CR signatures of Dipole-interacting Fermionic Dark Matter

- Electromagnetic Interactions (effective dimension-5 dipole operators)
- Relic abundance (Strength of dipoles from present DM Relic abundance)
- Cosmic ray signatures (positrons, antiprotons, photons)
- Conclusion and Future work

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Galactic Rotation Curves

- Newtonian prediction ⇒ expect velocity to fall across the galactic disk as mass density falls.
  \[ \frac{v^2}{r} = G_N \frac{M(r)}{r^2} \Rightarrow v^2 \propto \frac{1}{r} \]

- Observed rotational curves not consistent with visible distribution of matter.

- Supports the view that galaxies are immersed in a halo of so-called dark matter.

- Appears to make up ~83% of mass in the Universe
World Composition
(mass-energy density)

Possible origin of Dark Matter

• Weakly interacting particles (WIMPS), with masses and interaction cross sections of order of the electroweak scale
  most compelling alternative

• Supersymmetry, with R parity conservation
  naturally provides a stable, neutral, dark matter candidate: $\tilde{\chi}^0$
• A spin $\frac{1}{2}$ Dirac fermion with a mass roughly near the electroweak scale (10~1000 GeV) and its nonzero electromagnetic dipole couplings.

**How dark is the dark matter??**

\[ \mathcal{L} = eF_1 \bar{\psi} \gamma_\mu \psi A^\mu + \frac{1}{2} \bar{\mu} \psi \sigma_{\mu\nu} \psi F^{\mu\nu} + \frac{1}{2} \bar{d} \psi \sigma_{\mu\nu} \psi \tilde{F}^{\mu\nu} + \bar{a} \psi \gamma_\mu \gamma^5 \psi (\partial_\nu F^{\mu\nu}) \]

unbroken $U(1)_Q$  

P and T violations  

C and P violation

No discrete symmetry violations
$e^+, \bar{p}, \gamma$ from DM Annihilation

Dark matter particles can annihilate and create other particles.

Indirect detection

**Anti-matter**: rarely produced in astrophysical background.

**Gamma rays**: can transport freely long distance without energy loss or transmutations of the direction.
Effective Lagrangian

The effective Lagrangian with **dimension-5 dipole couplings** (larger than 10GeV):

\[
\frac{1}{2} \bar{\mu} \psi \sigma_{\mu \nu} \psi F^{\mu \nu} \Rightarrow \frac{1}{2} \bar{\mu} B \bar{\psi} \sigma_{\mu \nu} \psi B^{\mu \nu}
\]

\[
\frac{1}{2} \bar{d} \psi \sigma_{\mu \nu} \psi \tilde{F}^{\mu \nu} \Rightarrow \frac{1}{2} \bar{d} B \bar{\psi} \sigma_{\mu \nu} \psi \tilde{B}^{\mu \nu}
\]

**B^{\mu \nu}**: field strength for hypercharge gauge boson (shifted photon)

Rotate w.r.t Weinberg angle:

\[
\mathcal{L}_{\text{eff}} = \frac{1}{2} \bar{\mu} \bar{\psi} \sigma_{\mu \nu} \psi \left( F^{\mu \nu} - \tan \theta_W Z^{\mu \nu} \right)
\]

**MDM**: no discrete symmetry violations

**EDM**: CP violating interaction

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ANNIHILATION PROCESS

\[ \gamma, Z \text{-mediated } s\text{-channel processes.} \]

Anihilation rates

\[
\sigma_f v_{rel} = \frac{1}{3} \sum_f N_C \alpha \beta_f \left[ \mu^2 (s + 8 M^2) + d^2 (s - 4 M^2) \right] \left[ \frac{Q_f^2 (s + 2 m_f^2)}{s^2} + \frac{s (c_V^2 + c_A^2) + m_f^2 (2 c_V^2 - c_A^2)}{4 c_W^4 [(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2]} - \frac{Q_f c_V (s - m_Z^2)(s + 2 m_f^2)}{2 s c_W^2 [(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2]} \right]
\]

\[
\sigma_W v_{rel} = \frac{1}{16} \alpha \beta_W \left[ \mu^2 (s + 8 M^2) + d^2 (s - 4 M^2) \right] \left[ \frac{1}{s} + \frac{s}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2} - \frac{2(s - m_Z^2)}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2} \right] \frac{s^3 + 20 s m_W^2 + 12 m_W^4}{m_W^4}
\]

\[
\sigma_{ZH} v_{rel} = \frac{\alpha E_2 \beta_Z \left[ \mu^2 (s + 8 M^2) + d^2 (s - 4 M^2) \right]}{2 c_W^2 m_W^2 \sqrt{s}} \frac{m_Z^4}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2} \left( 1 + \frac{E_2^2 \beta_Z^2}{3 m_Z^2} \right), \text{ where } E_2 \beta_Z = \frac{1}{2 \sqrt{s}} \left( (s - m_H^2 + m_Z^2)^2 - 4 s m_Z^2 \right)^{1/2}
\]

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✓ Fermionic annihilation products dominate.

✓ $\gamma-Z$ interference plays important role for W-boson channel.

✓ The contribution from ZH and neutrino channels is relatively small because of only Z-exchange
CONSTRAINT FROM RELIC ABUNDANCE

Thermal average for this annihilation

\[ \langle \sigma v_{\text{rel}} \rangle = \frac{x}{8M^5K_2^2(x)} \int_{4M^2}^{\infty} ds \sigma(s) (s - 4M^2) \sqrt{sK_1} \left( \frac{\sqrt{s}}{M} \right) \]

Relic density: Time evolution

Boltzmann equation

\[ \frac{dn_D}{dt} + 3Hn_D = -\langle \sigma v_{\text{rel}} \rangle [n_D^2 - (n_{D}^{\text{EQ}})^2] \]

\[ \Omega_{\text{CDM}}h^2 \simeq \frac{(1.07 \times 10^9)x_F}{\sqrt{g^*m_{\text{Pl}}}(\text{GeV})\langle \sigma v_{\text{rel}} \rangle} \]

This implies the new physics will be \( O(\Lambda) \sim 10 \text{TeV} \)

WMAP data

\[ 0.0946 < \Omega_{\text{CDM}}h^2 < 0.1286 \quad \text{(at 2\sigma)} \]

Constant inverse freeze out temperature: \( x_f \sim 20 \)

Constant annihilation rate: \( \langle \sigma v \rangle \sim 0.62 \text{pb} \)
Source for Cosmic Ray Signals

• Emissivity/energy at location \( x \) from the galactic center

\[
Q_{\alpha}(x, T) = \frac{1}{4} B \langle \sigma v \rangle_f \left( \frac{dN_f}{dT} \right)_\alpha \left( \frac{\rho(x)}{M} \right)^2
\]

Pair-annihilation

Injected
particle spectra

DM density at location \( x \)
(DM halo profile):
NFW, Moore, core isothermal, Einasto

Boost factor

• Fluxes

\[
\phi_{e^+/\bar{p}} = B \frac{v_{e^+/\bar{p}}}{4\pi} \left( \frac{dn}{dE} \right)_{e^+/\bar{p}}
\]

\[
\phi_\gamma = B \frac{\langle \sigma v \rangle_f}{16\pi M^2} \left( \frac{dN_f}{dE} \right)_{\gamma} \int_{\text{los}} \rho^2(r(s, \psi))ds
\]

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Boost factors

• Subhalo structure: \( <\rho^2(x)> \geq \rho(x)^2 \)
  less than 10 or 20 at GH, \( \text{Cirelli et al., NPB 800, 204 (2008)} \)
  it can be very large \(~100(000)\) around GC

• Sommerfeld nonperturbative effect:

  \[
  \overline{\nu}(p')\sigma^{\mu\nu}q_\nu u(p) = i\overline{\nu}(p')(2M\gamma^\mu + (p' - p)^\mu)u(p)
  \]

  Sommerfeld enhancement factor:

  \[
  S = \frac{\pi\alpha_\mu/\nu}{1 - e^{-\pi\alpha_\mu/\nu}} \approx \nu \frac{\pi\alpha_\mu}{\nu}
  \]

  \( \alpha_\mu = 16\pi\mu^2M^2 \)

  \( S \approx 16 \)

• Breit-Wigner resonance: In case that mediators have mass just below twice the DM mass

  \( \Rightarrow \) annihilation rates can be enhanced
Propagation of CRs

Diffusion equation:

\[ \frac{\partial}{\partial t} \left( \frac{dn}{dT} \right)_a - \nabla \cdot \left( K(T) \nabla \left( \frac{dn}{dT} \right)_a \right) - \frac{\partial}{\partial T} \left( b(T) \left( \frac{dn}{dT} \right)_a \right) + \frac{\partial}{\partial z} \left( \text{sign}(z) V_C \left( \frac{dn}{dT} \right)_a \right) = Q_a (x, T) - 2\hbar \Gamma_{\text{ann}} \delta(z) \left( \frac{dn}{dT} \right)_a \]


Three propagation models: MIN, MED, MAX

\Rightarrow Correspond to minimal (MIN), medium (MED), maximum (MAX) antiproton fluxes.

Positrons:

\[ -K(E) \nabla^2 \left( \frac{dn}{dE} \right)_{e^+} - \frac{\partial}{\partial E} \left( b(E) \left( \frac{dn}{dE} \right)_{e^+} \right) = Q_{e^+} (x, E) \]

Antiprotons:

\[ \frac{\partial}{\partial z} \left( \text{sign}(z) V_C \left( \frac{dn}{dT} \right)_p \right) - \nabla \cdot \left( K(T) \nabla \left( \frac{dn}{dT} \right)_p \right) = Q_a (x, T) - 2\hbar \Gamma_{\text{ann}} \delta(z) \left( \frac{dn}{dT} \right)_p \]

The number density \( \frac{dn}{dT} \) with the steady state condition \( \frac{\partial}{\partial t} \left( \frac{dn}{dT} \right) = 0 \), and boundary conditions in a two-zone model.

Delahaye et al., PRD 77, 063527 (2008)
Positrons

• Predicted signals have almost no difference in halo profiles or diffusion models.

• Predicted fractions exhibit rather sharp distribution at $E \sim M$, since our candidate can directly annihilate into electron-positron pair.

• Predicted signals with the boost factor, 30-80 nicely fit measurements of the PAMELA, Fermi LAT, etc.

• We predict that an enhancement of 16 factor comes from Sommerfeld effect, and the rest 2-5 enhancements from the subhalo structure (dark clumps).

$\phi_{e^+}^{\text{TOA}} (E) = \frac{E^2 - m_{e^+}^2}{(E + |Z| e\Phi)^2 - m_{e^+}^2} \phi_{e^+}^{\text{IS}} (E + |Z| e\Phi)$

Gleeson et al., Astropart. Phys. 154, 1011 (1968)
Antiprotons

- No difference in halo profiles
- Sensitive to the propagation models
- Viable in MIN propagation model
- Likely rule out for other propagation Models, MED and MAX
- The MED propagation parameters are in uncertainty of one order of magnitude.
- The MED propagation model might be viable, if we consider uncertainty of Propagation parameters.
Gamma-Rays from GH

- Almost no difference in the halo profiles
- Slightly touch EGRET anomaly

The predicted signals are within the current unobservable experimental constraint.
Gamma-Rays from around GC

Most complex regions in galaxy due to many possible sources: difficult to model the diffuse emission, and discriminate the DM annihilation signals from background.

**Smoking-gun signatures**: monochromatic gamma-ray lines

\[
\langle \sigma v \rangle_{\gamma\gamma} = \frac{\mu^4 M^2}{2\pi}
\]

\[
\langle \sigma v \rangle_{\gamma Z} = \frac{\mu^4 M^2 \beta_Z^2 \tan^2 \theta_W}{4\pi}
\]

Suppressed by magnetic dipole \( \mu^4 \)
Additional suppression by Weingberg angle for \( \gamma Z \) final state
Signals from around GC

- Predictions are under experimental exclusion limits
  Fermi. Col., astro-ph/1205.12739

C. Weniger, hep-ph/1205.1045

The recent tentative analysis, 1 - 3 \times 10^{-27} \text{ cm}^3 / \text{s} excess at DM mass around 130 GeV can be explained with a subhalo enhancement (~100)

A. Kounine, astro-ph/1009.5349;
http://ams.cern.ch.

- The predicted signals are in the potential probe at the AMS-02 with the better experimental method (energy resolution 1.5-2\%, Fermi LAT 11-13\%).
  \sim 10^{-30} - 10^{-29} \text{ cm}^3 / \text{s}
CONCLUSION

• The signals from spin $\frac{1}{2}$ fermionic dark matters are nicely fit the experimental measurements of the PAMELA, Fermi LAT with the enhancements of 30-50 factor.

• Simultaneously, no excess of antiproton over proton gives a severe restriction for this scenario. The MIN propagation model is viable, but likely ruled out for other propagation models, MED, MAX.

• The predicted signals from GH are within current unobservable experimental constraint.
• The signals from regions close to GC as monoenergetic lines are under experimental exclusion limits of the Fermi LAT.

• The recent tentative analysis for the gamma ray excess can be accounted for, provided the subhalo boost factor of about 100.

• Our predicted signals from regions close to GC are in the potential probe at a planned experiment, AMS-02, with the better experimental method.
Future Work

**Neutrino Telescopes:** We need the magnetic profile of the SUN

Thanks for the attention