Probing dark matter with cosmic rays and AGN jets

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Padova - January 11, 2012
Conventional paradigm for indirect dark matter searches with gamma rays

- Pair annihilation
- Decay
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- Pair annihilation
- Decay

Can we search for a new signature?
The idea

• Study scattering processes of high-energy electrons (or protons) off of dark matter with emission of photons.
• Can we detect such photons?
Where should we look?
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1. Source of high energy electrons and/or protons
2. Region with high density of dark matter
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2. Region with high density of dark matter

Two potentially good candidates:
1. Galactic center
2. Active Galactic Nuclei (AGN)
Some extra motivation
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electron (proton) - DM scattering vs DM pair annihilation

Pros and Cons
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Difficult background Difficult background
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Happens for DM

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PART I

Our galaxy
Facts

• There are cosmic rays

• There are high densities of DM
Very rough estimates

Local rate per unit target for a generic WIMP model

\[ m_X \sim 100 \text{ GeV} \]
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DM pair annihilation

\[ q_{\chi\chi} \equiv \sigma_{\chi\chi} \ n_\chi \ \nu_{\text{rel}} \]

\begin{align*}
\sigma_{\chi\chi} & \sim \frac{\alpha^2}{m^2_{\text{EW}}} \sim \text{(few)} \times 10^{-36} \text{ cm}^2 \\
n_\chi & \sim 3 \times 10^{-3} \text{ cm}^{-3} \\
\nu_{\text{rel}} & \sim 10^{-3} c
\end{align*}

\[ q_{\chi\chi} \sim \text{few} \times 10^{-31} \text{ s}^{-1} \]
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Cosmic ray - DM scattering

\[ q_{e\chi \rightarrow e\chi \gamma} \equiv \left( E \frac{d\phi_e}{dE} \bigg|_{1 \text{ GeV}} \right) \times \sigma_{e\chi \rightarrow e\chi \gamma} \]

\[ E \frac{d\phi_e}{dE} \bigg|_{1 \text{ GeV}} \sim 4 \times 10^{-1} \frac{1}{\text{cm}^2 \text{s}} \]

\[ \sigma_{e\chi \rightarrow e\chi \gamma} \sim \frac{\alpha^3}{m_{\text{EW}}^2} \sim \text{(few)} \times 10^{-38} \text{ cm}^2 \]

\[ q_{e\chi \rightarrow e\chi \gamma} \sim \text{few} \times 10^{-38} \text{ s}^{-1} \]

enhancements? \[ \rightarrow \text{few} \times 10^{-34} \text{ s}^{-1} \]
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• Too low for models of asymmetric dark matter (often even further suppressed by some dark sector scale $\Lambda \sim \text{TeV}$)
• Are there DM models that allow for enhancements?
The die-hard MSSM

\[ e, q \rightarrow \chi, \hat{e}, \hat{q} \]

\[ \gamma \rightarrow e, q \]
Two enhancements for this process:

1. when the exchanged selectron (squark) goes on shell
2. log enhancement when the photon is collinear with the electron (quark)
Resonances in the cross section

$M_\chi = 60$ GeV \hspace{1cm} $M_{\tilde{e}} = 100$ GeV
The photon flux

\[
\frac{dN}{dE_\gamma} = r_\odot \rho_\odot \bar{J} \frac{1}{M_\chi} \int d\Omega_\gamma \int dE_e \frac{d\phi}{dE_e} \frac{d^2\sigma}{d\Omega_\gamma dE_\gamma}
\]

- angle between emitted photons and cosmic rays incident on DM

\[
\bar{J} = \frac{2\pi}{\Delta\Omega} \int_{\Delta\Omega} d\theta \sin \theta J(\theta)
\]

- Einasto profile

\[
J(\theta) = \int_0^{2r_\odot} ds \frac{1}{r_\odot \rho_\odot} \rho(r(s, \theta)) f(r(s, \theta))
\]

- to account for higher cosmic ray flux in the vicinity of galactic center

- differential cross section

- angle of observation from earth

\[
\Delta\Omega \sim 10^{-3}
\]

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From cosmic ray electrons

\[ E \frac{dN}{dE} \text{[MeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

- \( M_\chi = 10 \text{ GeV, } M_e = 10.5 \text{ GeV} \)
- \( M_\chi = 10 \text{ GeV, } M_e = 11 \text{ GeV} \)
- \( M_\chi = 50 \text{ GeV, } M_e = 51 \text{ GeV} \)
A different perspective...


Electrons
dN/dE [MeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

Protons

Fermi EGB data

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We are about 4 orders of magnitude below the isotropic diffuse background, this is hopeless!
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But the spectral feature is sharp and this process is *not* isotropic, its intensity correlates with the product of cosmic-ray density times dark matter density. Give the Fermi-LAT enough observation time and we might hope to detect this signature.
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PART II

AGN
Where it all began

Bloom and Wells had this original idea in 97/98.  

- Active Galactic nuclei live in the densest regions of the largest DM halos and are sources of powerful and collimated jets containing ultra relativistic electrons and protons.
- Study the scattering of those high energy particles off of the DM with photons in the final state.
AGN candidates

Requisites for the AGN
• Close by
• Jet at an angle with the line of sight

Centaurus A and M87 the best candidates.
Calculating the photon flux

\[
\frac{dN}{dE_\gamma} = \int \delta_{\text{DM}} \left( \frac{1}{d_{\text{AGN}}^2} \frac{d\Phi_e^{\text{AGN}}}{dE_e} \right) \left( \frac{1}{M_\chi} \frac{d^2\sigma_{e+\chi \rightarrow \gamma+\ldots}}{d\Omega_\gamma dE_\gamma} \right) \cos \theta_0 \, dE_e
\]
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\]

1. DM profile

\[
\delta_{DM} = \int_{r_{min}}^{r_0} \rho_{DM}(r) \, dr
\]
Calculating the photon flux

\[
\frac{dN}{dE_\gamma} = \int \delta_{DM} \left( \frac{1}{d^2_{AGN}} \frac{d\Phi_{e}^{AGN}}{dE_e} \right) \left( \frac{1}{M_\chi} \frac{d^2\sigma_{e+\chi \rightarrow \gamma+...}}{d\Omega_\gamma dE_\gamma} \right) \cos \theta_0 \ dE_e
\]

2. Electron energy distribution in the jet.
Calculating the photon flux

\[
\frac{dN}{dE_\gamma} = \int \delta_{\text{DM}} \left( \frac{1}{d^2_{\text{AGN}}} \frac{d\Phi^\text{AGN}_e}{dE_e} \right) \left( \frac{1}{M_\chi} \frac{d^2\sigma_{e+\chi \rightarrow \gamma+\ldots}}{d\Omega_\gamma dE_\gamma} \right) \cos \theta_0 dE_e
\]

3. Differential cross section
1. The DM profile

\[ \delta_{DM} = \int_{r_{min}}^{r_0} \rho_{DM}(r) \, dr \]

We consider the theoretically motivated profile for the inner region of the AGN by Gondolo and Silk


\[ \rho_{DM}(r) = \frac{\rho'(r)\rho_{core}}{\rho'(r) + \rho_{core}} \text{ where } \rho_{core} \approx \frac{M_\chi}{(\langle \sigma v \rangle_0 t_{BH})} \]
1.1 The DM profile

Normalization

We require that the DM enclosed in $10^5 \, R_S$ does not exceed the uncertainty over the black hole mass

$$M_{BH} = (5.5 \pm 3.0) \times 10^7 M_\odot$$

$$\int_{r_{low}}^{10^5 R_S} dr 4\pi r^2 \rho_{DM} \leq 3 \times 10^7 \, M_\odot$$
$$\delta_{DM} = \int_{r_{min}}^{r_0} \rho_{DM}(r) dr$$

Centaurus A

- $<\sigma v>_0 = 10^{-26}$ cm$^3$/s, $t_{BH} = 10^{10}$ yr
- $<\sigma v>_0 = 10^{-26}$ cm$^3$/s, $t_{BH} = 10^8$ yr
- $<\sigma v>_0 = 10^{-30}$ cm$^3$/s, $t_{BH} = 10^{10}$ yr
- $<\sigma v>_0 = 10^{-30}$ cm$^3$/s, $t_{BH} = 10^8$ yr
2. The electron energy distribution

Blob geometry: the electrons move isotropically in the blob frame with a power law energy distribution, and the blob itself moves with respect to the central black hole with a moderate bulk Lorentz factor.

\[
\frac{d\Phi_e^{AGN}}{d\gamma'} (\gamma') = \frac{1}{2} k_e \gamma'^{-s_1} \left[ 1 + \left( \frac{\gamma'}{\gamma_{br}} \right)^{s_2-s_1} \right]^{-1}
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for \( \gamma_{min} \leq \gamma' \leq \gamma_{max} \)
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\]

for \( \gamma'_{\text{min}} \leq \gamma' \leq \gamma'_{\text{max}} \)

Normalization from kinetic power of the jet

\( L_e \sim 10^{43} - 10^{46} \) erg/s
3. The differential cross section

![Diagram of particle interactions]

In PART I we integrated over the final photon angle:

$$\frac{dN}{dE_\gamma} = r_\odot \rho_\odot \bar{J} \frac{1}{M_\chi} \int d\Omega_\gamma \int dE_e \frac{d\phi}{dE_e} \frac{d^2\sigma}{d\Omega_\gamma dE_\gamma}$$

Now, in PART II the angle is fixed:

$$\frac{dN}{dE_\gamma} = \int \delta_{DM} \left( \frac{1}{d^2_{AGN}} \frac{d\Phi_e^{AGN}}{dE_e} \right) \left( \frac{1}{M_\chi} \frac{d^2\sigma_{e+\chi\rightarrow\gamma+\ldots}}{d\Omega_\gamma dE_\gamma} \right) \cos \theta_0 \ dE_e$$
Centaurus A, SUSY scenario

$E_\gamma$ [eV]

$\nu S_\nu$ [erg s$^{-1}$ cm$^{-2}$]

$\nu$ [Hz]

$M_e = 100$ GeV
$M_\chi = 60$ GeV

$M_e = 110$ GeV
$M_\chi = 95$ GeV

$M_e = 305$ GeV
$M_\chi = 300$ GeV

$M_e = 510$ GeV
$M_\chi = 500$ GeV

$\delta_{DM} = 10^9 M_{\odot}$ pc$^{-2}$, $L = 3 \times 10^{45}$ erg s$^{-1}$

$\delta_{DM} = 10^{10} M_{\odot}$ pc$^{-2}$, $L = 3 \times 10^{45}$ erg s$^{-1}$

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In Figure 4, we plot the 95\% CL bounds in the plane of $m_{\tilde{\chi}}$ and $\Delta m$, where $\Delta m \equiv m_{\tilde{\chi}} - m_{\tilde{e}}$ is the mass splitting between the neutralino and selectron. The upper panel corresponds to $\delta_{DM} = 10^{10} M_\odot$ GeV pc$^{-2}$ and the lower to $\delta_{DM} = 10^{11} M_\odot$ GeV pc$^{-2}$. These values correspond to a neutralino annihilation cross section of $\sigma v \sim 10^{-30}$ cm$^3$ s$^{-1}$ appropriate for a coannihilation scenario and a black hole lifetime of $t_{BH} \sim 10^8$ or $10^{10}$ years, respectively. We continue to assume a bino neutralino and selectrons which are degenerate in mass. Since the optimal energy bin for the search varies with $m_{\tilde{\chi}}$ and $m_{\tilde{e}}$, we derive the constrained region from each energy bin independently, as indicated on the figure. We find that the largest resolving power comes from the highest energy bins, but...
• We also considered UED models. Results and conclusions are very similar to the MSSM.
• We studied scattering of protons off of DM but they should be treated more carefully.
Conclusions
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• We studied gamma-ray spectra coming from the scattering of high energy electrons off of dark matter.
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• Looking at the galactic center, it seems that this signal is quite low, although, if you wanted to be optimistic, you would say it might be possible to detect the feature.
• Looking at AGN, we might be in the right ballpark for Fermi, but the astrophysical uncertainties are large and not completely understood.