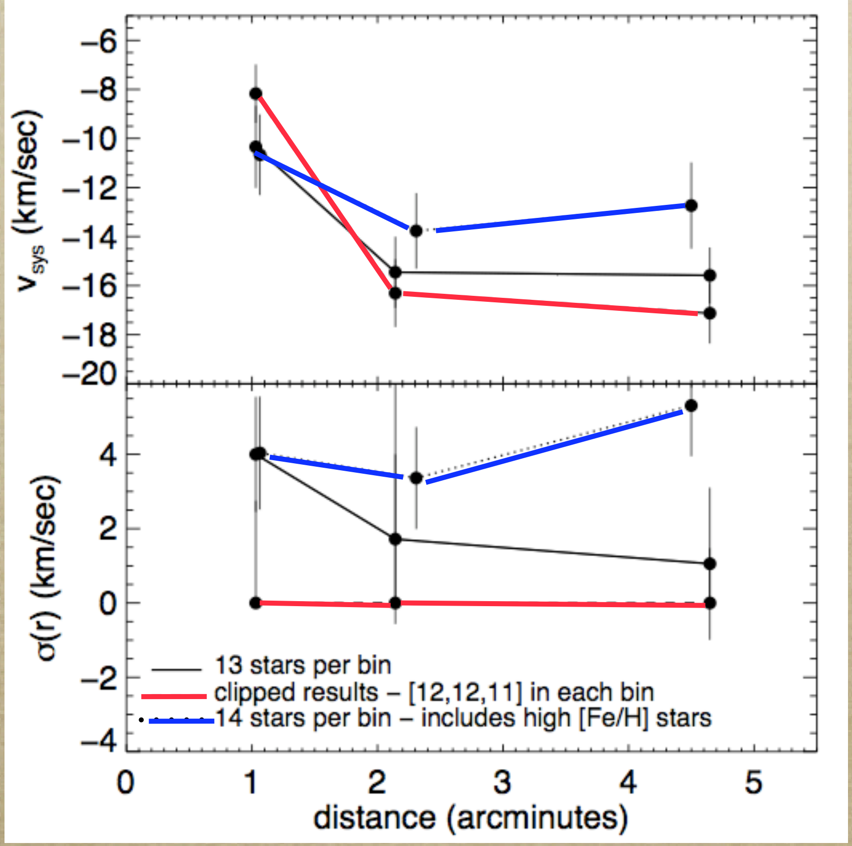
In absence of evidence, we assume stars are faithfully tracing gravitational potential.

Simon et al (2009, in prep)

In Contrast: Willman 1

From prototype to “enigmatic halo object”





(please don’t observe target this object in dark matter studies...)

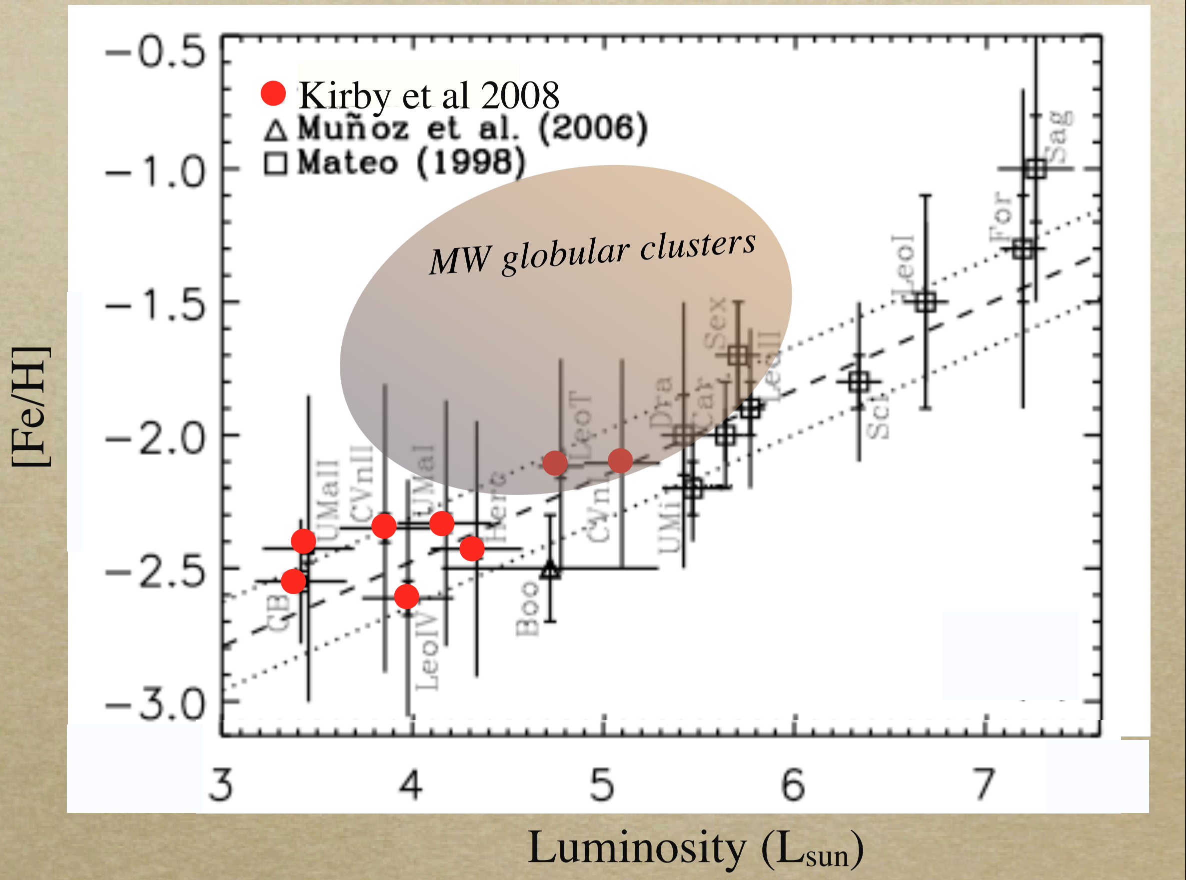
Willman et al (2009, in prep)

Metallicity of the Ultra-Faint Galaxies

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

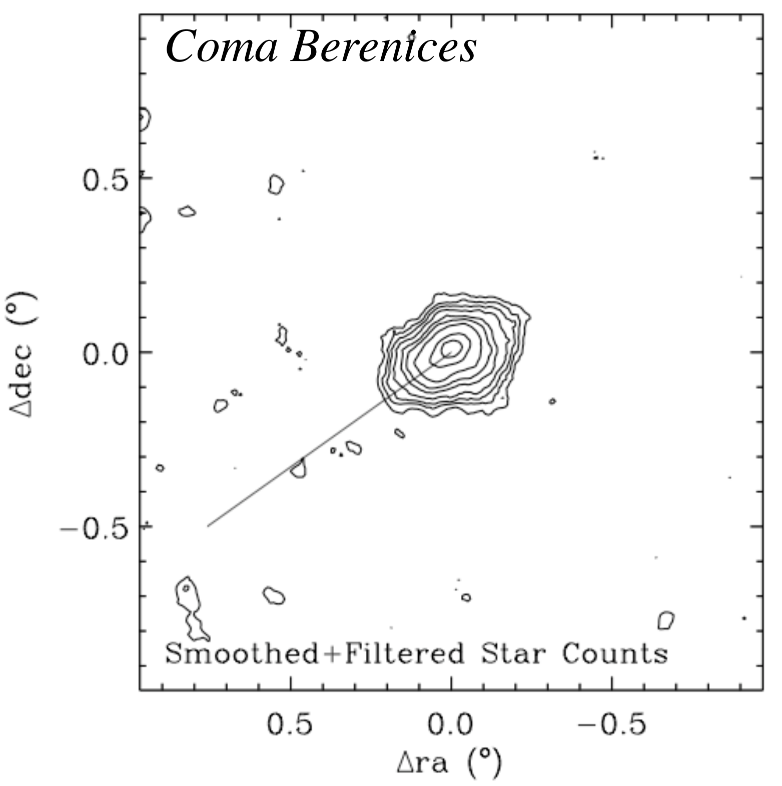
[Fe/H] - L relationship is further evidence that ultra-faints are true galaxies.

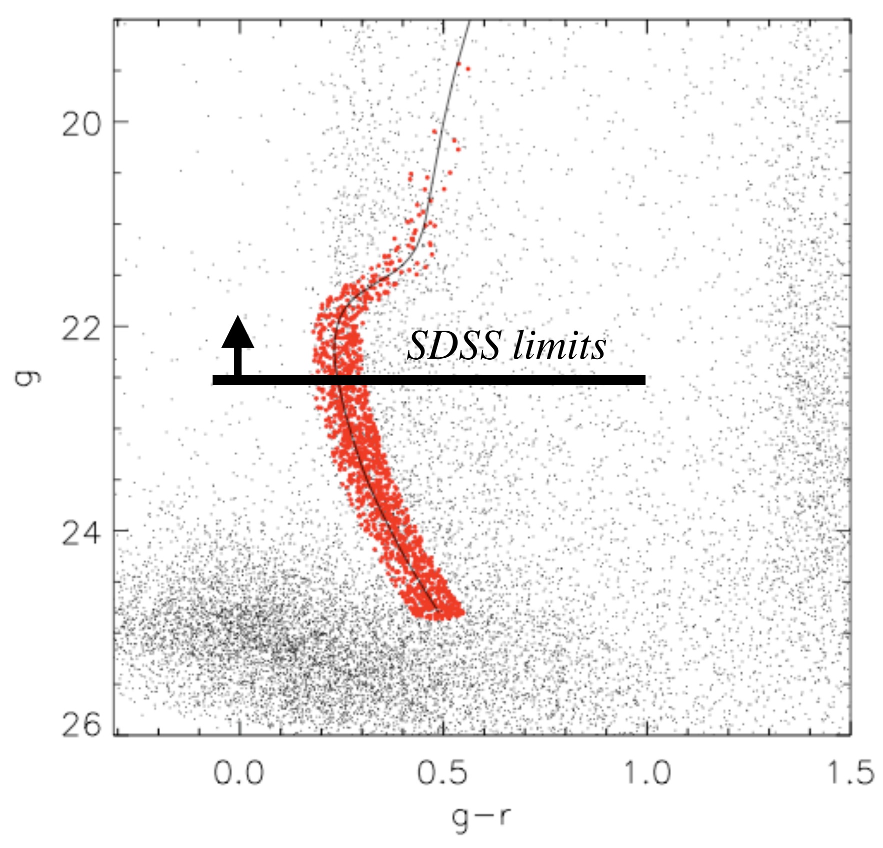
Also argues against significant tidally stripping of luminous component.



Testing Tidal Stripping Another Way

R. Munoz et al (2009): Deep CFHT MegaCam imaging

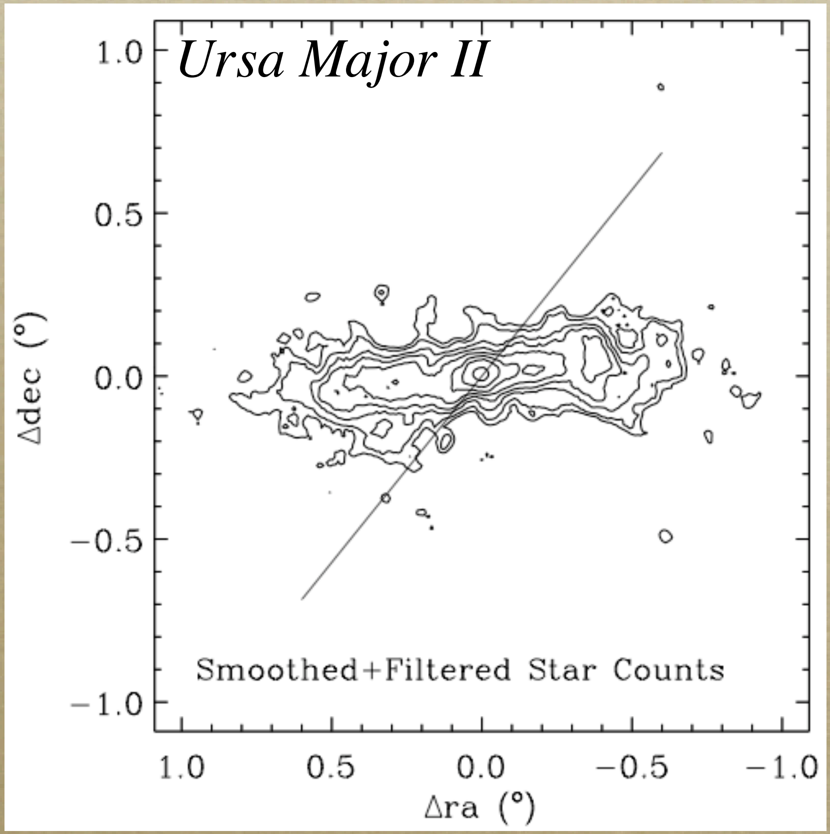




Coma does not show evidence for tidal stripping at large radius/ low surface brightness.

Testing Tidal Stripping Another Way

R. Munoz et al (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.

In absence of evidence, we assume stars are faithfully tracing gravitational potential.

Ultra-Faint Galaxies and Dark Matter

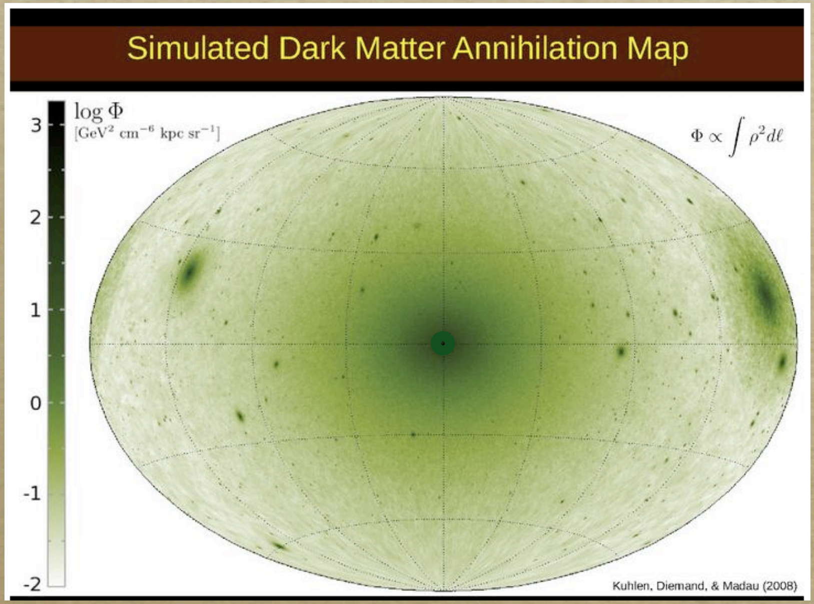
Keck
INSTITUTE FOR SPACE STUDIES

The ultra-faints are versatile probes of dark matter:

1. Good targets for indirect dark matter experiments.
2. Dark matter particle mass constraints from phase space density.
3. Galaxy formation and small scale fluctuations.

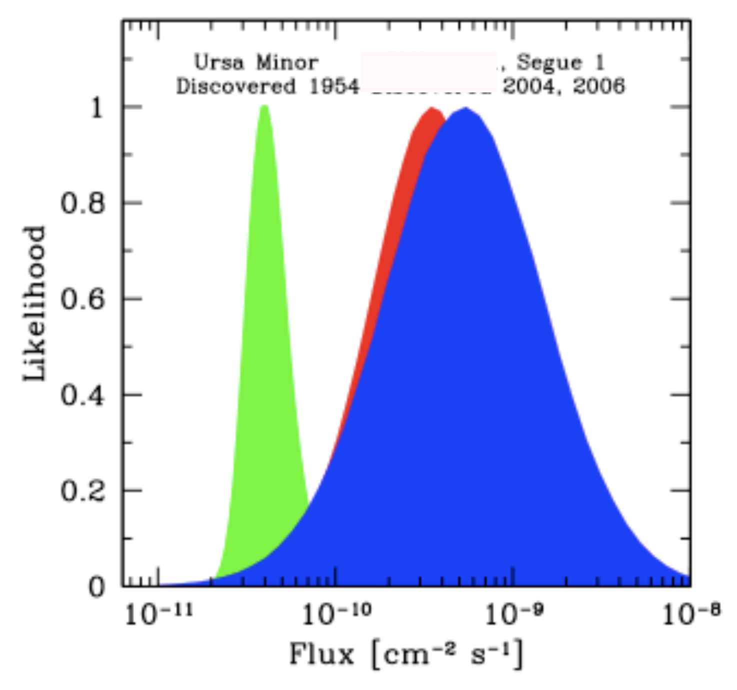
Indirect Dark Matter Detection

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



Kuhlen et al. (2008)

If we have measured the mass correctly, ultra-faints are promising sites for detecting this signal.

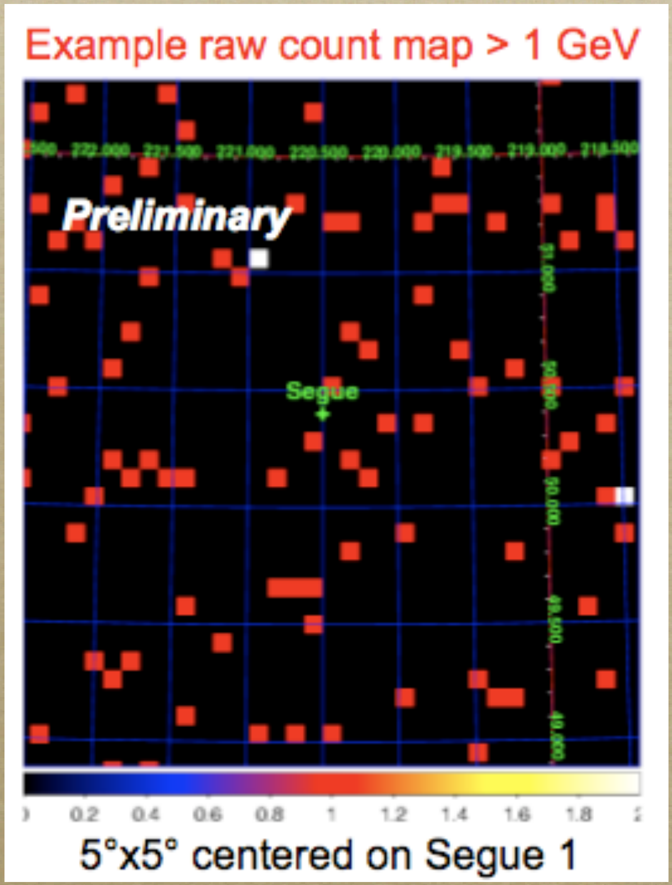


Strigari al. (2008)

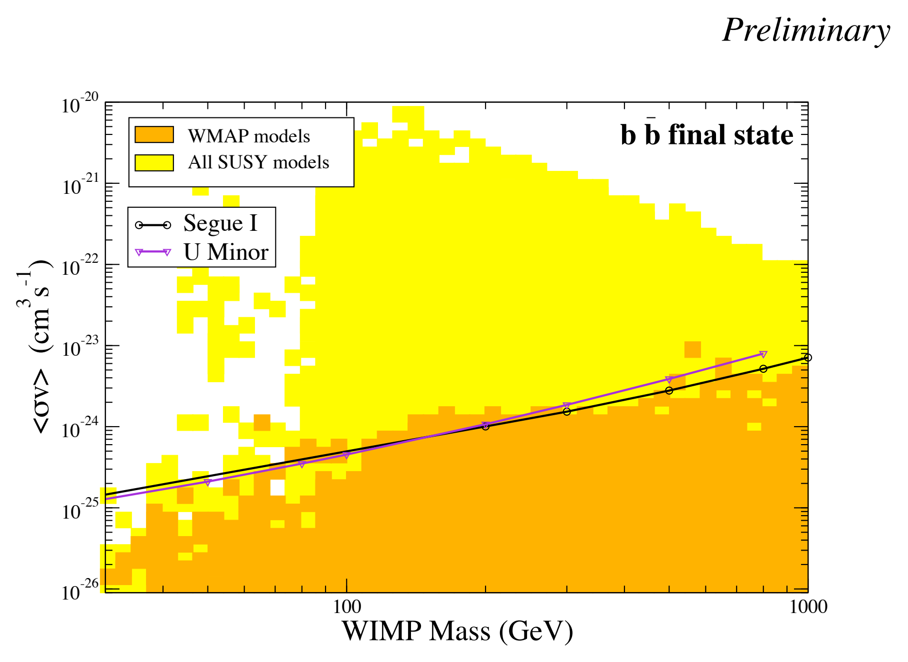
Indirect Dark Matter Detection

No satellites detected in 9-month Fermi data.

Upper limits nibble at SUSY parameter space.



From T. Jeltema and Fermi collaboration



From S. Profumo and Fermi collaboration

Phase Space Density Constraints

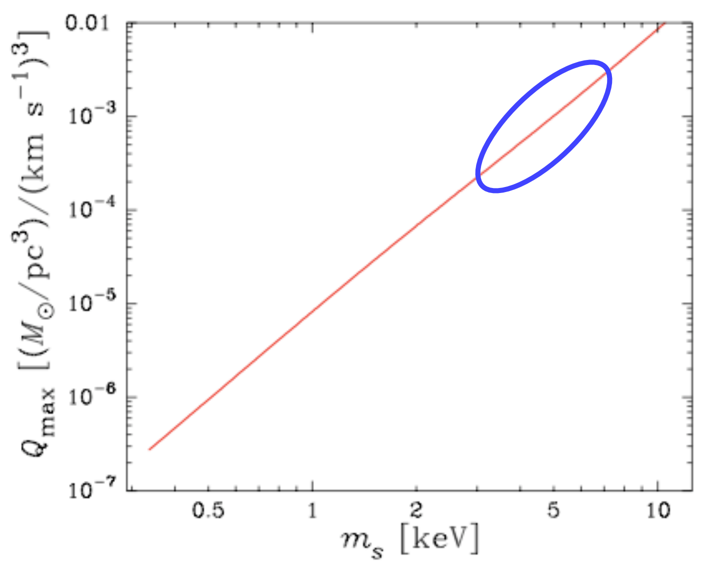
For collisionless systems, the density in phase space f(x,v) is conserved.

The quantity $Q \equiv \varrho / \sigma^3$ is defined as the coarse-grain phase space density, and can be measured.

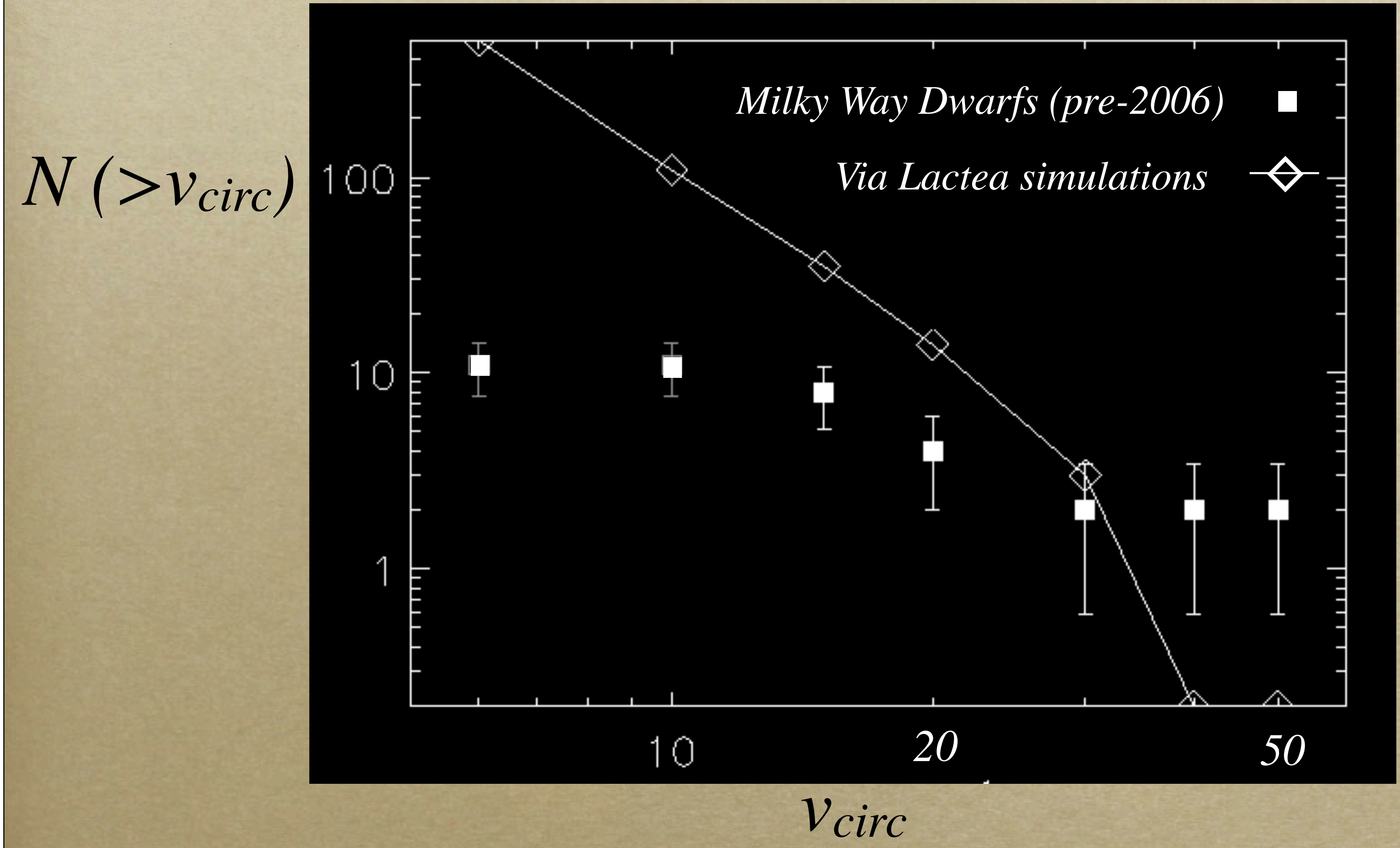
The coarse-grained phase space density only decreases with time, Q provides a lower limit to the primordial phase space density of the dark matter particles.

CDM: $Q \sim 10^{11}$ M_{sun} pc^{-3} $(km/s)^{-3}$
WDM: $Q \sim 10^{-3}$

Sterile neutrino limits (from K. Abazajian)



Have the Missing Satellites Been Found?



Simon & Geha 2007

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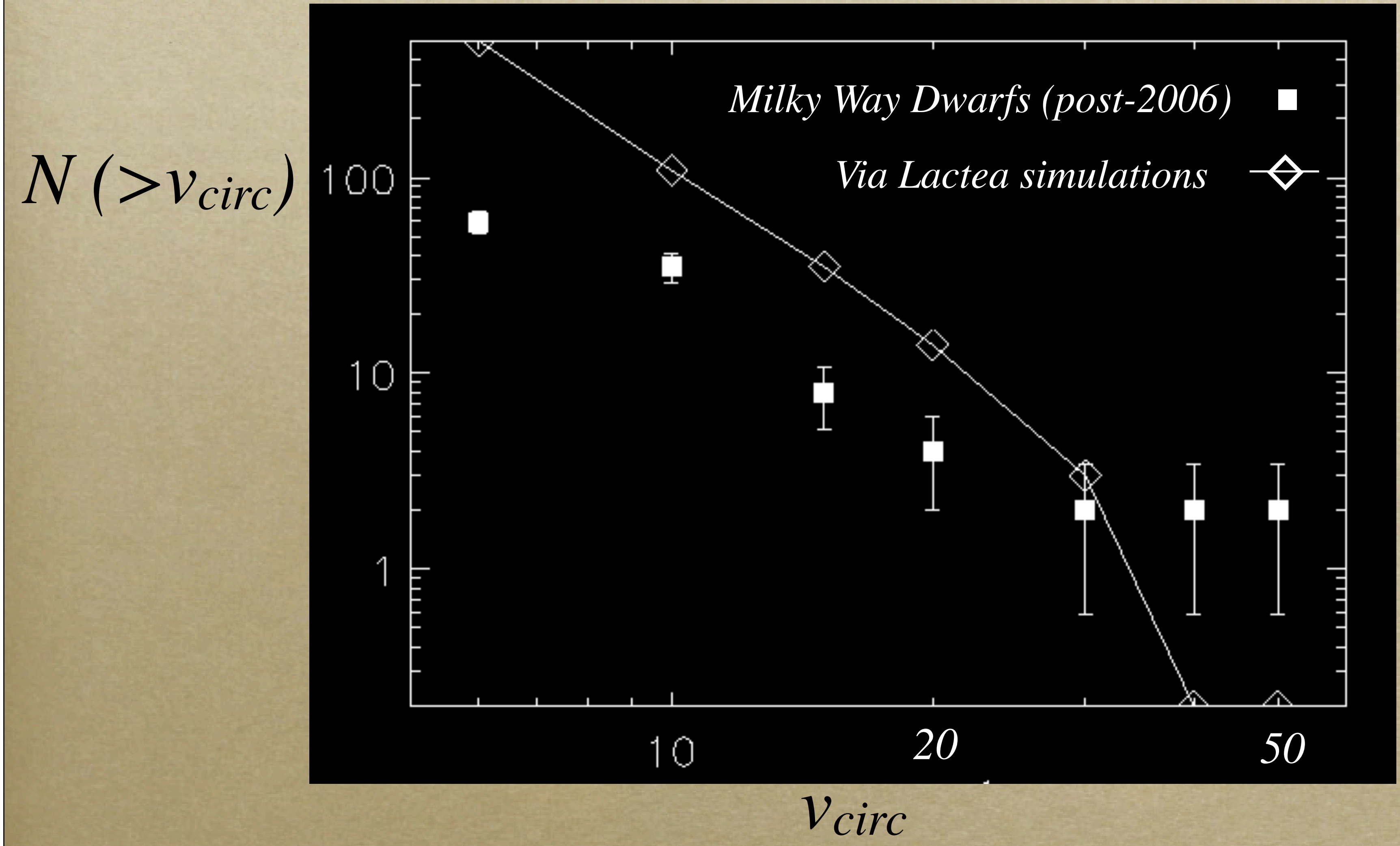

Simon & Geha 2007

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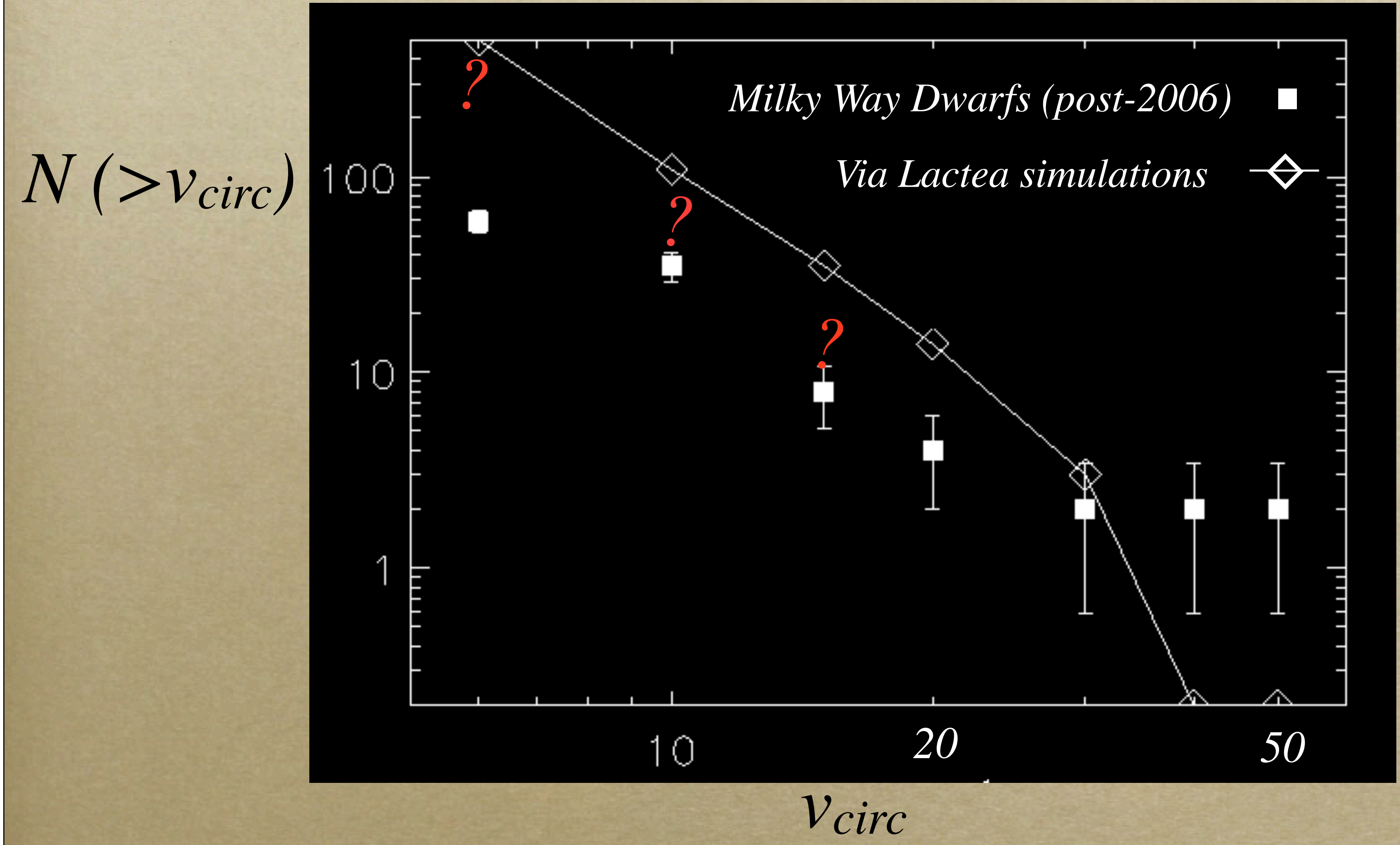
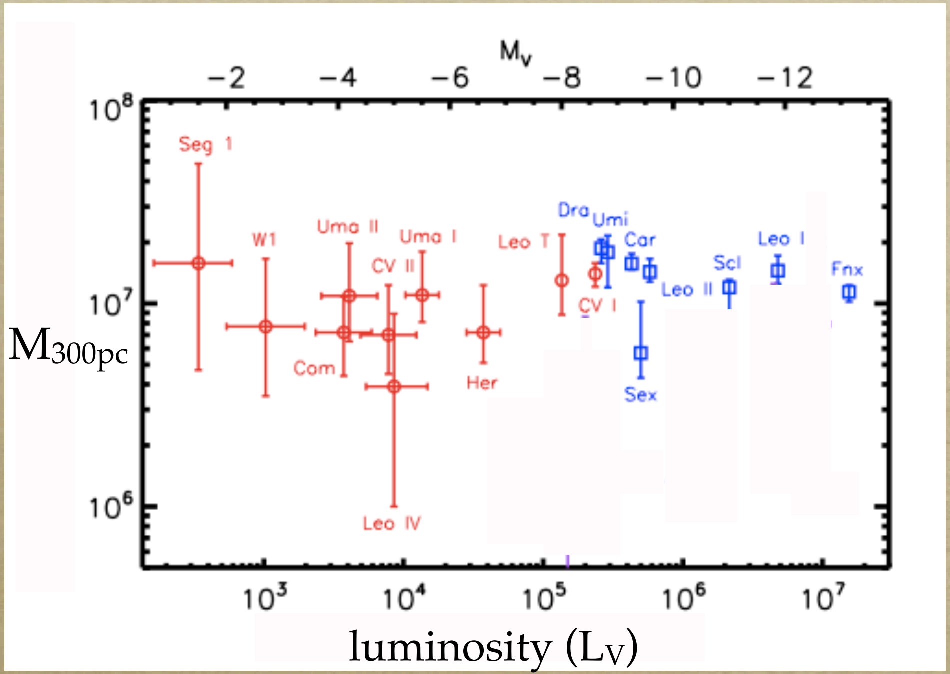


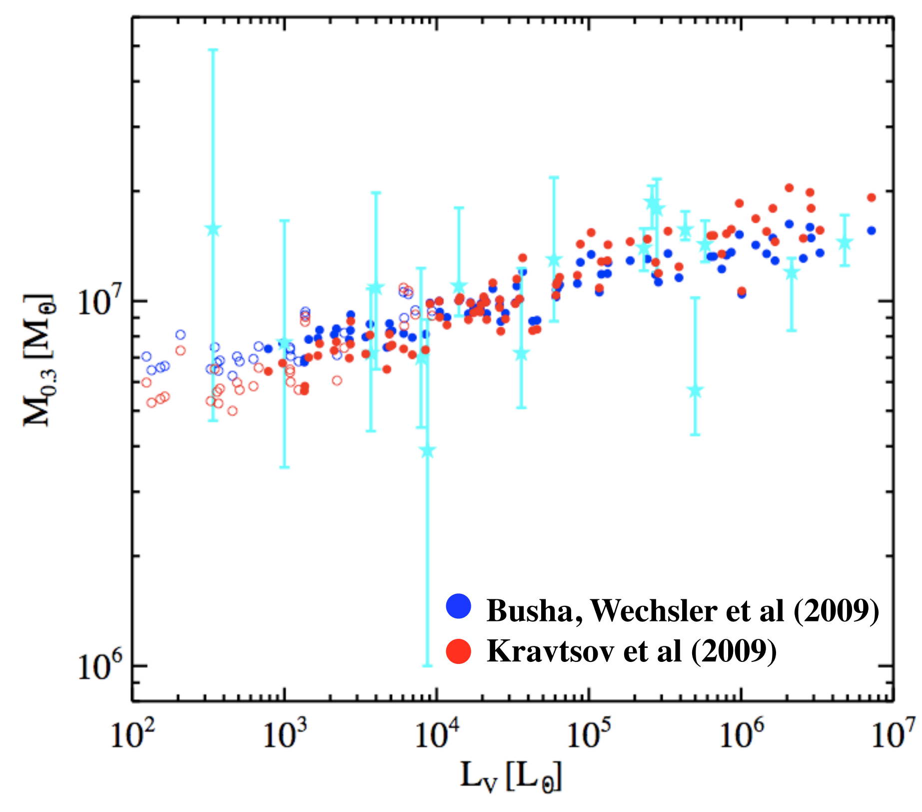
Simon & Geha 2007

Halo Mass of Ultra-Faint Galaxies?



Busha et al. (2009): Can reproduce M300 results for a straight-forward model of galaxy formation

Halo Mass of Ultra-Faint Galaxies?



Busha et al. (2009): Can reproduce M300 results for a straight-forward model of galaxy formation

1. Trace all sub-halos in Via Lactea simulation

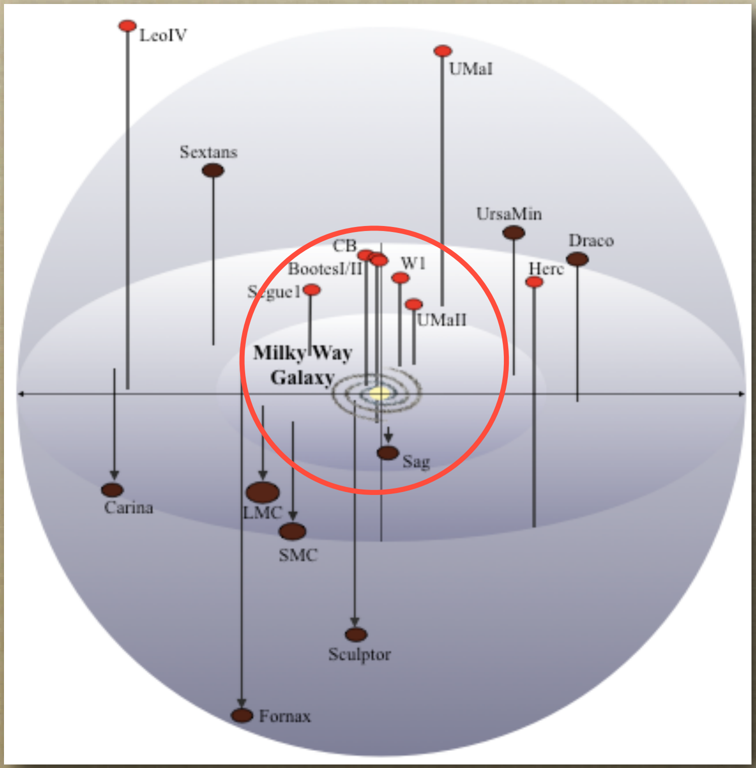
2. Halo contains galaxy if is above a threshold mass at time of reionization (and higher threshold afterwards).

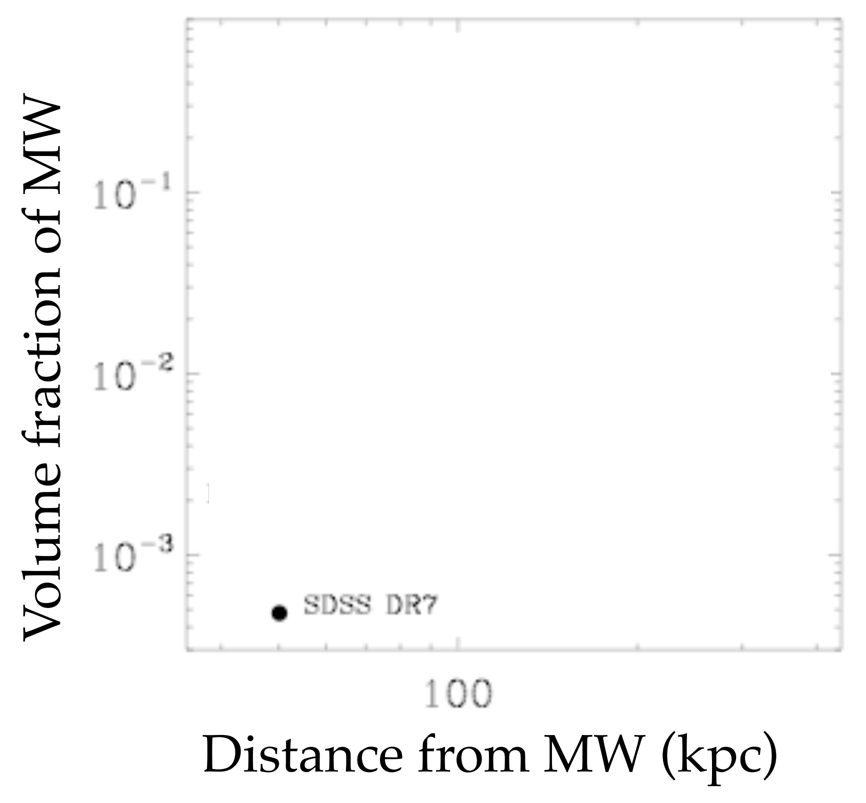
3. Set luminosity of halo based on $L \propto M^{2.5}$

MW satellites were formed in dark matter halos with masses ~ 10^9 M_{sun}.

Finding New Milky Way Satellites

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





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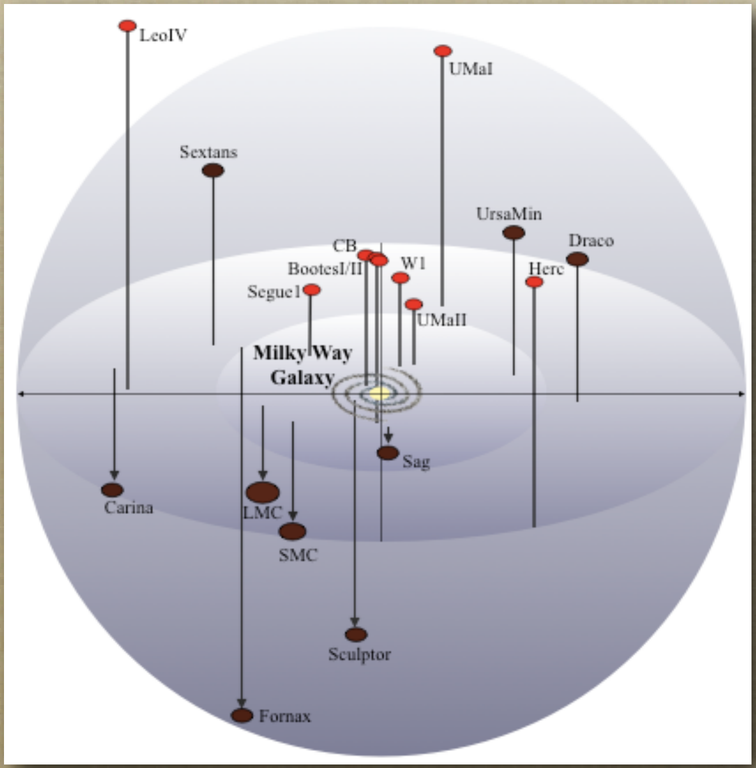

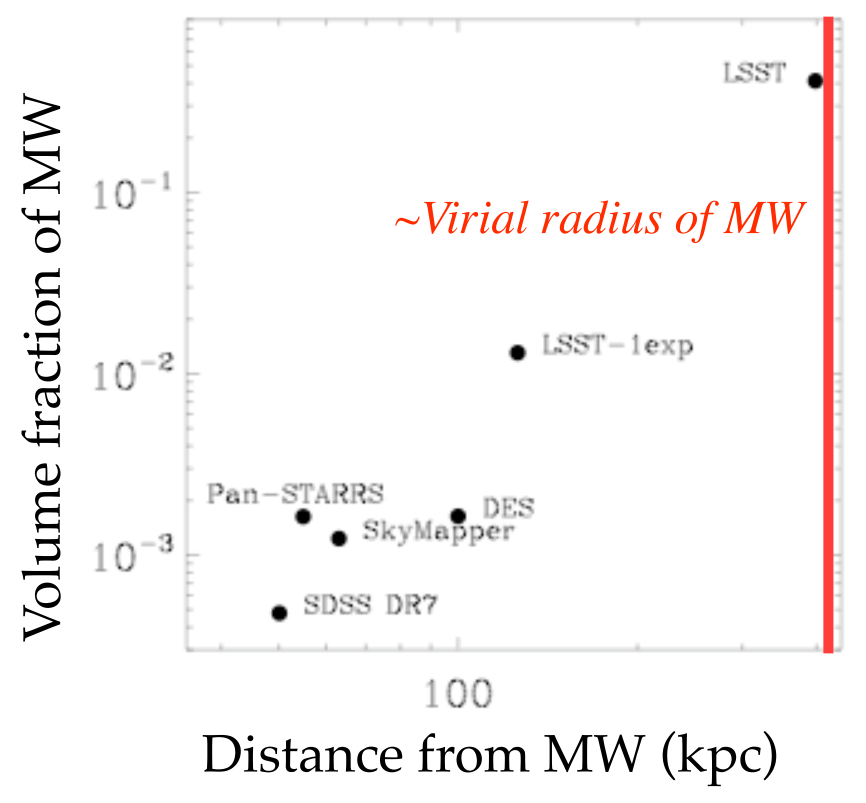

Conclusions

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] ~ -2.5)

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

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

ultra-faint dwarf galaxies

Did you mean: ultra-*fine* dwarf galaxies