The Darkest Galaxies

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Milky Way inner 100 kpc
Introduction to Dwarf Galaxies

\[ \text{Mass} < 10^{10} \, M_{\odot} \quad | \quad M_V > -18 \]

Dwarfs with gas
- SDSS dwarf
- Leo T
- IC 1613

\[ M_V = -16 \]

Dwarfs without gas
- Leo I
- UMa I

\[ M_V = -6 \]

\[ M_V = -12 \]
Dwarf Galaxies as Probes of Dark Matter

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

- The number of low mass objects provide strong constraints on cosmology.
The Milky Way Satellite Census

Sloan Digital Sky Survey (SDSS) coverage

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<tr>
<th>Name</th>
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2003 Milky Way Census Data:

- Classical dSphs = 11
The Milky Way Satellite Census

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<td>Segue II</td>
<td>2009</td>
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2009 Milky Way Census Data:

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

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 $\Lambda$CDM
   “the missing satellite issue”

c) **Particle Physics:**
   Indirect dark matter detection

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

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

\[\Rightarrow \text{biases remain in size and surface brightness} \Rightarrow\]
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 9000 Å
-- 0.33 Å pixel\(^{-1}\) \(\sim\) 12 km s\(^{-1}\) pixel\(^{-1}\)

Measure internal velocity dispersion and estimate mass of each object.
Kinematics of the Ultra-Faint Galaxies

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

Keck + DEIMOS data

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_\odot < 1000

Plot from J. Wolf
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.
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

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

$M_V \sim -1.5$

$L_V \sim 340 \, L_{\text{sun}}$

If mass from stars only $= 0.4 \, \text{km/s}$

Measured $= 4.5 \pm 1 \, \text{km/s}$

$M \sim 10^5 \, M_{\text{sun}}$

$M_{300 \, \text{pc}} \sim 10^7 \, M_{\text{sun}}$

Geha et al (2009)
Kinematics of Segue 1

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

$M_V \sim -1.5$

$L_V \sim 340 \ L_{\text{sun}}$

Velocity histogram

CMD

Spatial Distr.

If mass from stars only = 0.4 km/s

Measured = 4.5± 1 km/s

$M \sim 10^5 \ M_{\text{sun}}$

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

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

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.

In absence of evidence, we assume stars are faithfully tracing gravitational potential.
Ultra-Faint Galaxies and Dark Matter

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.
SUSY dark matter particles occasionally annihilate to produce observable $\gamma$-rays.

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

Kuhlen et al. (2008)

Strigari al. (2008)
Indirect Dark Matter Detection

No satellites detected in 9-month Fermi data.

Upper limits nibble at SUSY parameter space.
Phase Space Density Constraints

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

The quantity $Q \equiv \frac{\rho}{\sigma^3}$ 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: $Q \sim 10^{11} \, M_{\odot} \, \text{pc}^{-3} \, (\text{km/s})^{-3}$
WDM: $Q \sim 10^{-3}$

Sterile neutrino limits (from K. Abazajian)
Have the Missing Satellites Been Found?

$N(>v_{\text{circ}})$

Milky Way Dwarfs (pre-2006)

Via Lactea simulations

Simon & Geha 2007
Have the Missing Satellites Been Found?

$N(>v_{\text{circ}})$ vs. $v_{\text{circ}}$

Milky Way Dwarfs (post-2006)

Via Lactea simulations

Simon & Geha 2007
Have the Missing Satellites Been Found?

$N (> v_{\text{circ}})$

$v_{\text{circ}}$

Simon & Geha 2007
Halos Mass of Ultra-Faint Galaxies?

Busha et al. (2009): Can reproduce M300 results for a straight-forward model of galaxy formation.
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 $\sim 10^9 \, M_{\odot}$. 
Finding New Milky Way Satellites

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

Want to match number and radial distribution of satellites in Milky Way.
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 has evolved)
- Good targets for indirect dark matter detection experiments (Fermi, ACTs)
- Phase space density constraints