Reevaluating the WIMP Miracle

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Conclusion

**Thermal dark matter** from “realistic” models of string phenomenology could prove **challenging**.

This is **good news**, because **non-thermal dark matter** (in contrast to thermal production) could provide a new window on probing string based models.

A **complete understanding** of dark matter requires a concordance approach (cosmology, particle experiment, and fundamental theory).
Precision Cosmology

Cosmic Energy Budget

- Dark Energy 72%
- Dark Matter 23%
- Baryons 5%
- Early universe remarkably homogeneous
- Very small density contrast (1:100,000) at time of decoupling of CMB

All suggest physics beyond the standard model.
Cosmological Dark Matter

- Rotation curves
- CMB / LSS / Supernovae
- Evolution of LSS
- Gravitational Lensing

$t_{age} = 1.6$ Gyr
$t_{age} = 4.6$ Gyr
$t_{age} = 13$ Gyr
Cosmological Dark Matter

Cosmological Properties:
- **Cold** (Non-relativistic when structure forms)
- **Dark** (electrically neutral)
- **Stable** (or very long-lived)
- Weakly interacting with SM particles

"WIMPs"

\[ \Omega_{dm} \equiv \frac{\rho_{dm}}{\rho_{total}} = 0.233 \pm 0.013 \]
How is dark matter produced?
The "WIMP" Miracle

Dark Matter Abundance from Thermal Production

\[ \Omega_{dm} = 0.23 \times \left( \frac{10^{-26} \text{ cm}^3 \cdot \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]
The “WIMP” Miracle

Dark Matter Abundance from Thermal Production

\[ \Omega_{dm} = 0.23 \times \left( \frac{10^{-26} \text{ cm}^3 \cdot \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

Cosmological Measurement

Weak Scale Physics

As anticipated from particle theory
LHC and Dark Matter

LHC will probe our theories of EWSB.

\[ \Omega_{dm} = 0.23 \times \left( \frac{10^{-26} \text{ cm}^3 \cdot \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

Measure dark matter mass/interaction

--> End game?
Other probes of Dark Matter
Indirect Detection -- An Overview

Prior to BBN

\[ \Gamma_{ann} \sim n^2 \langle \sigma v \rangle \quad \Gamma_{ann} < H \]

Inside our galaxy the density can again reach levels that lead to annihilations

Many cosmic rays -- focus on anti-matter (rare)

\[ e^+ \quad \bar{p} \quad \gamma \quad \nu \]
Indirect Detection of Dark Matter

8.5 kpc
Indirect Detection of Dark Matter

- Dark Matter Annihilates

- 8.5 kpc
Cosmic-ray Flux in Positrons

Positron Flux ratio

Energy (GeV)
Annihilating Dark Matter?

Positron Flux ratio vs. Energy (GeV)
PAMELA

**Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics**

- Satellite mission -- online as June 2008

- Positron data reported from 50 MeV - 100 GeV (will go to 270 GeV max)

- Anti-proton data from 80 MeV up to 190 GeV (consistent with existing data, e.g. BESS)
A Possible Positron Excess

Positron Flux ratio

Energy (GeV)
A Possible Positron Excess

Solar modulation and charge bias

Positron Flux ratio

Energy (GeV)
A Possible Positron Excess

Positron Flux ratio
PAMELA -- Indirect Evidence for WIMPs?

Expected Positron Flux

\[ \Phi \sim \frac{\langle \sigma v \rangle}{m_X^2} \times \rho^2(r) \]

Microphysics    Astrophysics

Cosmological Constraint

\[ \Omega_{dm} = 0.23 \times \left( \frac{10^{-26} \text{ cm}^3 \cdot \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

Flux many orders of magnitude too low
PAMELA -- Indirect Evidence for WIMPs?

Expected Positron Flux

\[ \Phi \sim \frac{\langle \sigma v \rangle}{m_X^2} \times \rho^2(r) \]

Microphysics \quad Astrophysics

Important Considerations

- Astrophysical uncertainties: Halo profile, propagation, backgrounds
- Unknown astrophysical sources, e.g. Pulsars
- Proton contamination (10,000/1)

Taken alone probably not a compelling case for dark matter
Could another surprise be coming?
Experimental Result Leads to Excitement and Controversy
by Dennis Overbye

To the physicist, the above expression succinctly summarizes the recent surprising results coming from the Large Hadron Collider (LHC) located in Geneva, Switzerland. The equation symbolically represents the amount of dark matter in the universe, which from the initial findings of the experiment seem to fall short of expectations coming from cosmological observation.
Many explanations for a low relic density:

- Many additional dark matter particles possible in addition to WIMPs (e.g. neutrinos / axions)

\[ \Omega_{cdm}^{Total} = \sum_i \Omega_{cdm}^{(i)} \]

- Other light particles can result in a lower relic density (coannihilations)
- **Thermal origin** of dark matter may be **too simplistic**
Revisiting the WIMP Miracle

Dark Matter Abundance from Thermal Production

\[ \Omega_{dm} = 0.23 \times \left( \frac{10^{-26} \text{ cm}^3 \cdot \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

Cosmological Measurement

Weak Scale Physics

A larger cross-section would account for PAMELA and a surprise at LHC
SUSY Model Constraints Enforcing WMAP (blue)

Ellis, et. al. 2005
SUSY Model Constraints *Without* Enforcing WMAP (blue)
If dark matter is not produced thermally, how is it produced?
Example: Non-thermal Dark Matter from Light Scalars

Moroi and Randall -- hep-ph/9906527

Dark Matter from Scalar Decay:

• Moduli generically displaced in early universe
• Energy stored in scalar condensate
  \[ \Delta \Phi \rightarrow \Delta E \]
• Typically decays through gravitational coupling
  \[ T_r \simeq \left( \frac{m_\phi}{10 \text{ TeV}} \right)^{3/2} \text{ MeV} \]
• Large entropy production dilutes existing dark matter of thermal origin
  \[ \Omega_{\text{cdm}} \rightarrow \Omega_{\text{cdm}} \left( \frac{T_r}{T_f} \right)^3 \text{ Thermal abundance diluted} \]
Non-thermal Dark Matter

Given $T_r < T_f$ then dark matter populated non-thermally

$$\Omega_{cdm} \sim \frac{m_x}{T} \left( \frac{H}{T^2 \langle \sigma v \rangle} \right)_{T=T_f}$$

$$\Omega_{cdm}^{NT} = \Omega_{cdm} \left( \frac{T_f}{T_r} \right)$$

Freeze-out temp

Reheat temp

$T_f \sim \text{GeV}$ \quad $T_r \sim \text{MeV}$

Can vary over 3 orders of magnitude -- Allowed values still imply weak-scale physics “WIMP Miracle” survives
What do we expect from top-down model building?
What were the key ingredients?

1. “Light” Scalar
   \[ m_\phi \approx 10 \text{ TeV} \]

2. Gravitationally coupled
   \[ \Gamma_\phi \sim \frac{m_\phi^3}{M_p^2} \]

3. Stable dark matter particle
   \[ m_x \approx 100 \text{ GeV} \]
What were the key ingredients?

1. “Light” Scalar
   \[ m_\phi \approx 10 \text{ TeV} \]

   Light enough for decay after freeze-out,
   Heavy enough to evade BBN bounds

3. Stable dark matter particle
   \[ m_x \approx 100 \text{ GeV} \]
Guidance from Fundamental Theory

What is needed from a top-down approach:

• 4D Effective theory (under parametric control)
• Spontaneously broken SUSY (or alternative)
• Explanation for how $M_{EWSB} \ll M_p$
• Small and Positive Vacuum Energy

In String theory, all these problems are related and are essentially a problem of stabilizing scalars.
String Models that adequately meet these goals
String Models that adequately meet these goals

(joke)
The Cosmological Moduli Problem


“Model Independent properties and cosmological implications of the dilaton and moduli sectors of 4-d strings”
Carlos, Casas, and Quevedo -- Phys. Lett. B318, 1993

\[
V = e^{\frac{K}{m_p^2}} |DW|^2 - 3m_{3/2}^2 m_p^2
\]

Shift symmetry
\[
\Phi = \phi + i\alpha \rightarrow W \neq W(\Phi)
\]

Zero vacuum energy, stabilize scalar, break SUSY (spontaneously)

\[
\Delta V(\Phi) = m_{3/2}^2 m_p^2 f \left(\frac{\Phi}{m_p}\right)
\]

\[
m_\phi \sim m_{3/2} \sim \text{TeV}
\]
Ex: Type IIB -- KKLT

\[ W = W_0 + m_p^3 e^{-X} \quad K = -n m_p^2 \log (X + \bar{X}) \]

\[ V = e^{\frac{K}{m_p^2}} \left( |DW|^2 - 3m_{3/2}^2 m_p^2 \right) \]
\[ W = W_0 + m_p^3 e^{-X} \quad K = -n m_p^2 \log (X + \bar{X}) \]

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**SUSY Minimum**

\[ D_X W = 0 \rightarrow \langle X \rangle = \log \left( \frac{m_p}{nm_{3/2}} \right) \]

\[ V_{AdS} = -3m_{3/2}^2 m_p^2 \]
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\]

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V_{AdS} = -3m_{3/2}^2 m_p^2
\]

**Uplift and Break SUSY**

\[
\Delta V \sim m_{3/2}^2 m_p^2 \quad \delta X \to \delta X_c = \frac{\sqrt{n}}{\langle ReX \rangle} \delta X
\]
\[ W = W_0 + m_p^3 e^{-X} \quad K = -n m_p^2 \log (X + \bar{X}) \]

\[ V = e^{\frac{K}{m_p^2}} \left(|DW|^2 - 3m_{3/2}^2 m_p^2\right) \]

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**Uplift and Break SUSY**

\[ \Delta V \sim m_{3/2}^2 m_p^2 \quad \delta X \rightarrow \delta X_c = \frac{\sqrt{n}}{\langle ReX \rangle} \delta X \]

\[ m_X = n^{-\frac{1}{2}} \log \left(\frac{m_p}{nm_{3/2}}\right) \quad m_{3/2} \sim \left(4\pi^2\right)^{\frac{1}{2}} m_{3/2} \]

(Loaiza-Brito, Martin, Nilles, and Ratz)
Other models with possible non-thermal contribution:

- Large Volume Compactifications
  
  \[ W = W_0 + c_1 f(\phi) e^{-aX} + c_2 e^{-bX} \]

  e.g. Conlon and Quevedo -- arXiv:0705.3460

- F-theory (Jonathan’s talk)
  
  Heckman, Tavanfar, and Vafa-- arXiv:0812.3155

- M-theory on G2 manifolds (Gordy’s talk)
  
  Acharya, et. al. -- arXiv:0804.0863
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Remarks

- Many open questions:  
  Embedding visible sector, uplifting, path to 4d, SUSY breaking

- Scalar may be too light (then perhaps thermal inflation)

- Gaugino (dark matter ) has three robust patterns  

- Light scalar may be robust prediction  
  (a.k.a. cosmological moduli “problem”)
Moduli Stabilization Basics

If scalars stabilized without reintroducing electroweak hierarchy and accounting for small and positive vacuum energy this typically implies:

$$m_\phi \approx m_{3/2} \approx \text{TeV}$$

A new “WIMP” miracle

Scalars are gravitationally coupled giving

$$T_r \approx \left( \frac{m_\phi}{10 \text{ TeV}} \right)^{3/2} \text{ MeV}$$

Non-thermal dark matter!!!!
Given hints from LHC (April 1, 2010) and motivation from fundamental theory: Can the well-motivated neutralino account for PAMELA?
Non-thermal SUSY Dark Matter


Neutralino WIMPs (light, stable (R-parity), neutral)

\[ \tilde{\chi} = N_{i1} \tilde{B} + N_{i2} \tilde{W}^3 + N_{i3} \tilde{H}_1^0 + N_{i4} \tilde{H}_2^0 \]

Bino-like cross-section (P-wave suppression)

\[ \langle \sigma v \rangle \sim 10^{-26} \text{cm}^3 \text{s}^{-1} \quad \Omega_{lsp} \approx 0.23 \]

Wino-like cross-section (S-wave suppression)

\[ \langle \sigma v \rangle \sim 10^{-24} \text{cm}^3 \text{s}^{-1} \quad \Omega_{lsp} \approx 0.002 \]
The PAMELA Excess from SUSY Dark Matter


Positron Flux for 200 GeV SUSY Dark Matter

Positron Flux ratio

Energy (GeV)
PAMELA from Non-thermal SUSY Dark Matter


Light enough to explain PAMELA

\[ m_X \lesssim 300 \text{ GeV} \]

Heavy enough to avoid other indirect detection

\[ m_X \gtrsim 200 \text{ GeV} \]
Anti-Proton Bounds and Uncertainties


Anti-Proton Flux for 200 GeV Wino-like Neutralino
What about Gamma-rays and FERMI?
Gamma-ray fluxes and FERMI

Data taken from talk at Michigan workshop (MCTP) on LHC/CDM

Gamma-ray Flux

Energy (MeV)

Preliminary

Gamma-ray fluxes and FERMI

Data taken from talk at Michigan workshop (MCTP) on LHC/CDM

Gamma-ray Flux

Energy (MeV)
Conclusion

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This is **good news**, because **non-thermal dark matter** (in contrast to thermal production) could provide a new window on probing string based models.

A **complete understanding** of dark matter requires a concordance approach (cosmology, particle experiment, and fundamental theory)
Thank You
Backups
Could excess be due to annihilating SUSY dark matter?

**Wino leading decay channel:**

\[ \chi + \chi \rightarrow W + W \rightarrow e^+ + X \]

Bino-like requires large “boost” factor

\[ \text{Flux} \sim \langle \sigma v \rangle \times \left( \frac{\rho_{\text{halo}}}{m_{\chi}} \right)^2 \]
The \((m_{1/2}, m_0)\) planes in the CMSSM for (a) \(\tan \beta = 10, \mu < 0\), (b) \(\tan \beta = 10, \mu > 0\), (c) \(\tan \beta = 40, \mu < 0\) and (d) \(\tan \beta = 57, \mu > 0\), all assuming \(A_0 = 0\). We display the WMAP relic-density constraint, the experimental constraints due to \(m_h\), \(m_{\chi^\pm}\), \(b \rightarrow s\) and \(g\mu - 2\), and contours of the spin-independent elastic-scattering cross section calculated for \(= 45\) and \(64\) MeV (lighter, blue and black dotted contours, respectively), labelled by their exponents in units of picobarns.
Anti-proton flux for changing cylinder height

$\Phi_p (1/(\text{GeV m}^2 \text{s sr}))$

Kinetic Energy (GeV)

NFW Profile
$m_\chi = 200 \text{ GeV}$

BESS 95 + 97
Background
$L = 3 \text{ kpc}$
$L = 4 \text{ kpc}$
$L = 6 \text{ kpc}$
Anti-proton flux for changing halo profile

$m_\chi = 200 \text{ GeV}$
ISRF extends for significant distance above GP

Significant ICS at high lats.

Not so much in plane because of dust and star density decreases with R
Positron Flux for Changing Energy Loss

- PAMELA
- Astro Background
- Signal with Background (\(\tau=1.1\))
- Signal with Background (\(\tau=1.5\))
- Signal only (\(\tau=1.1\))
- Signal Only (\(\tau=1.5\))

\[ \frac{e^+/e^-} {\text{Energy [GeV]}} \]

 energies range from 1 to 100 GeV.
Dark Matter Self Annihilations

Source term for dark matter annihilations

\[ Q = \frac{1}{2} \frac{\langle \sigma v \rangle}{m_X^2} \sum_i \frac{dN_i}{dE} B_i(xx \rightarrow i) \times \rho(r)^2 \]

Microphysics

Astrophysics