Dark Matter from a Dark SU(N) Gauge Theory with a Single Quark Flavor

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Outline

• Theory Overview / Large-N estimates
• Thermally Decoupled Sectors
• Cosmic Evolution
• Results
The Dark SU(N) Theory

• We consider a SU(N) gauge theory with a single dark (effectively massless, $m_{\tilde{q}} \ll \Lambda$) “quark”

<table>
<thead>
<tr>
<th>field</th>
<th>$U(1)_Y$</th>
<th>SU(2)$_L$</th>
<th>SU(3)$_c$</th>
<th>SU(N)$_{\text{dark}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{q}_L$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>$N$</td>
</tr>
<tr>
<td>$\tilde{q}_R$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>$N$</td>
</tr>
<tr>
<td>$\tilde{q}^\dagger_L$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>$\bar{N}$</td>
</tr>
<tr>
<td>$\tilde{q}^\dagger_R$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>$\bar{N}$</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>$N^2 - 1$</td>
</tr>
</tbody>
</table>

• We take $N \gg 1$

• We assume that the dark coupling constants scales like:

  $g_{\text{dark}} \sim 1/\sqrt{N}$

• This allows us to compute the scaling of physical observables with $N$
Confinement

• The $\beta$-function is:

$$\beta(\mu) = -\left(\frac{11}{3} - \frac{2}{3} \frac{1}{N}\right) \frac{\tilde{g}^3}{16\pi^2} + O(\tilde{g}^5)$$

• At a scale Lambda, the theory will confine

• Below confinement, the relevant d.o.f. will be mesons and baryons

• Since we have a single quark, our asymptotic states are a $\tilde{\Delta}$-baryon and an $\tilde{\eta}'$-meson
Stable Asymptotic States

- $\tilde{\eta}'$ is very light: pseudo-Goldstone with mass proportional to chiral anomaly

- $\tilde{\Delta}$ is very heavy: made up of $N$ dark quarks

<table>
<thead>
<tr>
<th>field</th>
<th>mass</th>
<th>spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\eta}'$</td>
<td>$\sim \Lambda/\sqrt{N}$</td>
<td>0</td>
</tr>
<tr>
<td>$\tilde{\Delta}$</td>
<td>$\sim N\Lambda$</td>
<td>$N/2$</td>
</tr>
</tbody>
</table>
Interactions

- $\tilde{\eta}'$ interactions are described by $\mathcal{L}_{\text{ChPT}}$

$$\mathcal{L}_{\text{ChPT}} \supset L_1 \frac{f_{\eta'}^2}{\Lambda^2} \frac{(\partial_\mu \eta')^4}{f_{\eta'}^4} + L_2 \frac{f_{\eta'}^2}{\Lambda^2} \frac{(\partial_\mu \eta')^6}{f_{\eta'}^6} + \cdots$$

- $\Delta$ creation/annihilation exponentially suppressed (color matching)

- $\Delta$ scattering dominated by mediation of lightest scalar state

Number-changing

$$\mathcal{M} \sim e^{-cN}$$

Self-interaction

$$\sigma \sim \frac{m_\Delta^2}{m_\sigma^4}$$
Thermally Decoupled Theory

- If a theory is thermally decoupled from the SM, it may have a different temperature.
- Total entropy in dark and SM sectors will be conserved.
- Ratios of entropy densities will be constant.

\[
\text{constant} = \frac{S_d}{S_{SM}} = \frac{a^3 s_d}{a^3 s_{SM}} = \frac{h_d(T_d)T_d^3}{h_{SM}(T_{SM})T_{SM}^3}
\]

- We can determine dark temperature at later times if we know ratio at early time.
Thermally Decoupled Theory

• If the temperature ratio is known at $T_{SM}^\infty$, then:

$$\xi(T_{SM}) \equiv \frac{T_d}{T_{SM}} = \left( \frac{h_{SM}(T_{SM})}{h_{SM}^\infty} \frac{h_d^\infty}{h_d(\xi T_{SM})} \right)^{1/3} \xi^\infty$$

• For massive particles in thermal equilibrium

$$h(x = m/T) \sim x^3 K_3(x) \sim x^{5/2} e^{-x} \quad \text{(as } x \to \infty)$$

• As long as the dark sector is in thermal equilibrium, it will become exponentially hot relative to the SM
Dark sector becomes hot relative to SM due to entropy bottleneck.

\[ \xi \sim \frac{x}{\log(x)} \]

\[ \log(y_\eta') \]

\[ \log(\xi = T_d/T_{SM}) \]

\[ \xi = \xi_{f.o.} \frac{T_{SM}}{T_{f.o.}} \]

Frozen-out: redshift

\[ \log(x = m_{\eta'}/T_{SM}) \]
Cosmic Evolution

- High temperature we have a dark quark/gluon plasma
- For temperatures below confinement dark quarks/gluon confine to eta-prime and deltas
- Initial number density of delta is suppressed
- \( \tilde{\eta}'s \) change number via \( 4 \rightarrow 2 \)
- \( \tilde{\Delta}'s \) are produced via \( \tilde{\eta}' + \tilde{\eta}' \rightarrow \tilde{\Delta} + \bar{\Delta} \)
Experimental Handles

- Measurements from bullet cluster and shapes of halos put tight constraints on self interaction cross section:
  \[ \frac{\sigma_{\text{SI}}}{m_\chi} < \text{barn/GeV} \]

- From measurements of CMB, we have constraints on effective number of neutrino species: \( \Delta N_{\text{eff}}^{\text{CMB}} < 0.3 \)

- BBN additionally requires a small \( \Delta N_{\text{eff}} \)

\[
N_{\text{eff}}^{\text{CMB}} \sim 3.046 + \frac{4}{7} \left( \frac{11}{4} \right)^{4/3} g_d \xi^4 \\
N_{\text{eff}}^{\text{BBN}} \sim 3 + \frac{4}{7} g_d \xi^4
\]
Results

\[ \Omega^2 \sigma_{SI}^{A}/m_A + \Omega^2 \sigma_{SI}^{\Delta}/m_{\Delta} \]

\[ \Omega_{CDM}^2 \]

\[ N \]

\[ m (\text{GeV}) \]

\[ \sigma_{SI}/m > \text{barn/GeV} \]

\[ \sigma_{SI}/m > 10^{1.5}\text{barn/GeV} \]
Summary

• We can generically have $\eta'$ - DM

• Temperature ratio of dark/SM must be small (smaller the better)

• Self-interaction constraints (mostly) rule out $\Delta$-DM