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**Fundamental Physics with GeV Gamma Rays**

Based on: Kamionkowski & SP, 0810.3233 (subm. to PRL)
Jeltema & SP, 0808.2641 (JCAP in press)
Jeltema & SP, 0805.1054 (ApJ)
SP, 0801.0740 (PRD)
Colafrancesco, SP & Ullio, astro-ph/0607073 (PRD) and 0507575 (A&A)

KICP – October 27, 2008, Chicago, IL
1. “1 / v” WIMP Models

2. Fermi and Dark Matter Particle Properties

3. Beyond Gamma Rays: the Multi-wavelength Perspective
Detectable WIMP indirect detection signals typically imply some “boost factor” of the annihilation Cross Section expected in the Early Universe.

One possibility: 1/v WIMP models

\[ \sigma_v \sim 3 \times 10^{-26} \, \text{cm}^3/\text{s} \, \sigma_{26} \left( \frac{c}{v} \right) \]

- Right Relic Abundance \( (v \sim c/2) \)
- \( \sim 10^3 \) Enhancement Today \( (v \sim 150 \, \text{km/s}) \)

Models that can lead to a 1/v cross section include e.g. the case of **Sommerfeld** enhanced Dark Matter Cross Section, with a light interaction carrier, or **SUSY**, with \( m_\chi \sim \alpha_{\text{EW}} m_W \)
After chemical decoupling ("freeze-out"), WIMPs **kinematically** decouple at $T \sim T_{kd}$ from the relativistic thermal bath, and **protohalos** start to collapse.

$$M_c \simeq 33 \left( \frac{T_{kd}}{10 \text{ MeV}} \right)^{-3} M_\oplus.$$

$$z_c = 140 - \log_{10} \left( \frac{M_c}{M_\oplus} \right).$$

Diemand et al, astro-ph/0501589
Velocity Dispersion: \[ v \sim \frac{R}{t}, \]

Dynamical Time: \[ t \sim (G\rho)^{-1/2} \]

Size: \[ R \sim \left(\frac{M}{\rho}\right)^{1/3} \]

\[ v \sim M^{1/3}G^{1/2}\rho^{1/6}, \]

\[ \left(\frac{v}{c}\right) \sim 6.0 \times 10^{-9} \left(\frac{M_c}{M_\odot}\right)^{1/3} \left(\frac{z_c}{200}\right)^{1/2}. \]

Kamionkowski & Profumo, 0810.3233 [astro-ph]
WIMP annihilation rate in the first collapsed halos:

\[
\Gamma = 2.2 \times 10^{-17} \left( \frac{M_c}{M_\odot} \right)^{-1/3} \sigma_{26} B_{2.6} \left( \frac{z_c}{200} \right)^{2.5} \left( \frac{m_\chi}{\text{TeV}} \right)^{-1} \text{s.}
\]

where

\[
B = \frac{\int \rho^2 dV}{V \rho_v^2} = \frac{c_v^3 g(c_v)}{3[f(c_v)]^2}
\]

accounts for “clumpiness”

Fraction of Dark Matter particles that annihilate in the first halos:

\[
f \simeq \Gamma t \simeq 0.44 \left( \frac{M_c}{M_\odot} \right)^{-1/3} \sigma_{26} B_{2.6} \left( \frac{z_c}{200} \right)^{2.5} \left( \frac{m_\chi}{\text{TeV}} \right)^{-1}
\]

\( f \ll 1 \) already provide constraints… (we want DM today, and CMB implies a matter density at recombination within 10% of its value today…)

Kamionkowski & Profumo, 0810.3233 [astro-ph]
Two astrophysical constraints from annihilation in the first protohalos:

- Diffuse radiation Background
- IGM Heating and Ionization outside transparency window

**Diffuse Radiation Background Limit**

\[
\sigma_{26} \lesssim 6 \times 10^{-6} B_{2.6}^{-1} \left( \frac{M_c}{M_\oplus} \right)^{1/3} \left( \frac{z_c}{100} \right)^{-1.5} \left( \frac{E_\gamma}{\text{GeV}} \right)^{-1.11} \left( \frac{m_\chi}{\text{TeV}} \right).
\]

**IGM Heating and Ionization Limit**

\[
\sigma_{26} \lesssim 6 \times 10^{-7} \left( \frac{M_c}{M_\oplus} \right)^{1/3} B_{2.6}^{-1} \left( \frac{z_c}{100} \right)^{-2.5} \left( \frac{m_\chi}{\text{TeV}} \right).
\]

Kamionkowski & Profumo, 0810.3233 [astro-ph]
Punchline: 1/v models violate one or the other constraint by $\sim 6$ order of magnitude

Ways out:

- **Detect** Signature in Diffuse Galactic or Extra-Galactic Background!
- Resonant Elastic Scattering with protohalos suppression
- Velocity **cutoff** for the enhancement
- Larger enhancement by **minihalos today**, but something else for Relic Abundance!

Kamionkowski & Profumo, 0810.3233 [astro-ph]
Assess which Dark Matter particle properties can be deduced with gamma-ray spectral analyses, and associated theoretical systematics.

Jeltema & Profumo, 0808.2641 [astro-ph]
Fermi Science Tools simulation of the gamma-ray sky in the GC region

Jeltema & Profumo, 0808.2641 [astro-ph]
Use **XSPEC** to fit background and Dark Matter signal with **DMFIT**

![Graphs showing BCKG only and BCKG+DM]  

<table>
<thead>
<tr>
<th>Bkgd Model</th>
<th>DM Model</th>
<th>DM Mass</th>
<th>Bkgd Only Spectrum</th>
<th>Bkgd spec.</th>
<th>Bkgd spec. + DMFIT</th>
<th>bkgd spec. (fixed) + DMFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>167.5</td>
<td>1.22</td>
<td>1.20</td>
<td>1.10 [144^{+30}_{-10}]</td>
<td>1.09 [173^{+16}_{-5}]</td>
</tr>
<tr>
<td>1</td>
<td>B</td>
<td>92.8</td>
<td>1.22</td>
<td><strong>2.86</strong></td>
<td>1.36 [81.8^{+3.4}_{-8.7}]</td>
<td>1.39 [90.6^{+2.0}_{-2.0}]</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>167.5</td>
<td>0.99</td>
<td>1.24</td>
<td>0.946 [274^{+5.5}_{-58}]</td>
<td>0.891 [208^{+16}_{-16}]</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>92.8</td>
<td>0.99</td>
<td><strong>1.56</strong></td>
<td>1.29 [109^{+8}_{-16}]</td>
<td>1.21 [92.4^{+2.0}_{-2.0}]</td>
</tr>
</tbody>
</table>

Jeltema & Profumo, 0808.2641 [astro-ph]
**Mass & Annihilation Rate** estimates, for a bright DM source at the GC with and without best fit to background alone.

The Dark Matter model has a significant (15%) $\tau^+\tau^-$ component. This causes a bias in the mass extraction towards larger values!

Jeltema & Profumo, 0808.2641 [astro-ph]
Similar approach, but studying the relative **branching ratio** contribution

- With background under control, the **existence** of a second (15%) annihilation mode is pinned down at the 99% CL!

- Including a second annihilation channel, the **artificial bias** in the mass disappears

Jeltema & Profumo, 0808.2641 [astro-ph]
The simultaneous fit to **Background** also yields a systematic effect in the determination of particle Dark Matter properties.

Power law slope **correlates** with mass in some cases, and so does the power-law break energy.

Jeltema & Profumo, 0808.2641 [astro-ph]
Will be able to conclusively state that an unidentified source is associate to Dark Matter annihilation?

One handle: look beyond gamma rays into other wavelengths!
DM **annihilations** produce Gamma Rays as well as energetic **electrons/positrons**, with peculiar injection spectra.
Electrons and Positrons diffuse and loose energy

**Inverse Compton** off CMB and starlight photons, **Bremsstrahlung** and **Synchrotron** emission produce radiation from radio to gamma-ray frequencies

1. **Source Term**

\[
Q(E, \bar{x}) \propto \frac{\rho_{DM}^2(\bar{x})}{m_{DM}^2} \left\langle \sigma_{\chi \chi} v_{\text{rel}} \right\rangle \frac{dN_e(E)}{dE}
\]

2. **Transport Equation**

\[
\frac{\partial}{\partial t} \frac{dn_e}{dE} = \nabla \left[ D(E, \bar{x}) \nabla \frac{dn_e}{dE} \right] + \frac{\partial}{\partial E} \left[ b(E, \bar{x}) \frac{dn_e}{dE} \right] + Q(E, \bar{x})
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\[ b = b_{\text{IC}} + b_{\text{Coul}} + b_{\text{Syn}} + b_{\text{Brem}} \]
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   \]

3. **Compute the Signals**
   
   (IC off CMB/starlight, Synchrotron emission, …)

   \[
   n_e^{EQ}(E, \bar{x})
   \]
The **multi-wavelength spectrum** expected from a 41 GeV “bino” annihilating in the Coma cluster

Colafransceo, Profumo & Ullio, astro-ph/0507575
Hard X-ray emission: generic feature of DM multi-wavelength spectra

Significant **differences** at lower/higher energies

Fit the Hard X-ray emission from the **Ophiuchus** Cluster with Dark Matter

Compatible with **EGRET** limit on gamma ray emission (no detection from Oph.)

Profumo, 0801.0740 [astro-ph]
One Possibility: **Hard X-ray** emission is ascribed to **Dark Matter** Annihilation producing e+e- and IC scattering...

**Fermi-LAT** will conclusively test this scenario!

**Radio** follow-ups also crucial!

Profumo, 0801.0740 [astro-ph]
Down-side: Clusters host other sources of non-thermal activity!

Ideal environment for a multi-wavelength Dark Matter search campaign:

Nearby Dwarf Galaxies

Image credit: Marla Geha
Sensitivity of current X-ray detectors (with ~100ks) comparable to EGRET

Uncertain Diffusion Model, but comparable sensitivity in X and gamma ray!
• **Modifications** to the Annihilation Cross Section (e.g. \(\sim 1/v\)) are strongly constrained by diffuse radiation from the first **protohalos**

• **Gamma-Ray** spectra (and fits to them) can yield important information on the **fundamental** nature of dark matter (e.g. **annihilation modes**, mass)

• Gamma-Ray Indirect **searches** for dark matter annihilation can be enhanced by **multi-wavelength** observational campaigns