COSMIC RAY ANOMALIES, GAMMA RAY CONSTRAINTS AND SUBHALOS IN MODELS OF DARK MATTER ANNIHILATION

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based on work with A. Vincent and J. Cline

OUTLINE

- Cosmic Anomaly
- Dark Matter Subhalos outside
- Dark Matter subhalos inside
- Particle Physics realization
Cosmic Ray Anomaly

* Charged Cosmic Particles

* Positron fraction (>10 GeV)
  PAMELA

* Electron + Positron
  Peaking around 500 GeV
  Fermi
Dark Matter

* The Phenomena have no known astrophysics origin (Could be pulsar?)

* Attractive explanation: 1 TeV WIMP
  $\text{DM} + \text{DM} \rightarrow \text{messengers fields } \phi \text{ (on shell)}$
  $\rightarrow \text{SM particles.}$
  $m_\phi < 2m_{\text{proton}}$
  Sommerfeld enhancement to cross section
  $<\sigma v> = BF \times 3 \times 10^{-26}\text{cm}^3\text{s}^{-1}$

* Two issues:
  Gamma Ray?
  substructure?
From N-body Simulation

* Via Lactea II
  - 1 DM main halo in the centre
  - 100 inside the visible galaxy
  - 20,047 resolved DM subhalos

* Extend as far out as 4,000 kpc
  - Our Visible galaxy is 40 kpc across
Subhalos contributions

* Positive contribution
  - Large Number 20,000 subhalos
  - High density
  - small dispersion velocity
  - sub-substructure

* Negative contribution
  - long distance to the milky way
GALPROP + Vía Lactea II

* GALPROP Numerically solve diffusion equation of electrons and positrons

\[
\frac{d}{dt} \psi_{e\pm}(x, p, t) = Q_{e\pm}(x, E) + \nabla \cdot (D(E) \nabla \psi_{e\pm}(x, p, t)) + \frac{\partial}{\partial E} [b(x, E) \psi_{\pm}(x, p, t)]
\]

* Source

** Main halo: \( \rho_{Ein}(r) = \rho_s \exp \left\{ -\frac{2}{\alpha} \left[ \left( \frac{r}{r_s} \right)^\alpha - 1 \right] \right\} \)

** Subhalos: similar density profile,

* Change the boundary condition of GALPROP by using the subhalos data from Vía Lactea II
Mainhalo+Subhalo

+ better fit to PAMELA and Fermi with 2.2 TeV WIMP when subhalos are included (BF$_{SH}=3744$, BF$_{MH}=92$)

+ Larger mass is because of larger propagation distance. The energy loss is due to Inverse Compton Scattering with CMB, IR and Starlight
Best DM annihilation models predict much larger gamma ray fluxes near the galactic center (GC) from Final state radiation (Bresstrahlung) and Inverse Compton Scattering (ICS).

We used the first year of Fermi LAT diffuse gamma ray (Aug 8 2008 to Aug 25 2009) data available from NASA to constrain the allowable DM annihilation.
Numerical Result

* Adding subhalos and still explaining PAMELA and Fermi only slightly reduce the gamma ray constraints

* Density of DM main halo in the GC is still high

* DM profile and final state \((4e, 4\mu, \pi, e)\) has some impact on it, but not enough
What about local subhalo?

* 100(s) subhalos inside the galaxy from Via Lactrea
* small velocity, high density and close to us
* PAMELA and Fermí excess can come from the close subhalo
* We are within 3 kpc of subhalo centre, but further away than 20pc.
Where is the subhalo

* SH1 - SH4 are from Via Lactea, and SH5 is engineered by choosing parameters close to SH4. SH5 is with a higher density (so lower BF)
The five subhalos

* They are atypical in the sense of needing a higher-than-average central density.

* a large $r_s$ is unlikely at small distances from the GC due to tidal disruption.

* Each subhalo was situated along an optimal axis, namely that connecting the earth to the GC.

* The biggest contribution of Gamma Ray is from final-state bremsstrahlung rather than ICS.
Close Subhalo anisotropy

* Fermi Dipole anisotropy of electron and positron

$$\delta = \frac{3D(E) |\vec{\nabla}n_e|}{cn_e}$$

\[60 \text{ GeV Fermi upper bound (500 GeV bound too high to be seen)}\]
certain values for the cross section BF are needed for the subhalos
upper bound of BF for main halo
Is there simple Particle Physics model can be consistent with the requirements.
**Sommerfeld enhancement**

* The non-relativistic particles are moving in some potential. The wave function is distorted by the attractive potential. Or Summing over all the ladder Feynman diagram (QFT)

\[
\frac{1}{m} \frac{d^2 \psi(r)}{dr^2} - V(r)\psi(r) = -m\beta^2\psi(r)
\]

* Consider a DM particle with a U(1) coupling to a dark gauge boson of mass \(\mu (O(1) \text{ GeV})\)

* Using realistic velocity distribution and correct \(\alpha\), this typically predicts **too much enhancement**. Gamma ray constraints are immediately saturated.
Effective Boost Factor

* It is not obvious that one can find models with the desired BF for subhalos and main halo.

* Leptophilic DM is a subdominant component of the total DM, comprising some fraction 1/f.

* Cross section $\langle \sigma v \rangle \sim \alpha^2 / M^2$
  
  Parametrize $\alpha = \sqrt{f} \alpha_{th}$.
  
  By solving Boltzmann eq., the relic density is proportional to $\langle \sigma v \rangle^{-1}$
  
  Therefore, the rate of annihilations goes like $\rho^2 \sigma \propto 1/f$. Accordingly, we define an effective BF

$$\bar{S} = \frac{S}{f}$$
Theoretical fits

* Given \( \alpha \rightarrow \) boost factors for main and subhalos

* The working example (larger \( f \) is needed for a cuspy main halo)
Summary

* We can get better fit to the lepton data by including all the DM subhalos, but the gamma ray constraints are still too strong.

* close subhalo can explain PAMELA/Fermi, also consistent with Fermi LAT diffuse gamma ray survey.

* Caveat: Need large, dense subhalos.

* A realistic U(1) model typically produce too much enhancement. This can be solved if only part of the DM can annihilate to SM particles in this channel.
Thank you
Release Gamma Ray Constraints

* Electron-positron distribution

* Subhalos gamma rays are from all the directions outside

* Main halo gamma rays are largely from the centre of the galaxy, because of the peak of the density profile of DM
Gammas Ray Constraints

* We obtained the constraints for the MH boost factor in the case of Einasto DM profile, annihilation to 4e
\[ BF < 25(35) \text{ at } 1\sigma (2\sigma) \text{ for } M_{DM} = 1\,\text{TeV} \]
\[ BF < 42(52) \text{ at } 1\sigma (2\sigma) \text{ for } M_{DM} = 2.2\,\text{TeV} \]

* Increasing intermediate gauge boson to allow decay to \( \mu \) and \( \pi \)
\[ BF < 23(38) \text{ at } 1\sigma (2\sigma) \text{ for } M_{DM} = 1.2\,\text{TeV} \]

* And choosing a flatter isothermal DM density profile
\[ BF < 62(72) \text{ at } 1\sigma (2\sigma) \text{ for } M_{DM} = 1.2\,\text{TeV} \]
Diffusion Equation

Semi-analytic approach to solve the diffusion eq.

\[
\frac{d}{dt} \psi_{e\pm}(x, p, t) = Q_{e\pm}(x, E) + \nabla \cdot (D(E) \nabla \psi_{e\pm}(x, p, t)) + \frac{\partial}{\partial E} \left[ b(x, E) \psi_{e\pm}(x, p, t) \right]
\]

\( Q \) is the source term from subhalo

\[
Q = \frac{1}{2} \left( \frac{\rho(x)}{M} \right)^2 \langle \sigma v \rangle \frac{dN}{dE} = \frac{n_{DM}^2}{2} BF \langle \sigma v \rangle_0 \frac{dN}{dE}.
\]

Subhalo has the similar DM density distribution as the main halo.

\[
\rho_{Ein}(r) = \rho_s \exp \left\{ -\frac{2}{\alpha} \left[ \left( \frac{r}{r_s} \right)^\alpha - 1 \right] \right\}
\]

\[
\rho_{iso}(r) = \frac{\rho_s}{1 + (r/r_s)^2}
\]
Five subhalos

Sample subhalos from the Via Lactea II simulation. Using them fitting the PAMELA/Fermi lepton fluxes and Fermi gamma ray fluxes.

<table>
<thead>
<tr>
<th>Subhalo</th>
<th>$r_s$ (kpc)</th>
<th>$\rho_s$</th>
<th>$\log BF$</th>
<th>$d_{min}$ (pc)</th>
<th>$V_{max}$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>69</td>
<td>4.74</td>
<td>33.9</td>
<td>2.9</td>
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<tr>
<td>2</td>
<td>0.1</td>
<td>3.46</td>
<td>4.34</td>
<td>95.5</td>
<td>6.7</td>
</tr>
<tr>
<td>3</td>
<td>3.2</td>
<td>0.04</td>
<td>3.76</td>
<td>178</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
<td>1.27</td>
<td>2.35</td>
<td>165</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>1.1</td>
<td>2.0</td>
<td>1.70</td>
<td>170</td>
<td>55</td>
</tr>
</tbody>
</table>

Main halo, 4e channel

<table>
<thead>
<tr>
<th>Model</th>
<th>$\rho_0$</th>
<th>$\log BF$</th>
<th>$d_{min}$ (pc)</th>
<th>$V_{max}$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Einasto</td>
<td>25</td>
<td>$&lt; 1.40$</td>
<td>$1.48$</td>
<td>201 – 277</td>
</tr>
<tr>
<td>Isothermal</td>
<td>3.2</td>
<td>$2.32$</td>
<td>$&lt; 1.81$</td>
<td>$1.88$</td>
</tr>
</tbody>
</table>

Main halo, 4e + 4$\mu$ + 4$\pi$ channel

<table>
<thead>
<tr>
<th>Model</th>
<th>$\rho_0$</th>
<th>$\log BF$</th>
<th>$d_{min}$ (pc)</th>
<th>$V_{max}$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Einasto</td>
<td>25</td>
<td>$&lt; 1.36$</td>
<td>$1.45$</td>
<td>201 – 277</td>
</tr>
<tr>
<td>Isothermal</td>
<td>3.2</td>
<td>$2.32$</td>
<td>$&lt; 1.80$</td>
<td>$1.86$</td>
</tr>
</tbody>
</table>
Close Subhalo vs. main halo

* Gamma ray fluxes on galactic latitude b, in the region $-9^\circ < l < 9^\circ$ at $E=23$ GeV.
Relic Density Constraint

* Sommerfeld enhancement sensitively relies on $\alpha$

* Model: DM has a U(1) gauge symmetry. Kinetic mixing $\varepsilon B_{\mu \nu} F^{\mu \nu}$.

* There are two kinds of final states for annihilation of DM

$$\frac{1}{4} \sum |M|^2 = \begin{cases} 4g^4(1 + 2v^2), & \chi\chi \rightarrow BB \\ \frac{1}{2}g^4 q^2(1 - v^2 \cos^2 \theta), & \chi\chi \rightarrow h\bar{h} \end{cases}$$

$q$ is the U(1) charge of $h$ relative to $\chi$. 
Relic Density Constraint

* Include approximately the effect of Sommerfeld enhancement, the cross section is given by (Cline, Frey, Fang 1008.1784)

\[
\langle \sigma v \rangle_{rel} = \frac{\pi \alpha_g^2}{2M^2} \left( a \left( 1 + \alpha_g \sqrt{\frac{M}{T}} \right) + \frac{T}{M} \left( b - \frac{4}{3} a \right) \left( \frac{3}{2} + \alpha_g \sqrt{\frac{M}{T}} \right) \right)
\]

\[
a = 1 + \frac{1}{4} \sum_i q_i^2, \quad b = 2(1 - \frac{1}{12} \sum_i q_i^2)
\]

* \( \alpha = \sqrt{f} \alpha_{th}, \ f > 1 \)
why f?

* The failure to satisfy the bounds drives us to consider f

![Graph showing predicted and observed values of S against μ (GeV) for different velocity dispersion profiles.](image)
CMB and Relic Density constraints

* the dilution of DM density by $1/f$ insures that the model satisfies stringent CMB constraints from changing the optical depth (Slatyer, etc, 0906.1197, Cirelli and Cline, 1005.1779)