On the Challenge to Unveil the Microscopic Nature of Dark Matter

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References:

P. Grajek, G. Kane, D. Phalen, A. Pierce, S.W. arXiv:0807.1508
G. Kane, S.W. arXiv:0807.2244
B. Acharya, P. Kumar, K. Bobkov, G. Kane, J. Shao, S.W. arXiv:0804.0863
P. Grajek, G. Kane, D. Phalen, A. Pierce, S.W. TO APPEAR...
Conclusions

- We can **not** obtain a complete understanding of dark matter *from LHC data alone* -- "CDM Inverse Problem"

- **UV physics** and/or **early universe evolution** may play an essential role in determining the dark matter abundance

- We can not “calculate” the dark matter relic density from collider data, we must **measure** it.

- **Complete understanding** of dark matter **requires an interplay:** Astrophysics, cosmology, particle experiment, and fundamental theory. Need “**Concordance Approach**”
Precision Cosmology

- Dark Energy 74%
- Dark Matter 22%
- Baryons 4%
- 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

\[ t_{\text{age}} = 1.6 \text{ Gyr} \]
\[ t_{\text{age}} = 4.6 \text{ Gyr} \]
\[ t_{\text{age}} = 13 \text{ Gyr} \]
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”

$$\Omega_{cdm} h^2 = 0.1143 \pm 0.0034$$
How is dark matter produced?
As the universe expands it cools. Prior to BBN, temperature exceeds mass and dark matter is created in thermal equilibrium:

\[ \Omega_{cdm} h^2 \approx 0.1 \times \left( \frac{3 \times 10^{-26} \text{cm}^3\text{s}^{-1}}{\langle \sigma v \rangle} \right) \]
Cosmological versus Microscopic Dark Matter

\[ \Omega_{\text{micro}} \Omega_{\text{dm}} = ? \Omega_{\text{cosmo}} \Omega_{\text{dm}} \]

\[ \Omega_{\text{cdm}} h^2 \approx 0.1 \times \left( \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

\[ \Omega_{\text{cdm}} h^2 = 0.1143 \pm 0.0034 \]

New Physics at Weak Scale

\[ \langle \sigma v \rangle \approx 10^{-26} \text{cm}^3 \text{s}^{-1} \]
LHC and Dark Matter

LHC will probe our theories of EWSB.

Measure dark matter mass/interaction

--> End game?
Thermal Dark Matter

• Simplicity

• Doesn’t depend on cosmological priors

• Doesn’t depend on high energy physics

• Suggests scale of electro-weak symmetry breaking (as anticipated from particle theory)
Challenges for CDM Reconstruction at LHC

- LHC is proton-proton collider; constituent velocities uncertain.

- CDM is weakly interacting = missing energy; (Measure other particles -> deduce WIMP properties)

- Particles remain in detector $\sim 10^{-8}$ s; CDM lifetime $> 10^{17}$ s

- Matching signatures to theory will be challenging: Many degeneracies - model independent approaches needed. (work in progress at Michigan and elsewhere)
The CDM Inverse Problem

Even if we measure WIMP mass/cross-section, still many challenges:

• Many additional dark matter particles possible (e.g. neutrinos / axions)

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

• Coannihilations with other light particles can lower relic density

• Many assumptions go into thermal calculation
Cosmological Dark Matter

*Assumed equilibrium was reached
*Assumed radiation dominated universe at freeze-out
*Assumed no entropy production after freeze-out
*Assumed no other sources of cdm (e.g. late decays)
Plan for the Rest of Talk

Suggestions that thermal scenario may not be enough

- Indirect Detection of Dark Matter - recent results
- Guidance from theory - top/down approach
- Importance of concordance approach to microscopic dark matter
- Conclusions
Indirect Detection -- An Overview

• Prior to BBN, the density of dark matter was diluted by cosmic expansion until annihilations could no longer occur, i.e. “freeze-out”

• Inside gravitationally bound objects (e.g. Stars and Galaxies) densities are significant enough that annihilations can occur.

• Self-annihilation of dark matter can then lead to cosmic-rays and photons at energies detectable in current experiments.

\[ e^+ \bar{p} \gamma \nu \]
Cosmic-rays from Dark Matter Annihilation

8.5 kpc
Cosmic-ray Flux in Positrons

![Graph showing the cosmic-ray flux in positrons vs energy (GeV).]
Annihilating Dark Matter?

![Graph showing e+/e- vs Energy (GeV) for different masses and backgrounds.](graph.png)
Dark Matter Self Annihilations

Source term for dark matter annihilations

\[ Q = \frac{1}{2} \frac{\langle \sigma v \rangle}{m_X^2} \sum_i \frac{dN_i}{dE} B_i(xx \rightarrow i) \times \rho(\vec{r})^2 \]
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Navarro, Frenk, White (NFW) Halo Profile (Favored by N-body simulations)

\[ \rho(\vec{r}) = 0.3 \times \left( \frac{r_\odot}{r} \right) \left( \frac{1 + \frac{r_\odot}{20}}{1 + \frac{r}{20}} \right)^2 \text{ GeV/cm}^3 \]

small \( r \quad \rightarrow \quad \rho^2 \sim 1/r^2 \)
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\]

However, simulations do not account for effects of baryons

Baryons may cause clumping, suggests small “boost factor”

\[
\rho^2 \rightarrow B \rho^2 \quad B < 10
\]
Cosmic-ray Propagation

Cosmic rays are produced and some are confined by galactic magnetic fields.

Energy loss from a number of effects:
- Motion in galactic magnetic field,
- Scattering off ISM (e.g. hydrogen gas),
- Solar and galactic winds,
- Inverse Compton scattering,
- Synchrotron radiation

Solutions depend on empirical models along with analytic or numeric techniques. Feasible given lots of existing data, along with computer programs such as DARKSUSY and Galprop.
Key Uncertainties for Indirect Detection

- Halo Profile (probably at most factor of 10 -- although subhalos?)

- Propagation (gamma rays do not suffer directly)

- Backgrounds (well understood in some energy ranges)

- Experimental uncertainties (e.g. background rejection)
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

![Graph showing positron fraction vs. energy (GeV)]
A Possible Positron Excess

Solar modulation and charge bias
A Possible Positron Excess
Systematics: Is there an excess?

It is difficult to distinguish protons from positrons

PAMELA group has tried to account for this and finds it is a small effect.

Others are more skeptical.

Upshot: Systematics could result in lower peak.
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Upshot: Systematics could result in lower peak.
Astrophysical Explanation?

Could the excess be due to Pulsars?

E.g., Hooper, et. al. arXiv:0810.1527

Difficult to account for peak consistently with other data (e.g. gamma-rays)

Upshot: Important to consider astrophysical sources as part of the explanation.
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Upshot: Important to consider astrophysical sources as part of the explanation.
Can Dark Matter Account for PAMELA?

Source term for dark matter annihilations

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

**Microphysics**

**Astrophysics**

Thermal SUSY Dark Matter (with NFW Profile)

\[ \langle \sigma v \rangle \approx 10^{-26} \text{ cm}^3 \text{s}^{-1} \]

WMAP constraint

Resulting flux is many orders of magnitude off!
Can Dark Matter Account for PAMELA?

Possible explanations:

- **Astrophysical Uncertainties - a.k.a “boost factor”**
  Need factor $B > 10^3$ - not likely...

- **Sommerfield Effect**
  Annihilation cross-section enhanced as DM velocity decreases. Realistic models require new hidden sector and are quite elaborate (but predictive).

- **Non-thermal Dark Matter**
  If dark matter is produced from another source following freeze-out, cross-section can be enhanced by several orders of magnitude.

\[ \Phi \sim \langle \sigma v \rangle \left( \frac{\rho}{m_X} \right)^2 \]
Non-Thermal Dark Matter

G. Kane, S.W. arXiv:0807.2244
B. Acharya, P. Kumar, K. Bobkov, G. Kane, J. Shao, S.W. arXiv:0804.0863

Thermal Dark Matter

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Non-Thermal Dark Matter \[ \Phi \rightarrow X \]

E.g. Decay of light scalar to dark matter
Non-Thermal Dark Matter

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Non-Thermal Dark Matter

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E.g. Decay of light scalar to dark matter

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

Freeze-out temp
Decay temp
Non-Thermal Dark Matter

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Freeze-out temp
Decay temp

$$T_f \approx \frac{m_x}{20} \sim \text{GeV} \quad T_d \sim \text{MeV}$$

Increase by 3 orders of magnitude!
Guidance from Theory?

Many examples of theoretical models that generically predict non-thermal dark matter:

- Anomaly Mediated SUSY breaking
- Moduli Mediated SUSY breaking (SUSY breaking from string theory)
- Affleck-Dine condensates / Baryogenesis
- Wimpzillas
- Q-balls
- Light scalars are generic prediction of physics beyond SM
Light Scalars in the Early Universe

Expect many light scalars in **early universe**:

- Higgs / Inflatons (needed -- not explained)
- Size and shape of extra dimensions
- Locations of branes and strings
- MSSM flat directions
What is needed from string theory:

- 4D Effective theory
- Spontaneously broken SUSY
- Explanation for why $M_{EWSB} \ll M_p$
- $\Lambda \gtrsim 0$

Why String theory?
Rigid framework to constrain model building, requiring low-energy theories to be consistent at high scale and when combined with gravity (e.g. anomaly free).

Stated another way, it gives a way to constrain guesses!!!
• Including flux (generalized Maxwell fields) results in stabilizing potential for most scalars giving them large masses

• Kahler moduli (e.g. size of extra dimensions) are typically not stabilized by flux.

• These are stabilized by non-perturbative effects, e.g. gaugino condensation.

• Finally, uplift compactification to deSitter Space.
Moduli Stabilization Basics

If scalars stabilized without reintroducing electroweak hierarchy this typically implies:

\[ m_\phi \approx m_{3/2} \approx \text{TeV} \]

Scalar will be gravitationally coupled giving

\[ T_d \approx \text{MeV} \]

Non-thermal dark matter!!!!
SUSY Dark Matter

Neutralino WIMPs (light, stable, neutral)

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

Thermal Relic Density

\[ \Omega_{cdm} h^2 \approx 0.1 \times \left( \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

WMAP Result

\[ \Omega_{cdm} h^2 = 0.1143 \pm 0.0034 \]
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Wino-like cross-section (S-wave suppression)

\[ \langle \sigma v \rangle \sim 10^{-24} \text{cm}^3 \text{s}^{-1} \quad \Omega_{lsp} h^2 \sim 10^{-3} \]

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

\[ \langle \sigma v \rangle \sim 10^{-26} \text{cm}^3 \text{s}^{-1} \quad \Omega_{lsp} h^2 \sim 0.1 \]
SUSY Dark Matter

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Thermal Non-Thermally Produced!

\[ \Omega_{cdm} h^2 \approx 0.1 \times \left( \frac{3 \times 10^{-24} \text{ cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \right) \]

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Wino-like Neutralinos - Positron Excess

Could excess be due to annihilating dark matter?

Bino-like requires large “boost” factor (Recent simulations say small)

\[
Flux \sim \langle \sigma v \rangle \times \left( \frac{\rho_{\text{halo}}}{m_{\chi}} \right)^2
\]

Wino leading decay channel:

\[\chi + \chi \rightarrow W + W \rightarrow e^+ + X\]
The PAMELA Excess from SUSY Dark Matter

P. Grajek, G. Kane, D. Phalen, A. Pierce, S.W. arXiv:0807.1508

Positron Flux for varying Neutralino Mass

PAMELA data
Astro Background
- $m_\chi = 100$ GeV
- $m_\chi = 200$ GeV
- $m_\chi = 350$ GeV

$\frac{e^+}{(e^+ + e^-)}$ vs Energy [GeV]
The PAMELA Excess from SUSY Dark Matter

P. Grajek, G. Kane, D. Phalen, A. Pierce, S.W. arXiv:0807.1508

Energy loss rate: $5 \times 10^{16}$ s
PAMELA from Non-thermal SUSY Dark Matter

• Non-thermal dark matter is a natural consequence of (UV complete) theories beyond the standard model.

• Neutralino must be wino-like (W boson channel crucial).

\[ X + \bar{X} \rightarrow W^+ + W^- \rightarrow e^+ + Y \]

• Mass must be light (for \( e^+ \))

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

• Not too light (for pbar, and gammas)

\[ m_X \gtrsim 200 \text{ GeV} \]

• If this is the dark matter, FGST / GLAST and LHC should report signals.
GLAST / Fermi Prediction for 200 GeV WIMP

FGST 1 Year Observation

Flux $\phi$ [cm$^{-1}$ s$^{-1}$ GeV$^{-1}$] vs. Energy [GeV]

- Dark Matter
- Conventional Background
- Signal + BG
- Predicted Observation
Conclusions

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• **UV physics** and/or **early universe evolution** may play an essential role in determining the dark matter abundance

• We can not “calculate” the dark matter relic density from collider data, we must **measure** it.

• **Complete understanding** of dark matter requires an interplay: Astrophysics, cosmology, particle experiment, and fundamental theory. Need "**Concordance Approach**"
Thank you for your time.
Backups
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