Dynamical Dark Matter from Thermal Freeze-Out

Brooks Thomas

Based on work done in collaboration with:
• Keith Dienes, Jacob Fennick, and Jason Kumar [arXiv:1712.09919]

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Dynamical Dark Matter (DDM) is a theoretical framework in which constraints on dark matter can be satisfied without the hyperstability criterion \( (\tau_\chi \geq 10^{26} \text{ s}) \) typically required of traditional DM candidates.

In particular, in DDM scenarios...

- The dark-matter candidate is an ensemble consisting of a potentially vast number of constituent particle species.
- The individual abundances of the ensemble constituents are balanced against decay rates across the ensemble such that constraints are satisfied.
- The DM abundance and equation of state also exhibit a non-trivial time-dependence beyond that associated with Hubble expansion.
Dark Matter
Total (now) 26.8%
Atoms
4.6%
Dark Energy 72%

Will decay in the future

Decayed in the past

Decay Widths
Abundances

Nothing special about the present time! Dark matter is decaying before, during, and after the present epoch.
The viability of a DDM ensemble hinges on three fundamental *scaling relations* which describe how masses, abundances, and decay widths scale in relation to each other across the ensemble:

1. Abundance $\Omega(m)$ as a function of mass
2. Decay width $\Gamma(m)$ as a function of mass
3. Density of states $n(m)$ as a function of mass

One crucial ingredient is an *abundance-generation mechanism* which can provide an appropriate abundance spectrum $\Omega(m)$.

Realizations of DDM have typically relied on non-thermal mechanisms for abundance generation (e.g., misalignment production).

- $m_i \ll \mathcal{O}(\text{keV})$, highly suppressed couplings
- $\mathcal{O}(\text{keV}) \lesssim m_i \lesssim \mathcal{O}(\text{TeV})$, $\mathcal{O}(1)$ couplings

In this talk, however I will demonstrate that a viable set of scaling relations can also be achieved through *thermal freeze-out*.
DDM ensembles with masses and couplings in this regime can give rise to variety of **distinctive and characteristic experimental signatures**:

- **At Colliders**
  - Characteristic features in kinematic distributions of SM particles produced alongside the ensemble constituents. Dienes, Su, BT [1204.4183, 1407.2606]

- **At Direct-detection experiments**
  - DDM ensembles also give rise to distinctive features in recoil-energy spectra. Dienes, Kumar, BT [1208.0336]

- **And at Indirect-Detection Experiments**
  - In the shape of the differential flux spectra of cosmic-ray particles produced from dark-matter annihilation or decay. Dienes, Kumar, BT [1306.2959]
  - In characteristic features in the gamma-ray spectra of dwarf galaxies, the Galactic Center, etc. Boddy, Dienes, Kim, Kumar, Park, BT [1606.07440, 1609.09104]
Thermal Freeze-Out

• As an abundance-generation mechanism for dark matter, **thermal freeze-out** has a number of phenomenological advantages:
  - Insensitivity to initial conditions
  - Applicable to particles $\chi$ with weak-scale masses and couplings sufficiently large (compared to, say, axions) as to be relevant for collider physics, direct detection, etc.

• Characteristic dependence of the abundance when $\chi$ annihilates (e.g., through light mediators or $t$-channel diagrams) into light fields $\psi$:

$$\langle \sigma v \rangle \sim \frac{g_x^2 g_y^2}{m_x^2} \quad \rightarrow \quad \Omega_x \sim \frac{m_x^2}{g_x^2 g_y^2}$$
**Thermal DDM?**

The Question: Can thermal freezeout naturally provide the balancing of decay widths against abundances required for DDM?

- Typically, $\Gamma_i$ scales with $m_i$ to some positive power. For a viable ensemble, $\Omega_i$ must scale with $m_i$ to a sufficient inverse power.
- Consider an ensemble of dark-matter constituents $\chi_i$ which all couple to a common mediator $\phi$ which also couples to a light fields $\psi$.
- In the regime in which $m_\phi > m_i$ for all $\chi_i$, all constituents annihilate primarily to $\psi$ pairs via an $s$-channel $\phi$.

Scaling of $g(m_i)$ with $m_i$ can depend on underlying theory structure, renormalization, etc. For simplicity we take $g_i \equiv g_\chi$ to be universal.
Annihilation Cross-Sections

The way in which the annihilation cross-section scales with \( m_i, m_\phi, \) and \( m_\psi \) is dictated by the structure of the pertinent Lagrangian operators:

\[
\sigma_i \sim \frac{g_X^2 g_\psi^2}{m_i^2} v^{2r-1} \left( \frac{\mu}{m_i} \right)^{2(n_X+n_\psi)} \frac{(1 - m_\psi^2/m_i^2)^{s+1/2}}{(1 - m_\phi^2/4m_i^2)^2} \left( \frac{m_\psi}{m_i} \right)^t
\]

### Operators (On the Dark-Matter Side)

<table>
<thead>
<tr>
<th>( \chi_i )</th>
<th>( \phi )</th>
<th>coupling</th>
<th>( n_X )</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>spin-0</td>
<td>spin-0</td>
<td>( S: g_X \mu \chi^* \chi \phi )</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>spin-1/2</td>
<td>spin-0</td>
<td>( S: g_X \chi \bar{\chi} \phi )</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>spin-1/2</td>
<td>spin-0</td>
<td>( P: g_X \chi \gamma_5 \chi \phi )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>spin-0</td>
<td>spin-1 (time)</td>
<td>( V: g_X (\chi^* \partial_0 \chi) \phi^0 )</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>spin-0</td>
<td>spin-1 (spatial)</td>
<td>( V: g_X (\chi^* \partial_i \chi) \phi^i )</td>
<td>0</td>
<td>1</td>
</tr>
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<td>spin-1/2</td>
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<tr>
<td>spin-1/2</td>
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</table>

\( n_X \): mass dimension of operator coefficient

\( r \): whether initial state can be \( L=0 \) (\( r = 0 \)) or only \( L=1 \) (\( r = 1 \))
Annihilation Cross-Sections

• The way in which the annihilation cross-section scales with $m_i$, $m_\phi$, and $m_\psi$ is dictated by the structure of the pertinent Lagrangian operators:

$$\sigma_i \sim \frac{g_\chi^2 g_\psi^2}{m_i^2} \nu^{2r-1} \left( \frac{\mu}{m_i} \right)^{2(n_\chi+n_\psi)} \frac{(1 - m_\psi^2/m_i^2)^{s+1/2}}{(1 - m_\phi^2/4m_i^2)^2} \left( \frac{m_\psi}{m_i} \right)^t$$

Operators (On the Light-Particle Side)

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\psi$</th>
<th>coupling</th>
<th>$n_\psi$</th>
<th>$s$</th>
<th>$t$</th>
</tr>
</thead>
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<td>spin-0</td>
<td>spin-0</td>
<td>S: $g_\psi \mu \phi \bar{\psi} \psi$</td>
<td>1</td>
<td>0</td>
<td>0</td>
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<tr>
<td>spin-0</td>
<td>spin-1/2</td>
<td>P: $g_\psi \phi \bar{\psi} \gamma_5 \psi$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>spin-1 (time)</td>
<td>spin-0</td>
<td>V: $g_\psi \phi^0 (\psi^* \partial_0 \psi)$</td>
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</table>

$n_\chi$: mass dimension of operator coefficient

$s$: whether final state can be $L=0$ ($s=0$) or only $L=1$ ($s=1$)

$t$: whether coupling is chirality-suppressed ($t=1$) or not ($t=0$)
Abundance Spectrum

• The corresponding spectrum of abundances $\Omega_i$ for the ensemble is

\[
\Omega_i \sim \frac{m_i^2}{g_x^2 g_\psi^2} m_i^{2(n_x + n_\psi) + t} \frac{(1 - m_\phi^2/4m_i^2)^2}{(1 - m_\psi^2/m_i^2)^{s+1/2}}
\]

• Equivalently, we can parametrize this spectrum of abundances in terms of an ($m_i$-dependent) **scaling exponent** $\gamma(m_i)$:

\[
\Omega_i \sim m_i^{\gamma(m_i)}
\]

\[
\gamma(m_i) \equiv \frac{d \ln \Omega(m_i)}{d \ln m_i} = 2 + \Delta \gamma + \frac{1}{m_i^2/m_\phi^2 - 1/4} + \frac{2s + 1}{1 - m_i^2/m_\psi^2}
\]

where we have defined \( \Delta \gamma \equiv 2(n_x + n_\psi) + t \)
Integrating Out Before Freezing Out

- Decay widths typically scale as a positive power of $m_i$. Thus, DDM prefers $\gamma < 0$.
- This naturally occurs in the regime in which $m_\psi \ll m_i \ll m_\phi$.

![Diagram of Standard WIMP and Heavy Mediator]

**Standard WIMP**

$\chi \rightarrow \psi$  

**Heavy Mediator**

$m_\psi \ll m_i \ll m_\phi$

- $\gamma \approx 2$
- $\gamma \approx -2 + \Delta \gamma$

Ideal for DDM
Abundance Spectrum

$m_\phi/m_\psi = 10$

- Spectrum of $\Omega_i$ shown here for
  - $\phi$: scalar
  - $\chi_i$: fermion (S coupling)
  - $\psi$: fermion (A coupling)

- Corresponds to the parameters:
  $n_\chi = n_\psi = t = r = 0$  $s = 1$

Scaling Exponent

- Not a strong dependence on $s$, so curves basically the same for a simple $Z'$ scenario where:
  - $\phi$: vector
  - $\chi_i$: fermion (V coupling)
  - $\psi$: fermion (V coupling)
Abundance Spectra

\[ \Delta \gamma = 0 \quad \Delta \gamma = 2 \quad \Delta \gamma = 4 \]

\( m_\phi / m_\psi = 10 \)

\( m_\phi / m_\psi = 20 \)

\( m_\phi / m_\psi = 400 \)
Balancing Widths Against Abundances

- DDM requires a balancing of decay widths $\Gamma_i$ against abundances $\Omega_i$.

Abundance (function of $\Gamma$): $\Omega(\Gamma) \sim \Gamma^\alpha$

Density of states (per unit $\Gamma$): $n_\Gamma(\Gamma) \sim \Gamma^\beta$

- Assuming typical scaling behavior for $\Gamma_i$ and a typical mass spectrum

\[ \Gamma \sim m^y \quad m \sim k^\delta \]

...we find that:

\[ \frac{1}{y} \left( \gamma + \frac{1}{\delta} \right) \lesssim 0 \]

i.e.,

\[ \delta \geq \delta_{\text{min}} \equiv -\frac{1}{\gamma} \]

**The Upshot:** Easy to achieve the correct balancing!

For example: fermionic $\chi_i, \psi$; vector $\phi$ with $m_\psi \ll m_i \ll m_\phi$
Regimes of Interest

- For a standard WIMP: \( \Omega_\chi \propto \frac{1}{\langle \sigma_v \rangle} \sim \frac{m_\chi^2}{g_\chi^4} \)

- Likewise, for a DDM ensemble: \( \Omega_{\text{tot}} \propto \sum_i \frac{1}{\langle \sigma_i v \rangle} \sim \sum_i \frac{m_\phi^2}{16g_\chi^2g_\psi^2m_i^2} \)

\[ \sum_i \left( \frac{m_\phi}{m_i} \right)^2 \lesssim g_\chi^2g_\psi^2 \left( \frac{2.37 \text{ TeV}}{m_\phi} \right)^2 \]

- \( g_\psi \) and \( g_\chi \) must remain perturbative.

- \( m_i \gtrsim \mathcal{O}(\text{keV}) \) for all \( \chi_i \) (structure formation, etc.)

- Thus, our regime of interest for thermal DDM is one in which the \( \chi_i \) are \textbf{light}, the couplings are large, the mediator is below the TeV scale, and the annihilation products are primarily \textbf{dark-sector states}.

\[ \mathcal{O}(\text{keV}) \lesssim m_i \ll m_\phi \ll \mathcal{O}(\text{TeV}) \]
Summary

• In this talk, I have shown the appropriate scaling relations for DDM can arise in scenarios in which the dark-matter abundance is generated via **thermal freeze-out**.

• A **broad range of scaling behaviors** can be achieved, depending on the masses, spins, etc. of the particles involved.

• Straightforward to arrange a balancing between decay widths and abundances.

• A regime of interest emerges in which the ensemble constituents are light, couplings are large, and the mediator is at the TeV-scale – a regime ripe with phenomenological possibilities!