Milky Way Satellite Galaxies with DES

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The Milky Way is surrounded by small satellite galaxies. The luminosities range from $10^7 L_\odot$ to $10^3 L_\odot$. Close to Earth, within 25 kpc, these satellite galaxies are astrophysically simple and dominated by dark matter. Birth of near-field cosmology is also a key aspect of these satellite galaxies. Milky Way Satellite Galaxies

(Bullock, Geha, Powell)
The stars in dwarf galaxies are moving too fast to be explained by visible mass alone.
Finding Milky Way Satellite Galaxies
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Shapley (1938)

Sculptor

Johnson & Sandage (1956)

“Redness”
Finding Milky Way Satellite Galaxies

Select Stars with a Characteristic Age and Metallicity

Convolve with Spatial Kernel

Stellar Field

Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)
Discovery Timeline
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- SDSS Begins
- DECam Installed
- DES Year 1
- DES Year 2
- SDSS Begins

Cumulative Number

Year

- Confirmed
- Candidate
Fig. 1.— Locations of the eight new dwarf galaxy candidates reported here (red triangles) along with nine previously reported dwarf galaxy candidates in the DES footprint (red circles; Bechtol et al. 2015; Koposov et al. 2015a; Kim & Jerjen 2015b), five recently discovered dwarf galaxy candidates located outside the DES footprint (green diamonds; Laevens et al. 2015a; Martin et al. 2015; Kim et al. 2015a; Laevens et al. 2015b), and twenty-seven Milky Way satellite galaxies known prior to 2015 (blue squares; McConnachie 2012). Systems that have been confirmed as satellite galaxies are individually labeled. The figure is shown in Galactic coordinates (Mollweide projection) with the coordinate grid marking the equatorial coordinate system (solid lines for the equator and zero meridian). The gray scale indicates the logarithmic density of stars with $r < 22$ from SDSS and DES. The two-year coverage of DES is $\sim 5000$ deg$^2$ and nearly fills the planned DES footprint (outlined in red). For comparison, the Pan-STARRS 1 survey covers the region of sky with $z > 30$ (Laevens et al. 2015b).

**Legend:**
- Blue - Previously discovered satellites
- Green - Discovered in 2015 with PanSTARRS/SDSS
- Red outline - DES footprint
- Red circles - DES Y1 satellites
- Red triangles - DES Y2 satellites
Open Questions
Missing Satellites
Missing Satellites

- Galaxies inhabit dark matter halos
- Simulations predict that the Milky Way halo should contain thousands of dark matter subhalos
- We only “see” dark matter halo that are traced by baryons, and we only know of several dozen dwarf galaxies.
- Where are the missing satellites?
- What can we learn about galaxy formation and the nature of dark matter?

- Combine large photometric surveys (DES, SDSS, Pan-STARRS, etc.)
- Opportunities to work with Big Data, data mining, and statistics!
- Understand the galaxies that we *don’t see*. 
Galaxy Formation

- The Milky Way satellites found in DES are not distributed uniformly.
- Is the observed distribution of satellites consistent with LCDM?
  - Biases from the Solar position?
  - Accretion as satellites of the Magellanic Clouds?
  - Accretion along the same filament as the Magellanic Clouds?
  - A plane of satellites?
- Need larger photometric coverage to test these various hypotheses (new Magellanic Satellites Survey).
- Need spectroscopy and proper motions to determine the dynamics of satellite systems.
- Lots of opportunities to do photometry and spectroscopy!
Rapid absorption of free neutrons during explosive event

**Possible sites:** core-collapse SNe, neutron star mergers

Observed excess of r-process elements in Ret II relative to other ultra-faint dwarfs (by factor >100) suggests enrichment by a single (rare) event

→ Consistent with neutron star merger hypothesis
Origin of Heavy Elements

- Heavy elements are formed in extreme conditions through (r)apid and (s)low neutron capture processes
- Satellite galaxies are nearby relics of the early universe
- Are r-process elements created continuously by core-collapse supernova or in rare events like neutron star mergers?
Origin of Heavy Elements

Magellan/M2FS

Gemini/GMOS

VLT/GIRAFFE

AAT/AAOmega
Nature of Dark Matter

- Dark Matter Distribution
- Particle Propagation
- Particle Detection
- Dark Matter Annihilation

Neutral Particles
\( (\gamma, \nu) \)

Charged Particles
\( (e^\pm, p^\pm, etc.) \)
Nature of Dark Matter

Galactic Substructure:
- Lower statistics
- Lower background

Galactic Center:
- Larger signal
- Larger background

Residual Map: 1-3 GeV
Credit: Tim Linden
Nature of Dark Matter

\begin{align*}
\langle \sigma v \rangle \text{ (cm}^3\text{s}^{-1}) & = 10^{-27} \\
\text{DM Mass (GeV/c}^2) & = 10^1 \\
\text{Preliminary} & \\
\end{align*}

\textbf{Thermal Relic Cross Section (Steigman+ 2012)}
Shorter Term Projects

Filtered Stars

Tucana group of satellites
(Magellan observing this semester)

Tidal tails around Tucana III
(deeper photometry)

RR Lyrae stars in DES Y2 dwarfs
(SOAR observing this semester)

Satellites and stream around Fornax & Sculptor (Y3 DES data)
Scientific Skills

• These projects will develop a wide range of skills.
• Observing Experience
  – Photometry: DECam, SOAR, Gemini
  – Spectroscopy: Magellan, VLT, AAT
• Astronomical Tools
  – Photometry of large survey data sets (DES, SDSS, DECaLS, Pan-STARRs,...)
  – Medium resolution spectroscopy for velocity determination
  – High resolution spectroscopy and spectral synthesis for elemental abundances
• Computational Tools
  – Parallelized processing of big data
  – Machine learning and data mining
  – Statistical modeling with frequentist and bayesian techniques
Working in DES

- The DES Collaboration provides an extensive support structure.
- Opportunities to meet and interact with scientists around the world.
- Opportunities in other science areas, public outreach, etc.
- Milky Way science is undersubscribed in DES — DES provides a large audience, a lot of support, and little competition.

- Chicago is at the heart of DES
  - Josh Frieman (FNAL/UChicago)
  - Rich Kron (UChicago)
  - Brian Yanny (FNAL)
  - Scott Dodelson (FNAL/UChicago)
  - … and many other faculty, staff, post-docs and students!
Even More Questions

- Optimized searches for low-luminosity dwarf galaxies beyond the MW virial radius.
- Satellite systems of nearby galaxies
- Understanding the structure of the Milky Way halo using various stellar tracers (i.e., MSTO stars, HB stars, etc.)
- High resolution spectroscopy of Carbon-enhanced metal poor (CEMP) stars.
- Identifying high proper motion stars in DES (white dwarfs?)
- Using internal proper motions to understand the dark matter distribution of Milky Way satellite galaxies.
- many, many more…