Collider Probes of Dark Matter Genesis

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dark matter facts

We know that dark matter is

• dark (electrically neutral)

• around (cosmologically stable)

• abundant \( (\Omega h^2=0.11) \)
WIMP miracle

The present day abundance of dark matter,

$$\Omega h^2 \sim \frac{1 \text{ pb}}{\langle \sigma v \rangle}$$

is more or less correct given a weak-scale annihilation cross-section.
Solving hierarchy problem yields dark matter!

<table>
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<th>theory</th>
<th>$Z_2$</th>
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<td>Supersymmetry</td>
<td>R-parity</td>
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<tr>
<td>Extra Dimensions</td>
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WIMP miracle is a well-motivated and highly predictive framework which

- links dark matter to the hierarchy problem.
- implies signals for direct detection & LHC.
theory space

observables

$\langle \sigma v \rangle$
The WIMP is just the tip of the iceberg!
The WIMP miracle requires:

Dark matter thermalized with SM at temperatures of order its mass.

Let us consider the complementary space:

Dark matter NOT thermalized with SM at temperatures of order its mass.
1 sector:

2 sectors:
This setup is actually quite familiar.

**gravitino:**

MSSM \(-\tilde{G}\)

**axion:**

SM \(-\alpha\)

Are there other motivations for this setup?
hidden worlds?

- hidden sector
- hidden sector
- hidden sector
- visible sector
- heavy states
Consider the following general setup.

\[ X, X' = Z_2 \text{ odd} \quad \text{m, m'} = \text{weak-scale} \]
example: gravity mediation + R-parity

\[ X \ (\text{NLSP}) \quad \text{and} \quad X' \ (\text{LSP}) \]

\[ X, X' = R \text{ odd} \quad \text{and} \quad m, m' = \text{weak-scale} \]
decays to dark matter

Since $m > m'$ the portal mediates the decay

$$X \rightarrow X' + \ldots$$

We are interested in $10^{-13} \text{ sec} < \tau < 1 \text{ sec}$.

May contain SM fields.
sector equilibration

initially, two heat baths

ultimately, one heat bath
Only a handful of parameters fix $\Omega$:

1 sector: 

\[ \langle \sigma v \rangle \]

2 sector: 

\[ \xi = \frac{T'}{T} \]
\[ \tau \]
\[ m, \langle \sigma v \rangle \]
\[ m', \langle \sigma v \rangle' \]
Only a handful of parameters fix $\Omega$:

1 sector: $\langle \sigma v \rangle$ accessible at colliders

2 sector: 
\[
\xi = \frac{T'}{T} \\
\tau \\
m, \langle \sigma v \rangle \\
m', \langle \sigma v \rangle'
\]
Only a handful of parameters fix $\Omega$:

**1 sector:**

\[ \langle \sigma v \rangle \]

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**2 sector:**

\[ \xi = \frac{T'}{T} \]

\[ \tau \]

\[ m, \langle \sigma v \rangle \]

\[ m', \langle \sigma v \rangle' \]

accessible at colliders
The cosmological history varies substantially as a function of the lifetime:

$10^{-13}$ sec $\rightarrow$ ?? $\rightarrow$ BBN $\rightarrow$ co-DM

1 sec $\rightarrow$ $10^{17}$ sec

thermalized
The cosmological history varies substantially as a function of the lifetime:

$10^{-13}$ sec \hspace{1cm} 1 sec \hspace{1cm} $10^{17}$ sec

thermalized \hspace{1cm} freeze-in \hspace{1cm} freeze-out and decay \hspace{1cm} BBN \hspace{1cm} co-DM
outline

• general setup
• two sector cosmology
• cosmological phase diagram
• collider signals
• neutrinos
two sector cosmology
Define the ratio $\xi = \frac{T'}{T}$.
Inflaton may dominantly decay into and reheat the visible sector!

\[ \xi_R = \frac{T'_R}{T_R} \]
Assuming conserved entropy in each sector, 

\[ \xi(T) \propto \left( \frac{g_{s}(T)}{g'_{s}(T)} \right)^{1/3} \]

where \( g_{s} \) and \( g'_{s} \) are the number of degrees of freedom in each sector.
energy budgets

The effective number of relativistic species at BBN is bounded by

$$\Delta N_\nu = \frac{4}{7} g'_* (T_{\text{BBN}}) \xi (T_{\text{BBN}})^4 < 1.4$$

Colder hidden sectors are safe!
yield variables

The yield of $X$ is defined to be

$$Y = \frac{n}{s}$$

The yield of $X'$ is defined to be

$$Y' = \frac{n'}{s}$$
yield

visible sector freeze-out (FO)

\[ y = \frac{m}{T} \]
The yield $Y_{FO}$ for visible sector freeze-out (FO) is given by:

$$Y_{FO} \propto \frac{\sqrt{g_*}}{g_{*s}} \frac{1}{m_{Pl} m\langle \sigma v \rangle}$$

where $x = m / T$. 

The graph shows the yield as a function of $x$. The visible sector freeze-out (FO) is indicated by the curve reaching a plateau at lower values of $x$. The $y$-axis represents the yield, and the $x$-axis represents $x = m / T$.
yield

$x = \frac{m}{T}$

hidden sector freeze-out (FO')
hidden sector freeze-out (FO')

\[ Y_{FO}' \approx \xi \frac{m\langle \sigma v \rangle}{m'\langle \sigma v \rangle'} Y_{FO} \]
yield

$Y$

$Y'$

$FO + FO'$

$x = \frac{m}{T}$
portal operator

\[ O \]

visible sector

hidden sector

e.g. \[ O = [L^\dagger L X']_D \]
yield

\[ Y \]

\[ Y' \]

\[ x = \frac{m}{T} \]

\[ FO + FO' \]
yield

freeze-out and decay (FO&D)

\[ x = \frac{m}{T} \]
$Y_{FO} = Y'_{FO&D}$

freeze-out and decay (FO&D)

$y = m / T$
superWIMPs

FO&D is actually familiar from Feng et al.
$x = \frac{m}{T}$

freeze-out and decay (FO&D)
yield

freeze-in (FI)

\[ x = \frac{m}{T} \]
$x = \frac{m}{T}$

$Y_{FI}' = \Gamma t$
Since $t \propto 1/H$ at the time when $X$ becomes non-relativistic, the final yield of $X'$ is

$$Y_{FI}' \propto \frac{\Gamma m_{Pl}}{m^2}$$

fast decays, small masses $\rightarrow$ more!
If the yield of $X'$ exceeds a critical value, then $X'$ will begin to (re-)annihilate and in turn deplete the abundance.
re-annihilation

For each mode of dark matter genesis is a “re-annihilated” variant:

\[
\begin{align*}
\text{FO\&D} & \rightarrow \text{FO\&D}_{r} \\
\text{FI} & \rightarrow \text{FI}_{r}
\end{align*}
\]
cosmological phase diagram
Some of the parameters which dictate the cosmological history can be measured.

accessible

\[ \tau \]
\[ m, \langle \sigma v \rangle \]
\[ m' \]

inaccessible

\[ \xi \]
\[ \langle \sigma v \rangle' \]
Plot “phase diagram” of dominant mode of dark matter genesis, subject to $\Omega h^2 = 0.11$.

Inaccessible parameters scanned inclusively:

\begin{align*}
10^{-3} &< \xi < 10^{-1} \\
10^{-5} \text{ pb} &< \langle \sigma v \rangle' < 10^{5} \text{ pb}
\end{align*}

and accessible parameters are the axes.
Cosmology imprints observables!

\[ \langle \sigma v \rangle / \langle \sigma v \rangle_0 \]

\[ \tau [\text{sec}] \]

\[ \langle \sigma v \rangle_0 = 1 \text{ pb} \]
\[ m = 100 \text{ GeV} \]
\[ 1/4 < m'/m < 1/3 \]
What are there phenomenological signals for these cosmological scenarios?

- Direct detection is a lost cause.
- How about X decays at LHC?

\[ X \rightarrow X' + \ldots \]
Hidden sectors imply long lifetimes.

\[\langle \sigma v \rangle / \langle \sigma v \rangle_0 \]

\[\tau \text{ [sec]}\]

\[\langle \sigma v \rangle_0 = 1 \text{ pb}\]
\[m = 100 \text{ GeV}\]
\[1/4 < m'/m < 1/3\]
Afterwards, we go on to discuss the portal interactions, and present a detailed discussion of the FO&D visible and hidden sectors couple only through gravitational interactions. We begin with an analysis of our setup in a decoupled structures depicted in Figure 1, leaving a more detailed collider study to a companion paper [7].

The purpose of the present work, however, is to establish a comprehensive understanding of the FO&D, FO&D interactions. We then introduce the LHC even in this much broader framework compared to that of standard single sector FO.

Because each production mechanism lies in a distinctive region in the plane, we are left with the tantalizing possibility that the origin of DM might be successfully reconstructed at all parameters but $\sigma v$. Each point corresponds to a narrow region in the band in $\langle \sigma v \rangle / \langle \sigma v \rangle_0$. Even though $\sigma v$ might be measured at all sectors, these mechanisms are defined by $10^{3} < m \langle \sigma v \rangle / m < 10^{4}$, while in the right panel, the masses have been scanned over a generous range, one sees that FO&D couples only through gravitational interactions. For example, see the left panel of Figure 1.

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collider signals
long-lived CHAMPs

If X is charged or colored, it may be stopped!

hep-ph/0612060 (Hamaguchi, Nojiri, de Roeck)
hep-ph/0506246 (Arvanitaki, Dimopoulos, Pierce, Rajendran, Wacker)
hep-ph/0409278 (Feng, Smith)
hep-ph/0409248 (Hamaguchi, Kuno, Nakaya, Nojiri)
Search for Stopped Gluinos in $pp$ collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

The results of the first search for long-lived gluinos produced in 7 TeV $pp$ collisions at the CERN Large Hadron Collider are presented. The search looks for evidence of long-lived particles that stop in the CMS detector and decay in the quiescent periods between beam crossings. In a dataset with a peak instantaneous luminosity of $1 \times 10^{32}$ cm$^{-2}$s$^{-1}$, an integrated luminosity of 10 pb$^{-1}$, and a search interval corresponding to 62 hours of LHC operation, no significant excess above background was observed. Limits at the 95% confidence level on gluino pair production over 13 orders of magnitude of gluino lifetime are set. For a mass difference $m_{\tilde{g}} - m_{\tilde{\chi}^0_1} > 100$ GeV/c$^2$, and assuming BR($\tilde{g} \rightarrow g\tilde{\chi}^0_1$) = 100%, $m_{\tilde{g}} < 370$ GeV/c$^2$ are excluded for lifetimes from 10 $\mu$s to 1000 s.
Consider the example \( \mathcal{O} = [L^\dagger L X']_D \).
lifetime (τ) measurement

mass (m’) measurement
By ascertaining the lifetime of extremely long-lived CHAMPs we can extend LHC reach.

\[ \tau = 1 \text{ sec} \quad \mathcal{O}/m_{\text{GUT}} \]

\[ \tau = 3 \text{ hrs} \quad \mathcal{O}/m_{\text{Pl}} \]

LHC can probe the GUT scale!
We can verify the origin of dark matter!

\[ \frac{\langle \sigma v \rangle}{\langle \sigma v \rangle_0} \]

\[ \tau \text{ [sec]} \]

\[ \langle \sigma v \rangle_0 = 1 \text{ pb} \]
\[ m = 100 \text{ GeV} \]
\[ 1/4 < m'/m < 1/3 \]
Dark matter from freeze-in.

\( \langle \sigma v \rangle_0 = 1 \text{ pb} \)
\( m = 100 \text{ GeV} \)
\( 1/4 < m'/m < 1/3 \)
Dark matter from freeze-out and decay.

\[
\langle \sigma v \rangle / \langle \sigma v \rangle_0
\]

\[
\tau \ [\text{sec}]
\]

\[
\langle \sigma v \rangle_0 = 1 \ \text{pb}
\]

\[
m = 100 \ \text{GeV}
\]

\[
1/4 < m'/m < 1/3
\]
Now, onwards to a well-known example...
...neutrinos!
The see-saw is a hidden sector “in disguise”.

\[ \lambda_{ij} [L_i N_j H_u]_F \]

visible sector

\[ [M_i N_i N_i]_F \]

\[ N_i \]
Integrating out the sterile neutrinos yields the active neutrino masses:

$$m_{ij} = v_u^2 \left( \lambda M^{-1} \lambda^T \right)_{ij}$$

probed experimentally to be $m_{ij} \approx 0.1$ eV.
Since $m_{ij}$ is constrained, $M_i$ and $\lambda_{ij}$ are related. The neutrino see-saw can be:

\begin{align*}
\text{high-scale} & \quad \text{or} \quad \text{low-scale} \\
M_i \sim 10^{14} \text{ GeV} & \quad \lambda_{ij} \sim 1 \\
M_i \sim 100 \text{ GeV} & \quad \lambda_{ij} \sim 10^{-6}
\end{align*}
Since $m_{ij}$ is constrained, $M_i$ and $\lambda_{ij}$ are related. The neutrino see-saw can be:

**high-scale**

- $M_i \sim 10^{14} \text{ GeV}$
- $\lambda_{ij} \sim 1$

**or**

**low-scale**

- $M_i \sim 100 \text{ GeV}$
- $\lambda_{ij} \sim 10^{-6}$

Small Yukawas are okay by me! (e.g. electron)
In the low-scale supersymmetric see-saw,

\[ \lambda_{ij} \sim 10^{-6} \]

and sectors are very weakly coupled.

Claim: despite the tiny coupling, we can probe the see-saw directly at colliders!
See-saw can be verified at LHC if:

- LSP = sterile sneutrino
- NLSP = charged
- degenerate masses, $M_i \approx \tilde{M}_i$
\[ \tilde{h}^\pm \quad E_{\ell_i} \leftrightarrow M_j \quad \ell_i^{\pm} \quad \tilde{n}_j \]
$m_{\tilde{\chi}^\pm} = 150$ GeV

$M_3 = 100$ GeV  \quad M_2 = 80$ GeV  \quad M_1 = 50$ GeV

$E_l$ (GeV)
$\tilde{h}^\pm$ \hspace{1cm} $E_{\ell_i} \leftrightarrow M_j$ \hspace{1cm} $\ell^\pm_i$ \\

$\tilde{n}_j$
\[ \tilde{h}^\pm \leftrightarrow \tilde{\eta}_j \]

\[ \tau + \text{BR}(\tilde{h}^\pm \rightarrow \ell_i^\pm \tilde{\eta}_j) \leftrightarrow |\lambda_{ij}| \]

\[ E_{\ell_i} \leftrightarrow M_j \]
See-saw spectroscopy at the LHC!

\[ M_j + |\lambda_{ij}| = \text{order of mag. verification?} \]

\[ \text{large mixing angles?} \]

\[ \text{inverted hierarchy?} \]
NLSP = stau $\leftrightarrow$ measure $\lambda_{3j}$ and $M_i$ only
$\text{NLSP} = \text{squark} \leftrightarrow \text{measure } \lambda_{ij} \text{ and } M_i$
$m_{\tilde{q}} = 700$ GeV
$M_1 = 250$ GeV
$M_2 = 450$ GeV
$M_3 = 550$ GeV
conclusions
• There exists a rich array of alternatives to the WIMP paradigm of dark matter genesis.
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• These alternatives are dictated by a handful of (in some cases measurable) parameters.
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• CHAMPS offer a unique opportunity for probing high-scale / weakly coupled physics.
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• These alternatives are dictated by a handful of (in some cases measurable) parameters.

• CHAMPS offer a unique opportunity for probing high-scale / weakly coupled physics.

• We may be able to reconstruct the origin of dark matter at colliders!
thanks!
Boltzmann equations

Cosmological history is determined by

\[
\frac{dn}{dt} + 3Hn = -(n^2 - n_{eq}^2)\langle \sigma v \rangle - \Gamma(n - n_{eq})
\]

\[
\frac{dn'}{dt} + 3Hn' = -(n'^2 - n'_{eq}^2)\langle \sigma v \rangle' + \Gamma(n' - n'_{eq})
\]

where \( n^{(i)} \) is the number density of \( X^{(i)} \).
sector equilibration

Since FI produces $\Delta \rho = Y'_{FI} T^4 = T'^4$ energy in the hidden sector, this yields a temperature so demanding $\xi < 1$ bounds $\tau > \tau_{\text{min}}$.

$$\xi = \left(Y'_{FI}\right)^{1/4}$$
sector equilibration

There is a minimum lifetime given by

$$
\tau_{\text{min}} \simeq 10^{-13} \text{ s} \left( \frac{100 \text{ GeV}}{m} \right)^2 \left( \frac{100}{g^* (T \simeq m)/g_X} \right)
$$

at which the two sectors thermalize.
2 to 2 scattering

If $\mathcal{O}$ is a higher dimension operator then $X'$ particles are produced via 2 to 2 scattering

\[ Y'_{\text{scatt}} \propto m_{\text{Pl}} T_R \langle \sigma v \rangle_{\text{scatt}} \]

$Y'_{\text{scatt}}$ can be neglected for low $T_R$ or if there is substantial re-annihilation.