Searching for Galactic Dark Matter Substructure

Alex Drlica-Wagner

on behalf of the Fermi LAT Collaboration
Indirect Detection of Particle Dark Matter

**Standard particles**

- Quarks
- Leptons
- Force particles

**SUSY particles**

- Squarks
- Sleptons
- SUSY force particles

**INDIRECT SEARCHES**

- Fermi-LAT
- PAMELA
- IceCube

**WIMP?**

?

DM

SM

SM
Gamma Ray Flux
(measured by Fermi-LAT)

\[
\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{\langle \sigma_{\text{ann}} v \rangle}{2m_{\text{WIM}}^2} \sum_f \frac{dN_{\gamma}^f}{dE_\gamma} B_f \times \int \Delta \Omega(\phi, \theta) \int_{\text{los}} \rho^2(r(l, \phi')) dl(r, \phi')
\]

Particle Physics
(photons per annihilation)

\[
\int \Delta \Omega(\phi, \theta) \int_{\text{los}} \rho^2(r(l, \phi')) dl(r, \phi')
\]

Dark Matter Distribution
(line-of-sight integral)
1. Relatively nearby

2. Astrophysically boring

3. Abundant in simulations
   
   – Substructures hosting dwarf spheroidal galaxies.
   
   – Substructures without optical counterparts.
Dwarf Spheroidal Galaxies

- Roughly two dozen dwarf spheroidal satellite galaxies of the Milky Way
- Some of the most dark matter dominated objects in the Universe
- No astrophysical gamma-ray production expected
\[
d\Phi_\gamma \frac{dE_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{\langle \sigma_{\text{ann}} v \rangle}{2m_{\text{WIMP}}^2} \sum f \frac{dN_f}{dE_\gamma} B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l, \phi')) dl(r, \phi')
\]

Dwarf Spheroidal Galaxies

Cross Section Limits

Dark Matter Spectrum

Fermi Data

Factor of Mass?

Dark Matter Distribution

Schematic Diagram

Schematic Diagram
• Perform a combined analysis of multiple dwarf spheroidal galaxies.

• Include uncertainties in the integrated dark matter distributions from stellar kinematic data (model as point sources).

• Joint likelihood function

\[
L(D \mid p_m, \{p_k\}) = \prod_k L_{\text{LAT}}^{D_k}(D_k \mid p_m, p_k) \times \frac{1}{\ln(10) J_k \sqrt{2\pi\sigma_k}} e^{-(\log_{10}(J_k) - \log_{10}(\bar{J}_k))^2 / 2\sigma_k^2}
\]
Dwarf Spheroidal Galaxies

Robust constraints come from a joint likelihood analysis of:
- 10 dwarf galaxies
- 200 MeV - 100 GeV gamma-rays
- 2 years of data
- 4 annihilation channels

Exclude the conventional thermal cross section for a WIMP with mass < 30 GeV annihilating to $b\bar{b}$ or $\tau^+\tau^-$. Include uncertainties in the solid-angle-integrated J-factor.
Examine a 19-dimensional phenomenological scan of supersymmetry (pMSSM)

Calculate a “distance to constraint” from predicted cross sections and limits
• Examine complementarity between the LAT and direct detection searches (solid lines are current limits).

• Highlight in red models which the LAT may be sensitive to over a 10 year mission.

• Direct detection generally does better than the LAT with models that don’t saturate the WMAP bound low relic density.
N-body simulations predict an abundance of low-mass substructure.

Are dwarf galaxies the best component of substructure for dark matter detection?

Some substructure could be more detectable than the dwarf galaxies...

But we don’t know exactly where to look.
Unassociated Subhalos

Accepted to ApJ; arXiv:1201.2691

- Examine unassociated, high-latitude sources in First LAT Catalog.
- Search for non-power-law sources that may have been missed.
- Test for spatial extension ($\alpha_0 = r_s/D$) and spectral shape with 99% confidence.

<table>
<thead>
<tr>
<th>Spectral Index</th>
<th>Flux</th>
<th>$T_{S_{ext}}^{99}$</th>
<th>$T_{S_{spec}}^{99}$</th>
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<tbody>
<tr>
<td>0.9</td>
<td>$2.0 \times 10^{-10}$</td>
<td>6.18</td>
<td>2.38</td>
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<tr>
<td>0.9</td>
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<td>7.87</td>
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</tr>
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</table>

- 231 unassociated 1FGL sources
- 154 non-1FGL source candidates
- 10 representative models
Two Extended Source Candidates

Accepted to ApJ; arXiv:1201.2691

*Two candidate spatially extended sources*

- 1FGL J1302.3-3255 subsequently associated with a radio pulsar
- 1FGL J2325.8-4043 does not pass the spectral selection and is resolved as two sources in 2FGL (high probability of AGN association)

*Neither source satisfies our criteria for a dark matter satellite candidate.*

**NO VALID DARK MATTER SATELLITE CANDIDATES IN 1 YEAR OF DATA**
Detection Efficiency

<table>
<thead>
<tr>
<th>Flux (ph cm(^{-2}) s(^{-1}))</th>
<th>Extension (°)</th>
<th>0.5°</th>
<th>1.0°</th>
<th>2.0°</th>
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<tbody>
<tr>
<td>0.2 × 10(^{-8})</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
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<tr>
<td>0.5 × 10(^{-8})</td>
<td>0.16</td>
<td>0.28</td>
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<tr>
<td>1.0 × 10(^{-8})</td>
<td>0.74</td>
<td>0.76</td>
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<tr>
<td>2.0 × 10(^{-8})</td>
<td>0.99</td>
<td>1.0</td>
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</tr>
<tr>
<td>5.0 × 10(^{-8})</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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</tr>
</tbody>
</table>

- Calculate the detection efficiency for the subhalos in N-body simulations.
- Determine the probability of having no subhalos pass the selection criteria as a function of dark matter cross section.

\[ \langle \sigma v \rangle \sim 2 \times 10^{-24} \text{ cm}^3 \text{ s}^{-1} \]
Predictions and Conclusions

- Future dwarf spheroidal limits:
  - Increased observation time
  - Discoveries of new dwarfs
  - Gains at high energy

- Future searches for unassociated subhalos:
  - Increased observation time
  - Improvements source detection and characterization algorithms
  - A better understanding of the subhalo population.

- The canonical 100 GeV thermal WIMP appears to be within reach.

- Complementarity with direct detection and accelerator experiments is very exciting.
Back-Up Slides
Fermi-LAT Likelihood Analysis

- We like to ask the question:
  - Is there a new source of gamma rays?
  - How confident are we that this new source exists/does not exist?
- The LAT instrument response changes by orders of magnitude: events are not equal!
- Likelihood Analysis:
  - Probability of getting the observed data given a model.
    \[ \mathcal{L} = \prod_i \frac{m_i^{n_i} e^{m_i}}{n_i!} \]
  - Maximize the value of the likelihood function with respect to free parameters of interest (i.e., flux of new source).
  - Assess significance by changing parameter of interest around maximum.
The dark matter content of satellites come from the analysis of stellar dynamics.

The dark matter content for each dwarf galaxy is uncertain.

Some satellites with large dark matter content also have the large uncertainties.

Treat this uncertainty as a nuisance parameter in the likelihood.

Raises the upper limits on cross section.
Counts Maps
Submitted to PRD

Alex Drlica-Wagner | Fermi-LAT Dark
Model the satellite dark matter distribution with NFW profile:

\[ \rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2} \]

Astrophysical Detection Potential (J-factor):

\[ J = \int_{\Delta \Omega} \int_{l.o.s.} \rho(l(\psi))dld\Omega \]

\[ J \approx \frac{1}{D^2} \int_V \rho(r)^2dV \]

For NFW profile:

\[ J \propto \frac{r_s^3 \rho_s^2}{D^2} \]

Using VL-II Simulation:

\[ r_s \propto M^{0.39} \]
\[ \rho_s \propto M^{-0.18} \]
\[ J \propto \frac{M^{0.81}}{D^2} \]
• Could we expect to see any of these unassociated subhalos? Yes
• Does incompleteness in the simulations have much impact? No
Candidate Selection
Accepted to ApJ; arXiv:1201.2691

- Initial Source Selection:
  - 231 high-latitude (|b|>20 deg), unassociated sources from the 1FGL
  - 154 high-latitude (|b|>20 deg) source candidates from independent search (increased sensitivity to non-power-law sources).

- Dark Matter Satellite Selection Criteria:
  - Spatial extensions (for NFW) profile take: \( \alpha_0 = r_s / D \)
  - Hard spectrum (use b-\bar{b}bar as a proxy)
  - Set significance based on Monte Carlo simulations
Candidate Selection
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<td>11.87</td>
<td>6.02</td>
</tr>
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- Test spatial extension and spectral shape with 99% confidence.
- Evaluate for a range of source fluxes and spectral shapes (interpolate to values between).