Constraining the Nature of Dark Matter with Milky Way's Nearest Neighbors

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LineA
Sep 28th, 2017

Credit: Reidar Hahn, Yuanyuan Zhang
The Dark Energy Survey

Dark Energy Camera (DECam) + 4m Blanco Cerro Tololo Inter-American Observatory

5 year survey over 525 nights
5 filters: g, r, i, z, Y
~5,000 sq. degree
~24th mag in g-band with 10 tiling
The Dark Energy Survey (DES)

- Constrain the Dark Energy Equation of State with:
  - Supernova
  - Weak Lensing
  - Large Scale Structure
  - Galaxy Clusters

DECam
- 62 2k x 4k CCDs
- 570 megapixel camera
- < 20s readout time
- ~3 deg² field-of-view
- Unprecedented sensitivity

DES Year 1 Cosmology Results from 3x2pt

DES Collaboration 2017
Outline

• **Missing Satellites Problem — Dark Matter Models**
  • CDM vs. WDM vs. SIDM, etc.

• **Constraints on WIMP Cross Section — Indirect Dark Matter Detection**
  • WIMP: Weakly Interacting Massive Particles

• **Constraints on MACHO Abundance**
  • MACHO: MAssive Compact Halo Object
• ΛCDM model is in concordance with astronomical observations

Springel et al. (2006) *Nature*  
The large-scale structure of the Universe
Smallest Structures Probe Fundamental Characteristics of Dark Matter

Simulations

Cold Dark Matter

Warm Dark Matter

Lovell et al. (2012)

Cold Dark Matter

Self-Interacting Dark Matter

Vogelsberger et al. (2016)
Aquarius Simulation

1 Mpc$^3$ simulation box

One Milky-Way sized halo

Springel et al. (2008)
Aquarius Simulation

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One Milky-Way sized halo

Springel et al. (2008)
Large Magellanic Cloud

Small Magellanic Cloud
Classical Dwarf Spheroidal Galaxies (dSph)

Sculptor

ESO/DSS2
Dwarf Galaxy Discovery Timeline

“Classical” Satellites

Cumulative Number vs. Year
Dwarf Galaxy Discovery Timeline

"Missing Satellites Problem"

CDM predicts ~500-1000 subhalos for a Milky Way-sized galaxy, while Milky Way only has dozens of known satellites

"Classical" Satellites

Cumulative Number

Year

1920 1940 1960 1980 2000 2020

Confirmed
Candidate
Ultra-Faint Dwarf (UFD) Galaxies
Finding Milky Way Satellite Galaxies

Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)

Color-Magnitude Domain

Spatial Domain
Dwarf Galaxy Discovery Timeline

- **DECam Installed**
- **SDSS Begins**
- **DESY Year 1**
- **DESY Year 2**

Legend:
- **Confirmed**
- **Candidate**
New Dwarf Galaxy Candidates Discovered by DES

Year 1 + Year 2 data

Blue = Known prior to 2015
Red triangles = DES Year 2 candidates
Red circles = DES Year 1 candidates
Green = Other new candidates
Solving the “Missing Satellite Problem”

- Confirmed
- Candidate

$\Lambda$CDM Prediction
(Tollerud et al. 2008)

- DECam Installed
- SDSS Begins

Cumulative Number

Year

1920 1940 1960 1980 2000 2020
Solving the “Missing Satellite Problem”

Baryon Effects:
Astrophysical process prevent stars from forming in most low-mass halos
Solving the “Missing Satellite Problem”

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Astrophysical process prevent stars from forming in most low-mass halos

Observational Bias:
Observations are not detecting the faintest satellites due to the limited survey depth

Figure:
- Confirmed
- Candidate
- $\Lambda$CDM Prediction (Tollerud et al. 2008)

Timeline:
- SDSS Begins
- DECam Installed
What Are Dwarf Galaxies?

Milky Way Satellites are Most Dark-Matter-Dominated Galaxies.

Wolf et al. 2010
What Are Dwarf Galaxies?

Milky Way Satellites are Most Dark-Matter-Dominated Galaxies.

UFD  Classical

Wolf et al. 2010
Spectroscopic Campaign w/ 4-10 m

- Magellan/IMACS+M2FS
- VLT/GIRAFFE
- Keck/DEIMOS
- AAO/2df+AAOmega

- $R \sim 5k - 20k$
- Multiplexing: 50 - 400 stars
- FOV: 15 arcmin - 2 deg in diameter
- Velocity precision: 0.5 - 2 km/s (at high SNR)
Spectroscopic Followup w/ Magellan/IMACS

Magellan Telescopes
2 x 6.5m telescopes

Inamori Magellan Areal Camera and Spectrograph (IMACS)

Multi-Object Spectrograph
Magellan/IMACS

Field of View: 15’ x 15’
60-90 0.7”x5.0” slitlets per mask
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60-90 0.7"x5.0" slitlets per mask
Slit Mask Image

Spectral/Wavelength Dimension

Spatial Dimension
Wavelength Calibration Frame

Atomic emission lines from arc lamps
2D Stellar Spectra

Emission lines from sky
Wavelength recalibration
Reticulum II
Reticulum II

DES Collaboration
Reticulum II: One of Newest Dwarf Galaxies

- ~30 members identified in Reticulum II
- Velocity peak indicative of a genuine stellar association
- Dynamical mass calculated from the width of the velocity dispersion
- Every measured characteristic of Reticulum is consistent with the known population of dwarf galaxies

<table>
<thead>
<tr>
<th>Quantity</th>
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<tbody>
<tr>
<td>Systemic Velocity</td>
<td>$v = 62.8 \pm 0.5 \text{ km s}^{-1}$</td>
</tr>
<tr>
<td>Velocity Dispersion</td>
<td>$\sigma_v = 3.3 \pm 0.7 \text{ km s}^{-1}$</td>
</tr>
<tr>
<td>Metallicity</td>
<td>$[\text{Fe/H}] = -2.65 \pm 0.07$</td>
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<tr>
<td>Metallicity Dispersion</td>
<td>$\sigma_{[\text{Fe/H}]} = 0.28 \pm 0.09$</td>
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<tr>
<td>Dynamical Mass</td>
<td>$M_{1/2} = 5.6 \pm 2.4 \times 10^5 \text{ M}_\odot$</td>
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<tr>
<td>Mass-to-Light Ratio</td>
<td>$M/L = 470 \pm 210 \text{ M}<em>\odot/\text{ L}</em>\odot$</td>
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Simon et al. 2015 (DES Collaboration)  
(see also Walker et al. 2015, Koposov et al 2015b)
Tucana III: classification unclear

26 members identified

- $V_{\text{hel}}$ (km s$^{-1}$) $\approx -102.3 \pm 0.4$
- $V_{\text{GSR}}$ (km s$^{-1}$) $\approx -195.2 \pm 0.4$
- $\sigma$ (km s$^{-1}$) $< 1.5$
- Mass (M$_{\odot}$) $< 8 \times 10^4$
- $M/L_V$ (M$_{\odot}$/L$_{\odot}$) $< 240$

- Velocity dispersion is NOT resolved

Need multi-object spectragraph with higher resolution and better stability to achieve higher velocity precision ($< 1$ km/s)!

Simon et al. 2017
(DES Collaboration)
Solving the “Missing Satellite Problem”
CDM Predictions for Future Dwarf Discoveries

- **ACDM Prediction (Hargis et al. 2014)**
- **Confirmed**
- **Candidate**
- **MagLiteS (Projected)**
- **DECam (Projected)**
- **LSST (Projected)**

**Predicted Dwarf Discoveries**

**"Smoothed" ACDM Prediction**
New Dwarf Galaxies in the Era of LSST

Homma et al. 2017

Depth limit w/ DES ~ 30 mag arcsec$^{-2}$
New Dwarf Galaxies in the Era of LSST

Observational Bias:
Observations are not detecting the faintest satellites due to the limited survey depth

Depth limit w/ DES ~ 30 mag arcsec$^{-2}$
New Dwarf Galaxies in the Era of LSST

- Two new ultra-faint galaxy candidates found in first 300 deg² of Hyper-Suprime Cam SSP data
- They are likely undetectable in any previous survey
- < 5 members can be followed spectroscopically with 8-10 m class telescope

Need 30 m class telescopes to confirm its dark matter content
New Dwarf Galaxies in the Era of LSST

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Homma et al. 2017
Why Studying the Milky Way Satellite Galaxies

• Missing Satellites Problem — Dark Matter Models
  • CDM vs. WDM vs. SIDM, etc.

• Constraints on WIMP Cross Section — Indirect Dark Matter Detection
  • WIMP: Weakly Interacting Massive Particles

• Constraints on MACHO Abundance
  • MACHO: MAssive Compact Halo Object
Many dark matter models predict annihilation into energetic Standard Model particles (e.g., gamma rays, neutrinos, electrons, …)

Annihilation rate scales as density squared
“Galactic Center GeV Excess”
Hooper & Goodenough 2009, 2011, Abazajian & Kaplinghat 2012,
Hooper & Slatyer 2013, Gordon & Macias 2013, Huang et al. 2013,
Cholis et al. 2014, Carlson et al. 2015, Gaggero et al. 2015,
LAT Collaboration 2015, Lee et al. 2015, Bartels et al. 2015

Many proposed interpretations, e.g.,
millisecond pulsars, outburst of cosmic rays,
dark matter annihilation, …
Many dark matter models predict annihilation into energetic Standard Model particles (e.g., gamma rays, neutrinos, electrons, …)

Annihilation rate scales as density squared

Nearby clumps of dark matter — dwarf galaxies — make ideal targets:
• Clean — no astrophysical source
• Dynamical mass inferred from stellar kinematics
• Cross-section upper limit from non-detection
Dark Matter Searches in Gamma Rays

- Reticulum II gamma ray excess
  - LAT Collaboration, Pass 8: local p-value = 0.06 (1.5σ)
  - Geringer-Sameth+2015, Pass 7: local p-value = 0.01 (2.3σ)

![Gamma-ray Counts Map (E > 1 GeV)](image)

Drlica-Wagner et al. (2015) (LAT & DES Collaboration)
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How strong the signal do we expect to see from Reticulum II?

J-factor — the strength of the annihilation signal, inferred from stellar kinematics

Simon et al. 2015 (DES Collaboration)

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Gamma-ray Counts Map (E > 1 GeV)

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Table 1. Reticulum II

Simon et al. 2015 (DES Collaboration)

Annihilation Cross Section

Drllica-Wagner et al. (2015)
(LAT & DES Collaboration)
Indirect Detection of Dark Matter
WIMP Annihilation

We will soon be able to either confirm or refute the dark matter interpretation of the Galactic Center excess using Milky Way satellites.

![Graph showing annihilation cross section vs. DM mass](image)

**Key Points**
- **Pass 8 Combined dSphs**
- **Fermi-LAT MW Halo**
- **H.E.S.S. GC Halo**
- **MAGIC Segue 1**
- **Abazajian et al. 2014 (1σ)**
- **Gordon & Macias 2013 (2σ)**
- **Daylan et al. 2014 (2σ)**
- **Calore et al. 2014 (2σ)**

**Graph Details**
- **Upper limit from 15 dwarf galaxies**
- **Galactic Center excess dark matter interpretation**

**References**
- Ackermann et al. 2015, PRL, 115, 231301
- LAT Collaboration
- Steigman et al. 2012
- Thermal Relic Cross Section

**Note:** The graph illustrates the annihilation cross section as a function of dark matter mass, with various data points and upper limits from different experiments.
Indirect Detection of Dark Matter
WIMP Annihilation

We will soon be able to either confirm or refute the dark matter interpretation of the Galactic Center excess using Milky Way satellites.

Sensitivity increase:
1. longer LAT monitoring
2. more dSphs
3. higher J-factor precision
Improve J-factor Uncertainty

The cross section analysis depend on J-factor uncertainty. Decreasing J-factor uncertainty can be a powerful way to improve sensitivity.

In order to achieve $\log(J)$ uncertainty < 0.2 dex:
- measure >200 stars in each ultra-faint dwarf
- w/ high velocity precision < 2 km/s

LAT and DES Collaboration
Albert et al. 2016

Reticulum II like system
Why Studying the Milky Way Satellite Galaxies

- Missing Satellites Problem — Dark Matter Models
  - CDM vs. WDM vs. SIDM, etc.

- Constraints on WIMP Cross Section — Indirect Dark Matter Detection
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- Constraints on MACHO Abundance
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MACHO Constraints
Eridanus II
• Dwarf galaxy candidate first discovered in DES
• Distant : ~370 kpc (beyond the virial radius of MW)
• Smallest galaxy that owns its star cluster.

Crnojevic et al. 2016
Eridanus II: Dark Matter Content

Li et al. 2017 (DES Collaboration)

28 members identified

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Eridanus II is dark matter dominated dwarf galaxy

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Rule out MACHO as the dominated DM at 10-100 Msun

Li et al. 2017 (DES Collaboration)
Summary

- Milky Way satellites are powerful tools to probe the nature of dark matter.

- Spectroscopic follow-up observations are necessary to confirm the ultra faint dwarf galaxy candidates.

- Ultra faint dwarfs are good site for indirect dark matter search.

- The survival of the central star cluster in the dwarf galaxies can put constraints on the MACHO abundance.

- Ultra faint dwarfs are important to understand the galaxy evolutions on the smallest scale.
backup slides
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• Constraints on WIMP Cross Section — Indirect Dark Matter Detection
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• Star Formation in Dwarf Galaxies
Star Formation in Dwarf Galaxies

Baryon Effects: Astrophysical process prevent stars from forming in most low-mass halos
Star Formation in Dwarf Galaxies

Reionization?
80% of the stars formed 13 Gyr ago
100% of the stars formed 12 Gyr ago
Quiescent Milky Way Dwarfs

Ram Pressure Stripping?
Quiescent vs Star Forming

HI: Neutron Hydrogen Gas

Speakers et al. 2014

Brown et al. 2004
Star Formation in Dwarf Galaxies

80% of the stars formed 13 Gyr ago
100% of the stars formed 12 Gyr ago

What makes these satellites stop forming stars?
Stripping vs. Reionization?

Ram Pressure Stripping?
Quiescent vs Star Forming

Reionization?

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Brown et al. 2004
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Brown et al. 2004
Orbit and Infall History

- $V_{\text{hel}} = 75.1 \text{ km/s}$
- $V_{\text{GSR}} = -67.0 \text{ km/s}$
- Moving towards Milky Way
- Compared with N-body simulations
- Bound to Milky Way
- Most likely on its second passage
  - orbit w/ high eccentricity

Li et al. 2017 (DES Collaboration)