Cosmic-Ray Signatures of Dark Matter Decay

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1. Unstable Dark Matter and Indirect Detection
2. Cosmic Rays from Dark Matter Decay
3. Gravitino Dark Matter
4. Conclusions
1 Unstable Dark Matter and Indirect Detection

2 Cosmic Rays from Dark Matter Decay

3 Gravitino Dark Matter

4 Conclusions
Dark matter clearly exists and is

- massive
- electrically neutral and colorless
- cold
- non-baryonic
- stable
We do not know if the dark matter particles are perfectly stable – they only need to be stable on cosmological timescales in order to be observable today,

$$\tau_{DM} > \tau_{universe} \sim 4 \times 10^{17} \text{ s}$$
Dark matter clearly exists and is

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What Do We Know about Dark Matter?

Dark matter clearly exists and is

- massive
- electrically neutral and colorless
- cold
- non-baryonic
- stable very long-lived
Extensions of the Standard Model typically contain new heavy states.
If the lightest new particle is long-lived enough (and neutral etc.), it may be a viable dark matter candidate.
In SUSY, the lightest neutralino typically has a lifetime of $\tau_\chi \sim 10^{-25}$ s if there is no extra suppression of its decays to the Standard Model.
Extensions of the Standard Model typically contain new heavy states.
If the lightest new particle is long-lived enough (and neutral etc.), it may be a viable dark matter candidate.
In SUSY, the lightest neutralino typically has a lifetime of $\tau_\chi \sim 10^{-25} \text{ s}$ if there is no extra suppression of its decays to the Standard Model. → imposing $R$-parity ensures absolute stability of the LSP.
(Supersymmetric) WIMPs are excellent dark matter candidates, but they make up only a small part of the parameter space suitable for finding dark matter candidates.

Super-weakly interacting particles like the gravitino are natural candidates for dark matter and typically have long lifetimes.
Super-WIMPs only require a moderate suppression of couplings to obtain a lifetime compatible with dark matter.

There are viable dark matter candidates that are unstable, possibly creating detectable exotic cosmic rays via their decays.
Some Candidates for Decaying Dark Matter

- Gravitino dark matter with broken $R$-parity
  → See talk by Wilfried Buchmüller on Tuesday
  [Takayama, Yamaguchi '00], [Buchmüller, Covi, Hamaguchi, Ibarra, Yanagida '07]
  [Ibarra, DT '08], [Ishiwata, Matsumoto, Moroi '08]
  [Chen, Ji, Mohapatra, Nussinov, Zhang '08, '09]
  [Buchmüller, Ibarra, Shindou, Takayama, DT '09]

- Hidden sector gauge bosons/gauginos → Also see talk by E.J. Chun
  [Ibarra, Ringwald, DT, Weniger '08, '09]
  [Chen, Takahashi, Yanagida '08, '09]

- Right-handed sneutrinos in models with Dirac masses
  [Pospelov, Trott '08]

- Hidden sector fermions
  [Hamaguchi, Shirai, Yanagida '08]
  [Arvanitaki, Dimopoulos, Dubovsky, Graham, Harnik, Rajendran '08, '09]

- Bound states of strongly interacting particles
  [Hamaguchi, Nakamura, Shirai, Yanagida '08]
  [Nardi, Sannino, Strumia '08]
Different Approaches to Dark Matter Detection

1. Collider searches: $\text{SM SM} \rightarrow \text{DM X}$
2. Direct detection: $\text{DM nucleus} \rightarrow \text{DM nucleus}$
3. Indirect detection: $\text{DM DM} \rightarrow \text{SM SM}$, $\text{DM} \rightarrow \text{SM SM}$
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Annihilating dark matter:
\[ Q_i(E, r, z) = \langle \sigma v \rangle \frac{\rho_{DM}^2(r, z)}{m_{DM}^2} \frac{dN_i}{dE} \]

Decaying dark matter:
\[ Q_i(E, r, z) = \frac{\rho_{DM}(r, z)}{(m_{DM}\tau_{DM})} \frac{dN_i}{dE} \]

Important qualitative differences:
- Indirect signatures of dark matter decay are less sensitive to the choice of halo profile
- No signal enhancement from dark matter substructures
  → strategies such as looking for annihilation signals from the center of the Galaxy or from the Sun/Earth are not applicable
What dark matter properties can we infer from electron experiments?

Examine various dark matter decay channels for different masses and free lifetimes (the best-fit lifetimes are $\mathcal{O}(10^{26})$ s)

For fermionic dark matter particles:
$$\psi_{DM} \rightarrow Z^0 \nu, \ W^\pm \ell^\mp, \ \ell^\pm \ell^\mp \nu$$

For scalar dark matter particles:
$$\phi_{DM} \rightarrow Z^0 Z^0, \ W^\pm W^\mp, \ \ell^\pm \ell^\mp$$

One gets hard leptons from direct decay as well as softer leptons from hadronization of the gauge bosons

Simulate hadronization using Monte Carlo code (PYTHIA 6.4) to obtain energy spectra $dN_i/dE$

Propagate injection spectra to our position in the Galaxy
Positrons from Gauge Boson Fragmentation

[Barra, DT '08, Barra, DT, Weniger '09, in preparation]

- The positron spectrum from hadronization of gauge bosons is too flat to account for the PAMELA results
Positrons from Direct Decay into Leptons

[1] The positron spectrum from hard electrons and muons is promising, tau leptons produce a spectrum that is too flat unless $m_{DM}$ is large
A lifetime of $10^{26}$ seconds?!

A possible interpretation: The lifetime of a TeV-mass particle decaying via a dimension-6 operator suppressed by a mass scale $M$ is given by

$$\tau_{DM} \sim 2 \times 10^{26} \text{ s} \left(\frac{\text{TeV}}{m_{DM}}\right)^5 \left(\frac{M}{10^{16} \text{ GeV}}\right)^4$$

$M$ is remarkably close to the Grand Unification scale $M_{\text{GUT}} = 2 \times 10^{16} \text{ GeV}$ for lifetimes $O(10^{26}) \text{ s}$

[Arvanitaki, Dimopoulos, Dubovsky, Graham, Harnik, Rajendran '08]
[Hamaguchi, Shirai, Yanagida '08]

Dark matter decay may be probing the GUT scale via cosmic rays
The flux of cosmic rays from dark matter decay is invariant under a rescaling of abundance/lifetime:

$$\text{Flux} \propto \frac{\rho_{\text{DM}}}{(m_{\text{DM}} \tau_{\text{DM}})}$$

It is conceivable that the anomalous cosmic-ray signatures are caused by the decay of a subdominant dark matter component into the dominant dark matter component.

The primary dark matter could then be completely stable and possibly detectable in direct dark matter searches.
Dark Matter Contribution to the Gamma-Ray Background

- For dark matter lifetimes $\mathcal{O}(10^{26})$ s one generally gets an $\mathcal{O}(0.1 \ldots 1)$ contribution to the diffuse gamma-ray background.
- Prediction of an anisotropic component in the background of “extragalactic” gamma rays due to the decay of dark matter particles in the Milky Way halo.

[Bertone, Buchmüller, Covi, Ibarra ’07]

- In addition, two-body dark matter decays could give rise to gamma-ray lines.
- Wait for Fermi LAT measurements to shed light on these questions.
In general, one expects the production of hadrons from the same decays that produce leptons – especially from decay modes including massive gauge bosons.

The prediction of primary antiproton flux from dark matter suffers from huge uncertainties due to a degeneracy between diffusion coefficient and diffusive halo height.

Despite the uncertainties, many dark matter scenarios clearly overproduce antiprotons → important constraint on model building.
Antideuterons can be produced by nuclear fusion of antiprotons and antineutrons $\rightarrow$ strong correlation between antiproton and antideuteron fluxes.

Cosmic-ray antideuteron is extremely rare: no detection so far, only upper bounds exist.

This can provide an important test of hadronic decay modes, since the low-energy spectrum from dark matter can drastically differ from the astrophysical background.

Next-generation experiments such as AMS-02 and GAPS may be able to detect antideuterons, but ONLY IF these antideuterons are of primary origin.
If the dark matter mass is not too large, the antideuteron flux from dark matter decay can exceed the background from spallation, while the antiproton flux remains consistent with measurements.

[Ibarra, DT '09]
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The Gravitino Problem

- Models with a high reheating temperature (e.g. thermal leptogenesis) suffer from problems with BBN due to energy release from late gravitino decays
- If the gravitino itself is the LSP, then the NLSP is long-lived and typically disrupts BBN processes
- A simple solution: $R$-parity is slightly broken $\rightarrow$ NLSPs decay before BBN, but the gravitino LSP also becomes unstable
- For $R$-parity violating couplings in the window permitted by baryogenesis and nucleosynthesis, the gravitino lifetime is

\[ 10^{23} \text{ s} \lesssim \tau_{3/2} \lesssim 10^{37} \text{ s}, \]

- easily compatible with gravitino dark matter
Decay Rates and Branching Ratios

- Small $R$-parity violation yields a consistent thermal history of the Universe, but also leads to decaying dark matter.
  - Calculate decay rates and branching ratios into Standard Model particles.
- Gravitino interactions are fixed by symmetries → predictive scenario from the particle physics point of view.
- Branching ratios are fairly model-independent. However, the flavor-dependence of the decays is not predicted.

![Graph showing branching ratios as a function of $m_{3/2}$ (GeV)]

[Covi, Grefe, Ibarra, DT '08]
We examined gravitino masses of $100 - 600$ GeV, motivated by typical supergravity models.

At masses of a few hundred GeV, $\text{BR}(\psi_{3/2} \rightarrow W^\pm \ell^\mp) \sim 50\%$

Assume $R$-parity violation predominantly in the first generation, $\psi_{3/2} \rightarrow W^\pm e^\mp$. For $m_{3/2} = 200$ GeV:

![Graph showing positron fraction and PAMELA, HEAT, ATIC, Fermi LAT, and HESS data points for positron flux vs. energy.]

[Buchmüller, Ibarra, Shindou, Takayama, DT '09]

However, the non-observation of spectral features in the electron flux by Fermi makes this interpretation of the PAMELA results rather unlikely.
Still, antiproton constraints leave room for a sizable contribution to the electron and diffuse gamma-ray flux from gravitino decay.

For flavor-democratic decays and $m_{3/2} = 400$ GeV:

[Buchmüller, Ibarra, Shindou, Takayama, DT '09]
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Conclusions and Outlook

- Dark matter decay is an interesting scenario with some important qualitative differences to the standard dark matter annihilation scenario.

- If dark matter decay is responsible for the observed PAMELA/Fermi anomalies, this suggests $m_{\text{DM}} \gtrsim 300$ GeV or even $m_{\text{DM}} \gtrsim 1$ TeV, respectively, and that dark matter particles decay with a sizable fraction into hard leptons of the first and/or second generation with lifetime $\tau_{\text{DM}} \sim 10^{26}$ s.

- Taken as an explanation for the electron anomalies, there are predictions for the gamma-ray background from dark matter decay that will be tested by upcoming Fermi LAT results.

- Hadronic decay modes are tightly constrained, but not excluded and may be tested by antideuteron experiments AMS-02 and GAPS.
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Thank you for your attention!

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