Model-Independent Constraints on Dark Matter Annihilation in Dwarf Spheroidal Galaxies

Pearl Sandick

with Kim Boddy (JHU); Stephen Hill, Jason Kumar, and Danny Marfatia (UH)
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and ongoing work
DM Indirect Detection

- Neutrinos
- Electrons/Positrons
- Protons/Antiprotons
- Nuclei/Antinuclei

- Photons:
  - Direct annihilation
  - Radiation (Internal Brem.)
  - Decays/Hadronization/Cascades
  - Synchrotron, Inverse Compton
    Scattering of $e^+/e^-$

**Annihilation in Dwarf Galaxies**

**Fermi-LAT+DES (2017)**
This analysis:

- We constrain the number of DM annihilation photons, *completely independent of DM particle physics model or DM astrophysics.*
  - estimate the number of background (+foreground) photons empirically
  - constrain the number of DM annihilation photons statistically
- Similar to Geringer-Sameth and Koushiappas (2011):
  - background distribution determined empirically - *no modeling*
  - use only number of photon counts - *no spectral information*
  - simple stacked analysis - *all photon events weighted equally*
  - separates observational data, J factor, and details of DM physics
- Fermi LAT Pass 8 data set and 3FGL point source catalog
Details of Analysis

• Choose an ROI \( (i) \), centered on a target dwarf, with radius 10 degrees.

• Define the signal region as area within 0.5 degrees of the target’s location.

• Randomly choose \( 10^5 \) sample regions within the ROI of the same size as the signal region.

  • Reject any sample region whose boundary intersects the border of the ROI or the boundary of a known source region (within 0.8 degrees of a known point source).

• Histogram the number of counts for the surviving sample regions.

  ➡ Probability Mass Function: \( P^i_{bgd}(N^i_{bgd}) \)
Details of Analysis

Data file available at:
https://arxiv.org/src/1802.03826v1/anc

\[ P_{\text{bgd}}^i (N_{\text{bgd}}^i) \]

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arXiv:1802.03826
Targets

- Pre-defined sets:
  1. **45 objects** from 1611.03184
     (a) 28 confirmed dwarfs
     (b) 28 dwarfs + 13 likely galaxies
     (c) 27 dwarfs w/out contamination
  2. **27 dwarfs** from 1604.05599
  3. **24 dwarfs** w/ J-factors assuming non-spherical halos from 1603.08046
  4. **7 dwarfs** w/ J-factors assuming modified foreground effects from 1608.01749 and 1706.05481
  5. **5 dwarfs** w/ Sommerfeld-enhanced J-factors (Coulomb limit) from 1702.00408

- Choose your own adventure!
Statistics

• Stacking of targets: \[ P_{\text{bgd}}^{\text{tot}}(N_{\text{bgd}}^{\text{tot}}) \equiv \sum_{\sum_i N_{\text{bgd}}^i = N_{\text{bgd}}^{\text{tot}}} \prod_i P_{\text{bgd}}^i(N_{\text{bgd}}^i) \]

• Total number of observed photons: \[ N_{\text{obs}}^{\text{tot}} = \sum_i N_{\text{obs}}^i \]

• Assume Poisson-distributed number of expected signal photons:

\[ P_{\text{DM}}^{\text{tot}}(N_{\text{DM}}^{\text{tot}}; N_{\text{DM}}^{\text{tot}}) = e^{-N_{\text{DM}}^{\text{tot}}} \frac{(N_{\text{DM}}^{\text{tot}})^{N_{\text{DM}}^{\text{tot}}}}{N_{\text{DM}}^{\text{tot}}!} \]

• Upper bound on the expected number of photons from DM annihilation (at confidence level \( \beta \)) is \( N_{\text{bound}}(\beta) \):

\[ \sum_{N_{\text{bgd}}^{\text{tot}} + N_{\text{DM}}^{\text{tot}} > N_{\text{obs}}^{\text{tot}}} P_{\text{bgd}}^{\text{tot}}(N_{\text{bgd}}^{\text{tot}}) \times P_{\text{DM}}^{\text{tot}}(N_{\text{DM}}^{\text{tot}}; N_{\text{bound}}(\beta)) = \beta \]
Statistics

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• Assume Poisson-distributed number of expected signal photons:
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• Upper bound on the expected number of photons from DM annihilation (at confidence level \( \beta \)) is \( N_{\text{bound}}(\beta) \):
  \[ \sum_{N_{\text{bgd}}^{\text{tot}} + N_{\text{DM}}^{\text{tot}} > N_{\text{obs}}^{\text{tot}}} P_{\text{bgd}}^{\text{tot}}(N_{\text{bgd}}^{\text{tot}}) \times P_{\text{DM}}^{\text{tot}}(N_{\text{DM}}^{\text{tot}}; N_{\text{bound}}(\beta)) = \beta \]
Results

• Upper bound on the expected number of photons from DM annihilation (at confidence level $\beta$) is $N_{\text{bound}}(\beta)$:

$$\sum_{N_{\text{bgd}} + N_{\text{DM}} > N_{\text{obs}}} P_{\text{bgd}}(N_{\text{bgd}}) \times P_{\text{DM}}(N_{\text{DM}}; N_{\text{bound}}(\beta)) = \beta$$

P. Sandick
Constraining Dark Matter

- Following Geringer-Sameth and Koushiappas (2011), we constrain models that could have produced an excess over background.

\[
\overline{N}_{DM} = \Phi_{PP} \times J(\Delta\Omega) \times (T_{obs} \tilde{A}_{eff})
\]
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\[
\Phi_{PP} = \frac{(\sigma v)_0}{8\pi m_{X}^{2}} \int_{E_{th}}^{E_{max}} dE_{\gamma} \frac{dN_{\gamma}}{dE_{\gamma}} \frac{A_{eff}(E_{\gamma})}{A_{eff}}
\]

\[
J(\Delta \Omega) = \int_{\Delta \Omega} d\Omega \int dl \int d^{3}v_{1} f(r(\ell, \Omega), \vec{v}_{1}) \int d^{3}v_{2} f(r(\ell, \Omega), \vec{v}_{2}) \times S(|\vec{v}_{1} - \vec{v}_{2}|)
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\[
\sigma v = (\sigma v)_0 \times S(v)
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\]

Note: for decay, \((\sigma v)_0 / 2m_X \rightarrow \Gamma\) and \(J \rightarrow J_D \equiv \int_{\Delta \Omega} d\Omega \int d\ell \rho\)
Constraining Dark Matter

- Following Geringer-Sameth and Koussiappas (2011), we constrain models that could have produced an excess over background.

\[
\overline{N}_{DM} = \Phi_{PP} \times J(\Delta \Omega) \times (T_{obs} \overline{A}_{eff})
\]

\[
\Phi_{PP}^{\text{bound}}(\beta) \equiv N_{\text{bound}}(\beta) \left[ \sum_i J^i \times (T_{obs} \overline{A}_{eff})^i \right]^{-1}
\]
Results

- Constrain DM properties: \( \Phi_{PP} = \frac{(\sigma v)_0}{8\pi m_X^2} \int_{E_{th}}^{E_{\text{max}}} dE_\gamma \frac{dN_\gamma}{dE_\gamma} \frac{A_{\text{eff}}(E_\gamma)}{A_{\text{eff}}} \)

\( XX \rightarrow b\bar{b} \)
\( XX \rightarrow \mu^+ \mu^- \)
\( XX \rightarrow \tau^+ \tau^- \)
\( XX \rightarrow W^+ W^- \)

\[ \text{arXiv:1012.4515} \]
Results

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\[ \Phi_{PP} = \frac{(\sigma v)_0}{8\pi m_X^2} \int_{E_{th}}^{E_{max}} dE_\gamma \frac{dN_\gamma}{dE_\gamma} \frac{A_{eff}(E_\gamma)}{A_{eff}} \]

Internal Brem.

\[ XX \rightarrow \mu^+ \mu^- \gamma \]
Results

• Constrain DM properties: \( \overline{N}_{\text{DM}} = \Phi_{PP} \times J(\Delta \Omega) \times (T_{\text{obs}} \bar{A}_{\text{eff}}) \)

\[
\frac{dN}{dE} [\text{GeV}^{-1}] \\
\begin{align*}
E_r [\text{GeV}] & \quad 100 & \quad 10 & \quad 1 & \quad 0.1 & \quad 0.01 & \quad 0.001 \\
\hline
1.0 \times 10^{-28} & \quad 5.0 \times 10^{-29} & \quad 1.0 \times 10^{-29} & \quad 5.0 \times 10^{-30} & \quad 1.0 \times 10^{-30} & \quad 5.0 \times 10^{-31} & \quad 1.0 \times 10^{-31}
\end{align*}
\]

\( (m_0, m_{\text{max}}, \xi) \)
- (11 GeV, 1000 GeV, −5)
- (11 GeV, 1000 GeV, −1)
- (100 GeV, 110 GeV, −1)
- (100 GeV, 10000 GeV, −3)

Dynamical Dark Matter
\( X_i X_i \rightarrow \phi \phi \rightarrow 4\gamma \)

\[
\Phi = \frac{(\sigma v)_0}{8\pi m_0^2 \Omega_0^2 \Omega_{\text{tot}}^2 (\xi + 1) \Delta m} \left[ \left( \frac{m_{\text{max}}}{m_0} \right)^{\xi+1} - 1 \right]
\]

\( m_{0, n, \phi} \) [GeV]

arXiv:1609.09104

arXiv:1802.03826
MADHAT: Model-Agnostic Dark Halo Analysis Tool

Jason Kumar (UH), Kim Boddy (JHU)
Stephen Hill (UH)

- Everyone should be able to do this analysis!
- Stand-alone code
- Interface with GAMBIT and others
- Inputs: dwarf set and J factors; integrated spectrum of photons in relevant energy range, DM mass
- Outputs: Nbound, PhiPP, cross section limit (if relevant)
- Status: code works, release soon (~1 month)
MADHAT: Model-Agnostic Dark Halo Analysis Tool

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Stephen Hill (UH)

On velocity-dependent dark matter annihilations in dwarf satellites

\[ XX \rightarrow b\bar{b} \]
\[ XX \rightarrow \mu^+\mu^- \]
\[ XX \rightarrow \tau^+\tau^- \]
\[ XX \rightarrow W^+W^- \]
Summary

• We constrain the number of DM annihilation photons, completely independent of DM particle physics model or DM astrophysics.

  • estimate the number of background (+foreground) photons empirically
  • constrain the number of DM signal photons statistically

• There is a minor loss of sensitivity relative to model-dependent searches, but this is an important tool in light of new J-factor determinations and for DM models for which standard analyses are not applicable.

  • eg. multi-body annihilation final states, final-state cascades, multi-component DM, nontrivial velocity dependence, etc.

• MADHAT and GAMBIT-integrated version coming soon!