Indirect Probes of the Hidden Sector

February 2010

Tomer Volansky
Institute for Advanced Study, Princeton

Based on:
  P. Meade, M. Papucci, TV, [arXiv:0901.2925].
  P. Meade, M. Papucci, A. Strumia, TV, [arXiv:0905.0480].
  J. Ruderman, TV, [arXiv:0907.4373].
  J. Ruderman, TV, [arXiv:0908.1570].
  P. Meade, S. Nussinov, M. Papucci, TV, [0910.4160].
Intriguing idea. May be motivated by:

- Fine tuning in SUSY models (hidding the Higgs).
- Recent cosmic-ray anomalies.
- Some string theory constructions.
- LHC phenomenology (hidden valleys).
- ...
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[Strassler,Zurek, 2006]

[Falkowski,Ruderman,TV,Zupan, 2010]

[Cholis,Goodenough,Weiner, 2008; Arkani-Hamed,Finkbeiner,Slatyer,Weiner 2008...]

\[ \epsilon F'_{\mu\nu} B^{\mu\nu} \]
• For concreteness, we’ll assume that the hidden sector contains a new force (new, dark photon).

• Mass of dark photon ~ GeV.

• Then the SM fields are charged under new force:

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- Mass of dark photon ~ GeV.

- Then the SM fields are charged under new force:

\[ \gamma' \rightarrow e^+ + e^- \]

- The new photon can also decay into SM particles.
The hidden sector can be probed directly by various experiments:

- High-Energy colliders.

$$\epsilon \lesssim 10^{-6} - (10^{-9}?)$$
Experimental Probes: Direct

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- High-Energy colliders.
- Low-Energy $e^+e^-$ and $e^-p$ colliders.

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\[ \epsilon \lesssim 10^{-4} \]

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$\epsilon \lesssim 10^{-7}$
The hidden sector can be probed directly by various experiments:

- High-Energy colliders.
- Low-Energy $e^+e^-$ and $e^-p$ colliders.
- Fixed-target experiments.
- Meson decays.

<table>
<thead>
<tr>
<th>$X \rightarrow YU$</th>
<th>$n_X$</th>
<th>$m_X - m_Y$ (MeV)</th>
<th>$\text{BR}(X \rightarrow Y + \gamma)$</th>
<th>$\text{BR}(X \rightarrow Y + \ell^+\ell^-)$</th>
<th>$\epsilon \lesssim$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \rightarrow \gamma U$</td>
<td>$n_\eta \sim 10^7$</td>
<td>547</td>
<td>2 × 39.8%</td>
<td>6 × 10^{-4}</td>
<td>2 × 10^{-3}</td>
</tr>
<tr>
<td>$\omega \rightarrow \pi^0 U$</td>
<td>$n_\omega \sim 10^7$</td>
<td>648</td>
<td>8.9%</td>
<td>7.7 × 10^{-4}</td>
<td>5 × 10^{-3}</td>
</tr>
<tr>
<td>$\phi \rightarrow \eta U$</td>
<td>$n_\phi \sim 10^{10}$</td>
<td>472</td>
<td>1.3%</td>
<td>1.15 × 10^{-4}</td>
<td>1 × 10^{-3}</td>
</tr>
<tr>
<td>$K^0_L \rightarrow \gamma U$</td>
<td>$n_{K^0_L} \sim 10^{11}$</td>
<td>497</td>
<td>2 × (5.5 × 10^{-4})</td>
<td>9.5 × 10^{-6}</td>
<td>2 × 10^{-3}</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ U$</td>
<td>$n_{K^+} \sim 10^{10}$</td>
<td>354</td>
<td>-</td>
<td>2.88 × 10^{-7}</td>
<td>7 × 10^{-3}</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu U$</td>
<td>$n_{K^+} \sim 10^{10}$</td>
<td>392</td>
<td>6.2 × 10^{-3}</td>
<td>7 × 10^{-8a}</td>
<td>2 × 10^{-3}</td>
</tr>
<tr>
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$\epsilon \lesssim 10^{-6} - (10^{-9}?)$

$\epsilon \lesssim 10^{-4}$

$\epsilon \lesssim 10^{-7}$

$\epsilon \lesssim 10^{-3}$
- Hidden sector can be probed indirectly by searching for sources that produce the light hidden states.
- An attractive possibility:

\[ \delta M \quad \leftrightarrow \quad \text{Hidden Sector} \]

- Motivated by recent CR anomalies.
- In this talk we concentrate on two new probes:
  - Photon measurements. \( \epsilon \lesssim 10^{-9} \)
  - Neutrino Telescopes. \( \epsilon \lesssim 10^{-15} \)
Outline

• The Cosmic Ray Anomalies
• Model Independent Analysis
• Decaying DM: Probing a Hidden Sector
  • A Model
  • Predictions
• Seeing the Hidden Sector in Neutrino Telescopes
• Conclusions
The Cosmic Ray Anomalies
FERMI and HESS
FERMI and HESS
What can it be?

- **Systematics?**
  - PAMELA: sufficient proton rejection?
  - PAMELA and FERMI electron measurements consistent?

- **Propagation?**
  - $e^+$ created through interactions of CR-$p$’s with interstellar matter.
  - Propagation of positrons to us is model dependent and unknown.
  - PAMELA may encode information of the propagation model. Indicates a more significant energy loss at lower energies.
  
  [Blum, Katz, Waxman, 2009]

- **Astrophysical Source?**
  - Positrons from Pulsars
    [Hooper et al., 2008; Yuksel et al., 2008; Zhang, Cheng 2001; Profumo 2008]
  
  - Acceleration in SNR
    [Blasi, 2009]
  
  - Inhomogeneities of sources
    [Nakar, Piran, Shaviv, 2009]
  
  - ...
For the rest of the talk:

Assume anomalies are indirect evidence for DM
Model Independent Analysis
Identifying Dark Matter

DM is required to address:

- **Significant excess in** $e^\pm$: Electronic activity.
- **No excess in** $\bar{p}$: No hadronic activity.
- **No feature in FERMI**: DM mass must be $\gtrsim 1 \text{ TeV}$.
- **For annihilating DM**: In the absence of large local overdensity (boost factor), annihilation cross-section is $\mathcal{O}(1000) \times \text{WIMP}$.
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- For annihilating DM: In the absence of large local overdensity (boost factor), annihilation cross-section is $\mathcal{O}(1000) \times$ WIMP.

- Models of DM bifurcate into annihilating or decaying DM.

- Those that further explain absence of hadronic activity assume symmetry or kinematical constraint.
• Tension with measurements from Galactic Center.
• Tension with CMB Measurements.
• Tension with Extra-galactic photon measurements.
• Required enhancement of annihilation rate, $O(\text{few} \times 1000)$, hard to achieve.
Disclaimer

Astrophysics uncertainties do not allow for a robust statement. Annihilating models cannot be excluded definitively.
Annihilating DM is in Trouble

- Tension with measurements from Galactic Center.
- Tension with CMB Measurements.
- Tension with Extra-galactic photon measurements.
- Required enhancement of annihilation rate, $O(\text{few} \times 1000)$, hard to achieve.
• All 4-leptonic channels fit well.
• Positron faction expected to rise.
• **Diffuse photons provide (relatively) robust prediction.** Should be measured at $\sim 100$ GeV.

• Ann’ modes that produce $\pi^0$’s are disfavored by GC/GR.

• Ann’ modes that produce many $\nu$’s are disfavored by SuperK.

• $\tau^{\pm}$ channel predict a bump (due to $\pi^0$’s) in diffuse gamma, but is excluded by GC/GR and SuperK.

• **All annihilation channels are in tension with measurements in GC/GR.** Together with background they are excluded, unless DM profile is shallower.
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CMB Constraints

[Finkbeiner et. al. 2009;]
Annihilating DM is in Trouble

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- Tension with CMB Measurements.
- Tension with Extra-galactic photon measurements.
- Required enhancement of annihilation rate, $O(\text{few } \times 1000)$, hard to achieve.
• Requires large coupling to force carrier, \( \lambda \gtrsim 1 \).
• Same coupling \( \lambda \) sets the relic abundance.
• In practice, hard to write models that generate sufficient enhancement and the correct relic abundance.
Decaying DM works better...

- Correct lifetime to explain PAMELA+FERMI+HESS is obtained if DM decays through dimension-6 operators suppressed by the GUT scale:

\[
\tau \simeq \left( \frac{M_{DM}^5}{16\pi^2 M_{GUT}^4} \right)^{-1} \simeq 10^{26} \text{ sec} \left( \frac{M_{DM}}{1 \text{TeV}} \right)^{-5} \left( \frac{M_{GUT}}{5 \times 10^{15} \text{ GeV}} \right)^4
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[Eichler, 1989]
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- To ensure longevity: In \( M_{\text{GUT}} \to \infty \) limit, DM is completely stable due to a global (discrete) symmetry.

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- Simpler than annihilating: does not require large enhancement of thermal cross-section.

- Usual WIMP cosmology apply: Thermal relic.
Decaying DM: Constraints

- Dependence on DM density is weaker at the Galactic Center.
- **Decaying DM fits well and is not constrained by photons or neutrinos.**
- May be probed by FERMI as in the annihilating case.
- Can, in principle, be differentiated from annihilating case if hard spectrum is measured. This is excluded for annihilating models.

[Meade, Papucci, Strumia, TV 2009]
We now argue:

Low energy spectrum of hidden sector can be probed in the decaying DM case.
Models of Decaying Dark Matter
Models of decaying DM have problems explaining the absence of anti-protons and photons from the GC.

Typically require significant fine tuning or complicated and ad hoc structure.

Can be naturally achieved if DM decays into a hidden "dark" sector.
• Models of decaying DM have problems explaining the absence of anti-protons and photons from the GC.

• Typically require significant fine tuning or complicated and ad hoc structure.

• Can be naturally achieved if DM decays into a hidden “dark” sector.

• The DM, $\chi$, does not have to be charged under the dark sector.

• GeV scale explains the leptonic activity, through kinematics.

[Cholis, Goodenough, Weiner 2008]
A Model

- Assume:
  - GUT.
  - SUSY (natural with GUT and stable GeV scale).
  - Gauge mediation.

- To demonstrate:
  \[ G_{\text{dark}} \times G_{SM} = U(1)_d \times SU(5) \]
  \[ \chi + \bar{\chi} = (0, \mathbf{5} + \mathbf{ar{5}}) \]
\[ W_{\text{decay}} = (M_{\text{GUT}} + X)YY + M_{\text{GUT}}XX + \bar{X}\chi\bar{5}_f \]

\[ \frac{\alpha_d}{4\pi M_{\text{GUT}}^2} \int d^2\theta \chi\bar{5}_f W_d^2 \]
\[
\frac{\alpha_d}{4\pi M^2_{\text{GUT}}} \int d^2\theta \, \bar{\chi}_5 f W_d^2
\]

\[
W_{\text{DM}} = S \chi \bar{\chi}
\]

\[
\langle S \rangle = M_{\text{DM}}
\]

\[
M_{\text{DM}} \chi \bar{\chi}
\]
Scales

\[ \frac{\alpha_d}{4\pi M_{GUT}^2} \int d^2 \theta \chi \bar{\chi} f W^2_d \]

\[ \mathcal{L} \supset -\frac{\epsilon}{2} \int \sigma d^2 \theta W_d W_Y \Rightarrow \epsilon F_{\mu\nu} B^{\mu\nu} + \epsilon D_d D_Y \]

\[ \langle D_Y \rangle \quad \epsilon \sim 10^{-4} \]

\[ m_{\gamma_d}^2 \sim \epsilon M_{EW}^2 \]

[Dienes et. al. 1996; Baumgard et. al. 2009]
Supersymmetry Breaking

- Simplest mechanism to break SUSY without destabilizing the GeV scale: gauge mediation.
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• If D-term mixing is the dominant mechanism for generating GeV scale ⇒ Dark sector is approximately supersymmetric,

\[ \delta m_{h}^2 \simeq \epsilon^2 \frac{g_d^2}{g_Y^2} M_E^2 = (100 \text{ MeV})^2 \]

\[ \delta m_{\tilde{\gamma}_d}^2 \ll \delta m_{h}^2 \]
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\[ \tilde{\gamma}_d < 100 \text{ MeV} \]

\[ \gamma_d > 1 \text{ GeV} \]

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- If there are bi-fundamentals at the TeV (messengers), SUSY breaking is large (of order GeV).
• There are also strong limits from direct detection (CDMS, XENON) on DM that couples elastically to the $Z$.

• Mass eigenstates, $\chi_\pm = (\chi \pm \bar{\chi})/\sqrt{2}$ couple to $Z$:

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Bounds can easily be evaded by splitting the DM multiplets:

$$W_{\text{split}} = MN^2 + \chi H_d N \Rightarrow \delta M_{\text{DM}} = \frac{v^2}{M} \sim 10 \text{ GeV}$$

DM interacts inelastically, thereby evading bounds.
The triplet which resides in the DM multiplet must decay fast to evade constraints from exotic atom searches and BBN.

Dimension 5 operators can induce fast decay, $\tau_3 \sim 1$ sec:

$$\frac{1}{M_{\text{GUT}}} \int d^2 \theta \chi^2 \bar{\chi}^2 \bar{\chi}^2 f \quad \frac{1}{M_{\text{GUT}}} \int d^2 \theta \chi^{10} f s \quad \frac{1}{M_{\text{GUT}}} \int d^4 \theta \bar{\chi}^4 f s$$

$s$ is a singlet, $m_{\chi_2} < m_s < m_{\chi_3}$.

Assumes $m_{\chi_3} > m_{\chi_2}$ which is typically true due to RG running.
• The operator: $\int d^2\theta \, \chi \bar{5}_f W^2_d$ has several decay modes, with branching fractions depending on whether the DM is fermion or scalar.

• Example:
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• Example:
Decay Modes

- The operator: $\int d^2 \theta \chi 5_f W_d^2$ has several decay modes, with branching fractions depending on whether the DM is fermion or scalar.

- Example:

\[\begin{align*}
\chi \xrightarrow{\tilde{\gamma}_d} & \quad \tilde{G} \\
\quad \xrightarrow{\gamma_d} & \quad l^+ \\
\quad \xrightarrow{\epsilon} & \quad l^- \\
\quad \xrightarrow{\epsilon} & \quad l^+ \\
\quad \xrightarrow{l^-} & \quad l^-
\end{align*}\]

Dark Sector:
GeV Scale SUSY.
• The operator: \( \int d^2 \theta \, \chi \bar{5}_f W^2_d \) has several decay modes, with branching fractions depending on whether the DM is fermion or scalar.

• Example:

\[ \tilde{\gamma}_d, \; \gamma, \; \tilde{\nu}, \; \tilde{G} \]

Dark Sector: Approximate SUSY.
Decay Modes

- The operator: $\int d^2 \theta \, \chi \bar{5}_f \, W^2_d$ has several decay modes, with branching fractions depending on whether the DM is fermion or scalar.

- Example:

\[ \tilde{\gamma} d \rightarrow l^+ \nu \epsilon \]
\[ \tilde{\gamma} d \rightarrow \gamma \tilde{G} \]

- Dark Sector:
  Approximate SUSY.

- If DM is charged under SM, there is always a primary (hard) spectrum of neutrinos.

- If dark sector is approximately supersymmetric, there is a primary (hard) spectrum of photons.

- Primary photons will be generically produced if the lightest state in the dark sector is a fermion.
Smoking Gun Signatures

Neutrino Energy [GeV]

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

IceCube/DeepCore
- 1 Year
- 3 Year
- total
- primary
- soft

AMANDA DeepCore

Muon Flux [cm\(^{-2}\text{sec}^{-1}\text{sr}^{-1}]\]

SuperK
- annihilating
- decaying

Diffuse Photons
- FERMI09
- total
- primary
- brehm
- IC

HESS Galactic Ridge
- HESS AGIS (Projected)
- total
- primary

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

Phonon Energy [GeV]

Cone Half Angle [deg]
Is FERMI Seeing Decaying DM?

\[ E^2 \frac{dN}{dE} \left[ \text{GeV} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1} \right] \]

Diffuse Photons

FERMI Preliminary

IC

primary

brehm

Bg

0.25<|l|<29.75
0.25<|b|<4.75
Is FERMI Seeing Decaying DM?

- Fermi released a 1-year sky map.
- A template analysis shows an excess of photons at the center of the Galaxy.
Is FERMI Seeing Decaying DM?

[Dobler et. al. 2009]
The Hidden Sector at Neutrino Telescopes
Long Lived Particles (LOLIPs)

- For sufficiently small $\epsilon$, hidden sector is expected to have long lived particles which decay to SM.

- Examples:

\[
\begin{align*}
  c\tau &\sim \left(\epsilon^2 \alpha_{\text{EM}} m_{\gamma_d}\right)^{-1} \sim 1 \text{ km} \left(\frac{\epsilon}{10^{-8}}\right)^{-2} \left(\frac{m_{\gamma_d}}{1 \text{ GeV}}\right)^{-1} \\
  c\tau &\sim \left(\epsilon^4 \frac{\alpha_d \alpha_{\text{EM}}^2 m_h}{2\pi^2} \frac{m_f^2}{m_{\gamma_d}^2}\right)^{-1} \sim 10^7 \text{ km} \left(\frac{\epsilon}{10^{-4}}\right)^{-4} \left(\frac{m_{\gamma_d}}{1 \text{ GeV}}\right)
\end{align*}
\]
Production of LoLiPs

- If DM annihilates into hidden sector, signals can be measured at regions with high DM densities: Sun, Earth.
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- If DM annihilates into hidden sector, signals can be measured at regions with high DM densities: **Sun, Earth**.

- Probability to decay inside detector:

  \[ P_{\text{decay}} = e^{-d/L} \left( 1 - e^{-s/L} \right) \approx \begin{cases} \frac{s}{L} & L \gtrsim d \\ e^{-d/L} & L \ll d \end{cases} \]

  \[ L = \gamma c \tau. \]

  \[ s = \text{Size of detector}. \]
Event Types

- Neutrino telescopes are typical arrays of photomultiplier tubes.
- Roughly two types of signatures:
  1. Track-like signature, mostly Cherenkov radiation. (Mostly $\mu^\pm$).
  2. Localized source of light (e.g. $e^\pm$ or $\gamma$).
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- Roughly two types of signatures:
  1. Track-like signature, mostly Cherenkov radiation. (Mostly $\mu^{\pm}$).
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- Decay from LOLIPs may produce highly boosted di-muons. Typical separation is a few meters at most.

- Cherenkov radiation is doubled.

- Monte-Carlo simulations show an increase of $\times 3$ in effective area.

- Thus di-muons are recognized as single muons above critical energy (which is $\mathcal{O}(700 \text{ GeV})$ in water).

- Good handle for background:
  - Atmospheric neutrino flux is drops rapidly.
  - Differential light yield along track is different.
Event Rate

- Rate of events depends on:

\[
\# \text{ of events} \simeq \Gamma_{\text{ann}} \times d\Omega \times P_{\text{decay}}(c\tau)
\]

\[
\Gamma_{\text{ann}} \simeq \frac{1}{2} C \quad \text{(equilibrium)}
\]

- Capture rate can vary by many orders of magnitude, depending on whether DM interacts elastically or inelastically with nucleons, as well as on DM-nucleon cross-section and DM mass. For elastic case:

\[
C_\odot = 3 \times 10^{19} \text{s}^{-1} \left( \frac{\rho_\odot}{0.3 \text{ GeV cm}^{-3}} \right) \left( \frac{v_{\text{disp}}}{270 \text{ km s}^{-1}} \right)^{-3} \left( \frac{\sigma_{\chi n}}{10^{-43} \text{ cm}^2} \right) \left( \frac{m_\chi}{100 \text{ GeV}} \right)^{-2}
\]

- Measurement is therefore sensitive to \(c\tau, \sigma_{\chi n}, m_\chi\).
IceCube Reach

Model lines: Inelastic DM, $\delta = 200$ keV
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- Lightest state is scalar, $h$.

**IIIa:**

- $\sigma_{\chi n} \propto \frac{e^2}{m_{\gamma/d}^4}$

- $c\tau \propto (e^4 m_h)^{-1}$
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**IIIa:**

- $\sigma_{\chi n} \propto \frac{\epsilon^2}{m_{\gamma_d}^4}$
- $c\tau \propto (\epsilon^4 m_h)^{-1}$

**IIIb:**

- Lightest state is the vector, $\gamma_d$.
- Interacting with SM and dark sector.
- $\sigma_{\chi n} \propto \epsilon^0$
- $c\tau \propto (\epsilon^2 m_{\gamma_d})^{-1}$
IceCube Reach

Earth $e^\pm$ reach

$m_\chi=2$ TeV, $\delta=0$ keV, $m_{\text{LOLIP}}=25$ MeV

Earth $\gamma$ reach, $\sqrt{F}=10^3$ TeV

$m_\chi=170$ GeV, $\delta=0$ keV, $m_{\nu_\alpha}=50$ GeV
IceCube Reach

Sun $\mu^\pm$ reach
\[ \delta=0 \text{ keV}, m_{\text{LOLIP}}=500 \text{ MeV} \]

Earth $\mu^\pm$ reach
\[ \delta=0 \text{ keV}, m_{\text{LOLIP}}=500 \text{ MeV} \]
Conclusions

• Exciting time for DM physics!
• Motivates the existence of low scale hidden sectors.
• Hidden sectors could be probed in the near future.
• If related to DM, indirect measurements are very sensitive to such sectors: \( \epsilon \gtrsim 10^{-15} \).
• Photon measurement can also differentiate between DM models.
• To be continued...