Searching for Dark Matter in Galactic Substructure

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on behalf of the Fermi LAT Collaboration

Rencontres de Moriond - 2012
Indirect Detection of Particle Dark Matter

**Standard particles**
- u, c, t, γ, H
- Quarks, Leptons, Force particles

**SUSY particles**
- ~u, ~c, ~t, ~γ, ~H
- Squarks, Sleptons, SUSY force particles

**INDIRECT SEARCHES**
- Fermi-LAT
- IceCube
- PAMELA

Every ~3 Hours

20 MeV to > 300 GeV
Gamma Ray Flux
(measured by Fermi-LAT)

\[ \frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{<\sigma_{\text{ann}}v>}{2m_{\text{WIMP}}^2} \sum_f \frac{dN_f^{\gamma}}{dE_\gamma} B_f \]

Particle Physics
(photons per annihilation)

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

Dark Matter Distribution
(line-of-sight integral)
Dark Matter Point Source Schema

Schematic Flux Limit

\[ \log (\text{Flux}) \]

\[ \log (M_{DM}) \]

Schematic Cross Section Limit

\[ \log (\langle\sigma v\rangle) \]

\[ \log (M_{DM}) \]

\[ \frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{<\sigma_{\text{ann}} v>}{2m^2_{WIMP}} \sum_f \frac{dN^f_\gamma}{dE_\gamma} B_f \]

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

- All information incorporated into a likelihood analysis
  - LAT angular resolution and effective area are strongly energy dependent
  - Diffuse background has spatial structure
1. Relatively nearby

2. Astrophysically boring

3. Abundant in simulations
   - Substructures hosting dwarf spheroidal galaxies.
   - Substructures without optical counterparts.

Springel et al. 2008
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
Dwarf dark matter content from the line-of-sight velocities of the member stars (e.g. Martinez et al. 2009)

Mass within half-light radius of each dwarf is largely independent of assumptions on the cored or cuspy nature of the inner profile

Calculate the total integrated J-factor within a cone with angular radius of 0.5 degrees (~ comparable to LAT angular resolution)

The posterior distribution and likelihood function for J are well described by a log-normal function

Some of the new ultra-faint dwarfs have the largest J-factors and the largest uncertainties

<table>
<thead>
<tr>
<th>Name</th>
<th>$l$ (degree)</th>
<th>$b$ (degree)</th>
<th>$d$ (kpc)</th>
<th>$\log_{10}(J)$ (log$_{10}$[GeV$^2$ cm$^{-5}$])</th>
<th>$\sigma$</th>
<th>Reference</th>
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<tr>
<td>Bootes I</td>
<td>358.08</td>
<td>69.62</td>
<td>60</td>
<td>17.7</td>
<td>0.34</td>
<td>[1]</td>
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<td>Carina</td>
<td>260.11</td>
<td>−22.22</td>
<td>101</td>
<td>18.0</td>
<td>0.13</td>
<td>[2]</td>
</tr>
<tr>
<td>Coma Berenices</td>
<td>241.9</td>
<td>83.6</td>
<td>44</td>
<td>19.0</td>
<td>0.37</td>
<td>[3]</td>
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<td>Draco</td>
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<td>34.72</td>
<td>80</td>
<td>18.8</td>
<td>0.13</td>
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<td>Fornax</td>
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<td>Segue 1</td>
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<td>50.42</td>
<td>23</td>
<td>19.6</td>
<td>0.53</td>
<td>[4]</td>
</tr>
<tr>
<td>Sextans</td>
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<td>42.2</td>
<td>86</td>
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<tr>
<td>Ursa Major II</td>
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<tr>
<td>Ursa Minor</td>
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<td>44.80</td>
<td>66</td>
<td>18.5</td>
<td>0.18</td>
<td>[2]</td>
</tr>
</tbody>
</table>

• Perform a **combined analysis** of multiple dwarf spheroidal galaxies

• Approximate **integrated J-factor with 0.5 degrees** as a point-source contribution at the location of each dwarf

• Include **uncertainties** in the integrated dark matter distributions from stellar kinematic data.

• **Joint likelihood function:**

\[
L(D \mid p_m, \{p_k\}) = \prod_k L_{k}^{\text{LAT}}(D_k \mid p_m, p_k)
\]

\[
\times \left( \frac{1}{\ln(10) J_k 2\pi \sigma_k} e^{-(\log_{10}(J_{k}) - \log_{10}(J_{k}))^2 / 2 \sigma_k^2} \right)
\]

**Uncertainty in J-factor**
Dwarf Spheroidal Limits

PRL 107, 241302; arXiv:1108.3546

- 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

- Include uncertainties in the solid-angle-integrated J-factor

- Exclude the conventional thermal relic cross section for a WIMP with mass < 30 GeV annihilating to $bb$ or $\tau^+ \tau^-$
• Compromise between highly constrained MSSM scans (i.e., CMSSM, mSUGRA) and complete agnosticism about yet-undiscovered physics

• Goal is not to find the “best-fit” SUSY models, but rather to describe the range of possible spectra

• The pMSSM is a phenomenological scan over a 19-dimensional MSSM parameter space.
  – 10 squark masses, 3 gaugino masses, 3 tri-linear couplings, 3 Higgs sector parameters

• Impose existing constraints from experimental data (direct detection and pre-LHC collider experiments) to select experimentally valid models

• Take the lightest supersymmetric particle (LSP) to be the dark matter particle
  – LSPs are not required to saturate measured relic density (which is imposed only as an upper limit)
  – pMSSM contains LSPs in the mass range from 30 GeV - 600 GeV
• Take the pMSSM models and generate gamma-ray spectra with DarkSUSY

• Calculate a “distance to constraint” as $\frac{\langle \sigma v \rangle_{\text{Pred.}}}{\langle \sigma v \rangle_{\text{UL}}}$
• 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

Extrapolation to Low-Mass Subhalos

Greater Detection Potential than Draco

Less Detection Potential than Draco

\[ J \propto \frac{M^{0.81}}{D^2} \]
Examine unassociated, high-latitude sources in First LAT Catalog

Independent search for non-power-law sources that may have been missed in First LAT Catalog

Test for spatial extension \( \alpha_0 = r_s/D \) and spectral shape with 99% confidence

NO VIABLE CANDIDATES

Use N-body simulations to determine the probability of having no subhalos pass selection criteria as a function of \( \langle \sigma v \rangle \)

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

\[
\text{Prob}(\text{Don’t Detect Simulated Satellite } j) = \prod_{j} (1 - \epsilon_{i,j}(\langle \sigma v \rangle))
\]

\[
\text{Prob}(\text{Don’t Detect Any Satellites in Simulation})
\]
Predictions and Conclusions

- **Future dwarf spheroidal limits:**
  - Increased observation time
    - LAT is 5 (+5) year mission
  - Discovery of new dwarfs
    - SDSS surveys ~1/4 of the sky
    - DES in the south soon
  - Gains at high energy
    - Increased acceptance and energy range

- Unassociated sources may have better discovery potential
  - Known to be gamma-ray emitters

- Complementarity with direct detection and accelerator experiments

- The canonical 100 GeV thermal WIMP appears to be within reach
Back-Up Slides
• 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 angular resolution and effective area depend on energy and incident angle: events are not equal!
• Likelihood Analysis:
  – Probability of getting the observed data given a model
  – 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

\[ \mathcal{L} = \prod_i \frac{m_i^{n_i} e^{-m_i}}{n_i!} \]
Counts Maps
Submitted to PRD

Preliminary

Bootes I

Carina

Coma Berenices

Draco

Fornax

Sextans

Sculptor

Segue I

Ursa Major II

Ursa Minor

Stacking

Δ(Galactic Latitude)

Δ(Galactic Longitude)

5 deg

0 5 10 15 20 25 30 35 40

0 10 20 30 40 60 80 80

0 40 80 120 160 200 240 280 320

0 60 120 180 240 300 360 420 480

0 60 120 180 240 300 360 420 480

0 60 120 180 240 300 360 420 480

Δ(Galactic Latitude)

Δ(Galactic Longitude)

5 deg

0 5 10 15 20 25 30 35 40

0 10 20 30 40 60 80 80

0 40 80 120 160 200 240 280 320

0 60 120 180 240 300 360 420 480

0 60 120 180 240 300 360 420 480

0 60 120 180 240 300 360 420 480

Δ(Galactic Latitude)

Δ(Galactic Longitude)

5 deg

0 15 30 45 60 75 90 105

0 100 200 300 400 500 600 700 800
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.