Constraining Dark Matter in Galactic Substructure

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Image Credit: fermi.gsfc.nasa.gov
Outline

• Background: indirect detection

• Our model: making gamma-ray maps of annihilation radiation + backgrounds

• Analysis: can the Fermi telescope detect WIMPs?
Indirect Detection

• How can we detect dark matter?
  – Direct detection (e.g. CDMS, COUPP, etc.)
  – Collider (e.g. Tevatron, LHC)
    – **Indirect detection of annihilation products (e.g. gamma rays)**

• Advantages of indirect detection:
  – Gamma rays are “easy” to detect (e.g. Fermi Telescope)
  – Annihilation cross section sets flux of annihilation products *and* relic abundance

• Many places to look:
  – Diffuse dark matter in our galaxy
  – Extragalactic dark matter
    – **Galactic substructure**
Indirect Detection

- Rate of photon production:

\[ \Gamma = \frac{N_\gamma < \sigma v >}{m_\chi^2} \int_V \rho^2 dV \quad \text{[photons/sec]} \]

- Canonical WIMP:  
  \( < \sigma v > \approx 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1} \)
  
  \( m_\chi \approx 50 \text{ GeV} \)
  
  \( N_\gamma \approx 10 \)

\( f_{WIMP} \approx 10^{-28} \text{ cm}^3 \text{s}^{-1} \text{GeV}^{-2} \)
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The Model

• We have developed a model for the photon counts **Probability Distribution Function (PDF)** from galactic substructure + backgrounds
  – Based on work done by Lee et al. ‘09
  – We have calculated the probability, \( P_i(C) \), of observing \( C \) photons in the \( i^{th} \) pixel
  – 3 component model: **dark matter signal**, **galactic background**, and **extragalactic background**
The Model: Mass function and Mass-Luminosity relation

• The mass function of subhalos
  – Based on fits to ΛCDM simulations by Koushiappas et al. 2010:
    \[
    \frac{dN}{dMdV} \propto M^{-1.9} \left( \frac{r}{r_S} \right) (1 + \frac{r}{r_S})^2
    \]

• The mass-luminosity relation
  – Position-dependent with scatter (Koushiappas et al. 2010):
    \[
    P(\ln L_{SH} \mid M, r) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{[\ln L_{SH} - \langle \ln L_{SH} \rangle]^2}{2\sigma^2} \right]
    \]
    \[
    \langle \ln \left( \frac{L_{SH}}{s^{-1}} \right) \rangle = 77.4 + 0.87 \ln \left( \frac{M}{10^5 M_{\text{Sun}}} \right) - 0.23 \ln \left( \frac{r}{50 \text{kpc}} \right) + \ln \left( \frac{f_{\text{WIMP}}}{10^{-28} \text{ cm}^3 \text{s}^{-1} \text{GeV}^{-2}} \right)
    \]
    \[
    \sigma = 0.74 - 0.0030 \ln \left( \frac{M}{10^5 M_{\text{Sun}}} \right) - 0.0111 \ln \left( \frac{r}{50 \text{kpc}} \right)
    \]
The Model: Backgrounds

• Backgrounds
  – Galactic backgrounds:
    • Mainly the result of cosmic ray interactions with galactic matter + photons
    • Galactic background model taken from Fermi collaboration
  – Extragalactic (Isotropic) backgrounds:
    • Extragalactic gamma rays
    • Instrumental sources
  – Our background model:
    • Sum of galactic and extragalactic components
    • Treat normalizations of both backgrounds as free parameters
The PDF for a single subhalo: $P_1(F)$

Our $P_1(F), M_{\text{min}} = 0.01 M_\odot$

$P_1(F)$ from Lee et al., $M_{\text{min}} = 0.01 M_\odot$

Our $P_1(F), M_{\text{min}} = 10^{-6} M_\odot$
The Gamma-Ray PDF from Subhalos

PDFs shown correspond to $\psi = 40^\circ$ away from the galactic center

- Despite differences in models, our $P(C)$ is very similar to that of Lee et al. '09
- Similarities suggest that $P(C)$ calculation is robust
Mapping the Dark Matter Signal

- Region between -40 and +40 degrees in galactic latitude excluded because of large backgrounds
- Map is for 1 year of observation with Fermi telescope, 1 degree² pixels
Now with backgrounds…

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- Map is for 1 year of observation with Fermi telescope, 1 degree$^2$ pixels.
Likelihood Analysis

• Having $P(C)$ enables us to compute the exact likelihood of observations given model parameters

• We consider 3 parameters: $f_{\text{WIMP}}$, galactic background normalization, extragalactic background normalization

• Perform analysis in two ways:
  1) Using true $P(C)$
  2) Using Poisson $P(C)$ with same mean
     This will allow us to determine if knowing the true $P(C)$ is important
Constraints With No Backgrounds

- When there are no backgrounds, using the true P(C) is important.
- Using the wrong Poisson P(C) leads to a bias.
Constraints With Backgrounds

- When backgrounds are present, using a Poisson $P(C)$ doesn’t bias the results.

- However, using the Poisson $P(C)$ produces error bars that are \(~45\%\) larger.

![Graph showing comparison between True Errors and Poisson Errors in terms of $f_{\text{WIMP}}$ (cm$^3$ s$^{-1}$ GeV$^{-2}$) vs Trial Number.](graph.png)
Conclusions

• There is enough information in one year of Fermi data to detect a canonical WIMP
  – Of course, actual detection is complicated by large uncertainties in the model and background

• Using the incorrect $P(C)$ yields an unbiased estimate of $f_{\text{WIMP}}$, but with error bars that are $\sim 45\%$ larger

• Future work:
  – Incorporate energy information
    • Challenging – exact likelihood calculation may not be possible in the presence of backgrounds
  – Analyze actual data!
Signal and Backgrounds
The Model

- **Two step process:**
  1. Calculate the probability of observing a flux $F$ from a single subhalo, $P_1(F)$:

$$P_1(F; \psi_i) \propto \int_0^{l_{\text{max}}} dl \int_{M_{\text{min}}}^{M_{\text{max}}} dM \frac{dN(l, \psi_i)}{dM dV} P[L_{sh} = 4\pi l^2 F \mid M, l]$$