Excited Dark Matter
versus PAMELA/Fermi

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Based on

Fang Chen, JC, Andrew Frey,
“A New twist on excited dark matter…” (0901.4327);

F. Chen, JC, A. Frey,
“Nonabelian dark matter: Models and constraints” (0907.4746)

F. Chen, JC, A. Fradette, A. Frey, C. Rabideau,
“Exciting dark matter in the galactic center,” (0911.2222)

F. Chen, Marco Cirelli, JC, A. Frey,
“Excited dark matter confronts gamma ray constraints,” (1003.xxxx)
Cosmic ray puzzles

Several experimental anomalies suggest an unknown source of electrons and positrons, and perhaps dark matter in our galaxy

- INTEGRAL 511 keV gamma ray excess
- PAMELA positron excess at 10-100 GeV
- ATIC, PPB-BETS \((e^+ + e^-)\) excess up to 1 TeV
- Fermi/LAT, HESS \((e^+ + e^-)\) excess at similar energies
511 keV emission from galactic center

Discovered in 1972 by balloon experiment; confirmed by other balloon/satellite observations:

<table>
<thead>
<tr>
<th>instrument</th>
<th>year</th>
<th>flux [10^{-3} \text{ ph cm}^{-2} \text{ s}^{-1}]</th>
<th>centroid [\text{keV}]</th>
<th>width (FWHM) [\text{keV}]</th>
<th>references</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEAO-3(^a)</td>
<td>1979 – 1980</td>
<td>1.13 ± 0.13</td>
<td>510.92 ± 0.23</td>
<td>1.6(^{+0.0}_{-1.6})</td>
<td>Mahoney et al. 1994</td>
</tr>
<tr>
<td>GRIS(^b)</td>
<td>1988 and 1992</td>
<td>0.88 ± 0.07</td>
<td></td>
<td>2.5 ± 0.4</td>
<td>Leeventhal et al. 1993</td>
</tr>
<tr>
<td>HEXAGONE(^b)</td>
<td>1989</td>
<td>1.00 ± 0.24</td>
<td>511.33 ± 0.41</td>
<td>2.90(^{+1.10}_{-1.01})</td>
<td>Smith et al. 1993</td>
</tr>
<tr>
<td>TGRS(^c)</td>
<td>1995 – 1997</td>
<td>1.07 ± 0.05</td>
<td>510.98 ± 0.10</td>
<td>1.81 ± 0.54</td>
<td>Harris et al. 1998</td>
</tr>
<tr>
<td>SPI</td>
<td>2003</td>
<td>0.99(^{+0.47}_{-0.21})</td>
<td>511.06(^{+0.17}_{-0.19})</td>
<td>2.95(^{+0.45}_{-0.51})</td>
<td>this work</td>
</tr>
</tbody>
</table>

SPI spectrometer on International Gamma-Ray Astrophysics Laboratory (INTEGRAL) gives best current measurement
INTEGRAL/SPI 511 keV signal

(Weidenspointner et al., astro-ph/0702621):

A disk component of lower flux is also detected

Total flux $\Rightarrow 10^{43} e^+/s$ inside 1.5 kpc radius
Fig. 3. 511 keV flux spectrum obtained using a gaussian centred on the GC with a FWHM of 10°.

Positrons must be created with $E < 4 - 8$ MeV to have such a narrow annihilation line.
Possible sources?

Various proposals:

• pulsars, black holes
• radioactive nuclei from novae, supernovae, red giants
• cosmic ray interactions with ISM
• jets from x-ray binaries
• gamma ray bursts
• light DM annihilation
• DM decays
• DM excitation

No consensus that any of these is the true source
PAMELA experiment

Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics

Italian-Russian-German-Swedish collaboration
launched June ‘06
orbiting earth at $350 - 610$ km altitude
3 year mission

Goals are to measure:

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antiproton flux</td>
<td>80 MeV - 190 GeV</td>
</tr>
<tr>
<td>Positron flux</td>
<td>50 MeV - 270 GeV</td>
</tr>
<tr>
<td>Electron flux</td>
<td>up to 400 GeV</td>
</tr>
<tr>
<td>Proton flux</td>
<td>up to 700 GeV</td>
</tr>
<tr>
<td>Electron/positron flux</td>
<td>up to 2 TeV</td>
</tr>
<tr>
<td>Light nuclei (up to $Z=6$)</td>
<td>up to 200 GeV/n</td>
</tr>
<tr>
<td>Light isotopes ($D, ^3He$)</td>
<td>up to 1 GeV/n</td>
</tr>
<tr>
<td>Antinuclei search</td>
<td>(sensitivity better than $10^{-7}$ in antiHe/He)</td>
</tr>
</tbody>
</table>
Figure 11: The positron fraction $R$ obtained using a beta-fit with statistical and systematic errors summed in quadrature (red), compared with the positron fraction reported in [2] (black). The solid line shows a calculation by Moskalenko & Strong [40] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy.
Experiments at higher $e^{\pm}$ energies

- PPB-BETS (Polar Patrol Balloon, Balloon-borne Electron Telescope with Scintillation fibers) 2003-2004, Japanese

- ATIC (Advanced Thin Ionization Calorimeter); balloon-borne around south pole (2007), detected charged particles

- HESS (High Energy Spectroscopic System); Mirror array in Namibia, Cerenkov light telescope; European collaboration

- Fermi $\gamma$-ray telescope, satellite launched 06/09; LAT (Large Area Telescope); silicon strips detect charged particle tracks
High-energy data (Abdo et al., 0905.0025)
Arkani-Hamed, Finkbeiner, Slatyer, Weiner (0810.0713) propose that $SU(N)$ nonabelian dark matter models can explain these signals:

$$\mathcal{L} = \frac{1}{2} \bar{\chi}_i (i \slashed{D}_{ij} - M_\chi \delta_{ij}) \chi_j - \frac{1}{4g^2} B_\mu^a B_\mu^{a\nu} - \frac{1}{\Lambda} \Delta_a B_\mu^{a\nu} Y_{\mu\nu}$$

- dark matter
- dark gauge sector
- mixing with SM

Example: triplet DM in SU(2) gauge theory, with $\langle \Delta_2 \rangle / \Lambda = \epsilon \ll 1$:

$$\chi_2 \xrightarrow{\text{+ cyclic permutations}} B_3 \quad \chi_1$$

Notice that gauge interactions are \textit{off-diagonal} in $\chi_i$. 
DM can annihilate into $B$ gauge bosons, which decay to $e^\pm$:

But what about other charged particles, including antiprotons?

PAMELA sees no excess $\bar{p}$, only $e^+$.

Assume mass of $B$ is $\mu \lesssim 1$ GeV.

Then $B$ can decay only into light particles, $e^+e^-, \pi^+\pi^-, \mu^+\mu^-$
Fit to PAMELA+Fermi data

From Papucci, Strumia, 0912.0742:

DM $\rightarrow 4\mu$, isothermal profile

Needs cross section $\sim 300 \times$ greater than thermal freeze-out value —

“boost factor” $\sim 300$
Origin of boost factor

Boost factor can be explained by slow speed of DM in galaxy. More time to interact, higher cross section:

Quantum version is Sommerfeld enhancement. Can give boost factors of 1000 or more, depending on
\[
\alpha_g = \frac{g^2}{4\pi}, \quad \mu / M_\chi, \quad \text{and velocity of DM.}
\]
INTEGRAL low-energy positrons

Same models can potentially explain low-energy $e^+$ excess from galactic center (Finkbeiner, Weiner, astro-ph/0702587)

“Excited DM” mechanism (XDM)

Such mass splittings can occur naturally . . .
Origin of small mass splittings

With gauge symmetry spontaneously broken, radiative mass splittings are of order \( \delta M_{\chi} \sim \alpha g \mu \)

\[
\begin{align*}
\chi_1 & \quad + \quad \chi_2 & = -\frac{1}{2} \alpha (\mu_2 + \mu_3) \\
\chi_2 & \quad + \quad \chi_1 & = -\frac{1}{2} \alpha (\mu_1 + \mu_3) \\
\chi_3 & \quad + \quad \chi_1 & = -\frac{1}{2} \alpha (\mu_1 + \mu_2)
\end{align*}
\]

For \( \mu \sim 100 \text{ MeV} \) and \( \alpha g \sim 0.01 \), \( \delta M_{\chi} \sim \text{MeV} \).
XDM: does it really work?

Is the excitation cross section $\sigma_{\chi_1\chi_1 \rightarrow \chi_3\chi_3}$ large enough to give the observed rate?

Pospelov, Ritz hep-ph/0703128 claim unitarity limit on $\sigma$ makes effect too weak to explain INTEGRAL/SPI 511 keV signal.

$$\sigma(v) = \sum_l \pi \frac{(2l + 1)}{M_0^2 v^2} f_l(v)$$

Unitarity $\Rightarrow f_l \leq 1$.

But how many partial waves might contribute?

Must actually compute $\sigma$. 
Schrödinger eq. for XDM

Since $v/c \ll 1$, use NR QM (Arkani-Hamed et al., (0810.0713)

$$-\Phi''_l + \left( \frac{l(l+1)}{x^2} + \Gamma(\hat{V} - \Delta) \right) \Phi_l = 0, \quad \hat{V} = \begin{pmatrix} 0 & -e^{-\eta x} \\ -e^{-\eta x} x & 1 \end{pmatrix}$$

where $x = 2\frac{\delta M}{\alpha_g} r$ and

$$\Phi_l = \begin{pmatrix} \chi_1 \\ \chi_3 \end{pmatrix}_l, \quad \Gamma = \frac{\alpha_g^2 M \chi}{2\delta M}, \quad \Delta = \frac{k^2}{2 M \chi \delta M} = \frac{v^2}{v_t^2}, \quad \eta = \frac{\alpha_g \mu}{2\delta M}$$

$$(v_t = \text{threshold velocity for producing } \chi_3)$$

Must solve numerically for $f_l(v)$. For small $\mu$ (small $\eta$), hundreds of partial waves can contribute.

Numerically challenging!
Partial wave contributions

\[ \Sigma_{l} \frac{(2l+1)f_{l}}{\Delta}^{1/2} \]

first 200 partial waves

\[ \Gamma = 100, \eta = 0.5 \]

\[ \Delta - 1 = \frac{v^2}{v_t^2} - 1 \]
Numerical challenge:

For each different value of

DM mass $M$,

- gauge boson mass $\mu$,
- mass splittings $\delta M_{13}, \delta M_{23},$

must recompute these 100’s of functions
XDM: rate of $e^+$ production

Rate of $e^+$ production in galactic center is

$$R_{e^+} = 4\pi \int_0^{r_c} dr \ r^2 \frac{\langle \sigma v \rangle}{2} \left( \frac{\rho(r)}{M_\chi} \right)^2$$

where $\rho(r) =$ DM density profile and

$$\langle \sigma v \rangle (r) = \int d^3v_1 \int d^3v_2 \ f(v_1, r) f(v_2, r) \ \sigma(v_{\text{rel}}) \ v_{\text{rel}}$$

Distribution function is Maxwell-Boltzmann,

$$f(v, r) = N \exp \left( -\frac{v^2}{2v_{s}^2(r)} \right) \ \text{for} \ \ v \leq v_{\text{esc}}(r).$$
DM density profiles

Common parametrization of density is Einasto form:

\[ \rho = \rho_{-2} \exp \left( -\frac{2}{\alpha} \left( \left( \frac{r}{r_{-2}} \right)^\alpha - 1 \right) \right) \]

Smaller \( \alpha \) \( \rightarrow \) cuspier profile \( \rightarrow \) larger rate.

- \( N \)-body simulations (including baryons) suggest \( 0.1 \lesssim \alpha \lesssim 0.2 \)
- \( \rho \) in solar neighborhood \( r = r_\odot \cong 8.3 \) kpc is known to be
  \[ \rho_\odot = (0.3 - 0.4) \text{ GeV/cm}^3 \]
- Total mass inside \( r = 60 \) kpc constrained by circular velocities: \( (X.X. \ Xue \ et \ al., \ 0801.1232) \)
  \[ M_{60} = (4 \pm 0.7) \times 10^{11} M_\odot \]

These fix \( \rho_{-2} \) and \( r_{-2} \) in terms of \( \alpha \).
DM velocity dispersion profiles

$N$-body simulations including baryons Tissera et al., (0911.2316) measure velocity dispersion $v_s(r)$:

$$v_s(r) \propto r^{\chi} \rho(r)$$

with modified exponent

$\chi \sim 1.64$ (cf. 1.875 for pure DM)
$e^+$ production rate (Chen, JC, Frey, Fradette, Rabideau, 0911.2222)

We find that rate is too small to match observations unless $\delta M < 600$ keV.

But we need $\delta M > 2m_e$ for the decay $\chi_3 \rightarrow \chi_1 e^+ e^-$ to occur!
Chen, JC, Frey, 0901.4327 suggested a solution—inverted mass hierarchy. \( \chi_2 \chi_2 \rightarrow \chi_3 \chi_3 \) easier than \( \chi_1 \chi_1 \rightarrow \chi_3 \chi_3 \):

\[
\begin{array}{c}
\chi_3 \\
\chi_2 \\
\chi_1
\end{array}
\]

\[
\begin{array}{c}
\delta M \sim 100 \text{ keV} \\
\Delta M \geq 1 \text{ MeV} \\
\text{inverted hierarchy}
\end{array}
\]

\[
\begin{array}{c}
\chi_3 \\
\chi_2 \\
\chi_1
\end{array}
\]

\[
\begin{array}{c}
\Delta M \geq 1 \text{ MeV} \\
\delta M \sim 100 \text{ keV} \\
\text{normal hierarchy}
\end{array}
\]

- \( \chi_2 \) must be stable against \( \chi_2 \rightarrow \chi_1 + \ldots \); \( \mathbb{Z}_2 \) symmetry can insure this.
- Must compute washout of \( \chi_2 \) density due to \( \chi_2 \chi_2 \leftrightarrow \chi_1 \chi_1 \) downscattering.
We find examples that work

Contours of $\log(R_{e+}/R_{\text{obs}})$ in DM-gauge boson mass plane:

SU(2) triplet model, $\alpha = 0.17$, $\delta M = 100$ keV

Gauge coupling is fixed at $\alpha_g = 0.031$ to give correct relic density (Chen, JC, Frey 0907.4746)
Effect of more/less cuspy halos:

Contours of $\log(\frac{R_{e^+}}{R_{\text{obs}}})$ in DM-gauge boson mass plane

for $\alpha = 0.14, 0.17, 0.20$
Angular profile of 511 keV signal

Assuming $e^+$ annihilates close to where it was produced, 511 keV $\gamma$’s track $e^+$. 

$\alpha = 0.2$ profile gives best fit to angular dependence:

Direct measurement of $\rho(r)$ near galactic center! (unless $e^+$ propagate over $\gtrsim 250\,$pc before annihilating)
Outline

- The cosmic ray anomalies
- A dark matter explanation of the anomalies
- Excited dark matter and 511 keV gamma rays

- 511 keV versus PAMELA/Fermi anomalies
IC $\gamma$’s from high-energy $e^\pm$

$e^\pm$ from $\chi\chi \rightarrow 4e$ produce high-energy $\gamma$’s by inverse Compton scattering on background photons (starlight).

Fermi/LAT sees no evidence of excess high-energy $\gamma$’s; constrains the DM annihilation cross section.
IC $\gamma$’s from high-energy $e^{\pm}$

We use Papucci, Strumia 0912.0742 constraints, which depend on leptonic final states and DM density profile:

---

less cuspy

more cuspy

---
IC $\gamma$’s from high-energy $e^{\pm}$

Compare $4e$ with $4\mu$ channel (with $\alpha = 0.17$ Einasto parameter):

Provides weaker constraint on $\sigma$ than does $4e$ channel

True constraint is linear combination of $4e$ and $4\mu$, since $B_{\mu} \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$. 
Compatibility of XDM with PAMELA

Our working examples can simultaneously fit PAMELA and 511 keV anomalies, but not Fermi excess $e^\pm$:
XDM and PAMELA at $\alpha = 0.2$

By taking $\delta M = -100$ keV ($M_{\chi_2} > M_{\chi_3}$), we find examples that work for both 511 keV and PAMELA at $\alpha = 0.2$:
meaning of $\delta M < 0$

The stable state can be the one with highest mass:

\begin{align*}
\chi_3 & \quad \delta M \sim 100 \text{ keV} \\
\chi_2 & \quad \Delta M \geq 1 \text{ MeV} \\
\chi_1 & \quad \delta M > 0
\end{align*}

\begin{align*}
\chi_2 & \quad \delta M \sim -100 \text{ keV} \\
\chi_3 & \quad \Delta M \geq 1 \text{ MeV} \\
\chi_1 & \quad \delta M < 0
\end{align*}

No excitation is necessary; scattering induces de-excitation
Are there other predictions?

We would like to test the DM annihilation hypothesis using independent observables.

- Beam dump (fixed target) experiments

- Monoenergetic $\gamma$ ray from $\chi_3 \rightarrow \chi_1 \gamma$ at galactic center

transition magnetic moment interaction

(Chen, JC, Frey, 0907.0746)
Laboratory and other probes

Kinetic mixing $\epsilon$ and gauge boson mass $\mu$ parameter space is not highly constrained; provides opportunities for new fixed target searches

Bjorken et al., 0906.0580
\( \chi_3 \rightarrow \chi_1 \gamma \) decays in galaxy

Chen, JC, Frey, 0907.4746

we predict \( \chi_1 \) as well as \( \chi_3 \)

We predict constraint

\[
\alpha_g < 0.015 \left( \frac{250 \text{ MeV}}{\mu} \right)^2 \left( \frac{M}{300 \text{ GeV}} \right) \left( \frac{\delta M_{31} - 2m_e}{100 \text{ keV}} \right)^{3/2}
\]

based on nonobservation of such a line. Could saturate at freeze-out value \( \alpha_g = 0.03 \) for reasonable values of \( \delta M_{31} \).

\( \rightarrow \) INTEGRAL could discover such an extra line signal.
Conclusions

Hidden sector DM models are natural from particle physics point of view

DM annihilation/excitation can explain several of the cosmic ray anomalies, perhaps not all

XDM interpretation of 511 keV excess compatible with PAMELA positrons, but (so far) not Fermi excess

New data from Fermi could put more pressure on the models

Complementary observables in fixed-target experiments or galactic gamma ray spectroscopy could corroborate the models