Dark Matter Freeze-out during $\text{SU}(2)_L$ Confinement

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Particle physics and cosmological history

• Particles dominated in the early universe
• Particle interactions had profound downstream effects
• Studying particle interactions will help us understand the evolution of our universe
Studying particle interactions

- Studied particle interactions at $E \sim 100$ GeV
  - Indirectly probes the early universe $t \sim 0.01$ ns

- Leading to the **Standard Model** of Particle Physics

- Assuming that the early universe particles follow the Standard Model gives us the **Standard Cosmological History**

- However, this is only an assumption, the real cosmological history may differ
  - Direct probes are needed to say definitively
Alternate cosmological histories

• We know the Standard Model is incomplete

• Direct measurements only confirm a Standard Cosmology back to Big Bang Nucleosynthesis (BBN)

• Alternate cosmological histories may help provide explanations
Why consider alternate cosmological histories?

- Immediate practical benefits
  - Might lead to profitable results alleviating current constraints

- Scientifically important
  - Experimentally we can, so scientifically we should

- Long-term benefits
  - Exploring possibilities will help probe what actually happened

![Diagram showing time and energy scales with Big Bang, Direct experimental constraints, and Dark Matter label.](image-url)
How to modify cosmological history?

- **Common example:** Add new particle species
  - Standard WIMP Dark Matter

- **Weirder example:** Modify strengths of forces
  - Features of the early universe caused the strengths of the forces to evolve, eventually settling to what we see today

- **This talk:** Modify the Electroweak (EW) force to alleviate WIMP DM constraints

Overview

- WIMPs are an attractive model for dark matter (DM)
  - Simple extension of the Standard Model (SM) yields a WIMP miracle

- Experiments have endangered the scenario leading to the WIMP miracle

- However, this assumes a “standard” cosmological history

We find that a period of electroweak confinement contemporary with WIMP freeze-out helps restore the WIMP miracle
WIMP dark matter (DM) freeze-out

• A classic WIMP model considers DM as a Weakly charged particle
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- Force coupling is uniquely fixed
- Getting the correct relic abundance uniquely fixes the DM mass

This was assuming a standard cosmological history
A classic WIMP model considers DM as a Weakly charged particle.
- Force coupling is uniquely fixed.
- Getting the correct relic abundance uniquely fixes the DM mass.

This was assuming a standard cosmological history.

If instead there was an alternate cosmological history where the Weak force coupling was different during freeze-out, freedom in DM mass would be restored.

Strongly constrained by experiments.
Schematic outline of calculation

\[ \mathcal{L} \supset -\frac{1}{2} g_{\text{eff}}^2 \text{Tr}(W_{\mu\nu} W^{\mu\nu}) \]

\[ \frac{1}{g_{\text{eff}}^2} = \left( \frac{1}{g^2} - \frac{\langle \phi \rangle}{M} \right) \quad M > \text{TeV} \]

**EW Force confines DM into “pions”**

- \( \Pi_{\text{DM}} \)
- \( \Pi_{\text{SM}} \)

**DM pions interact / freeze-out**

- \( \Pi_{\text{DM}} \) interacts with \( \Pi_{\text{SM}} \)

**EW confined phase ends, pions deconfine**

- \( \langle \phi \rangle \neq 0 \)
- \( \langle \phi \rangle \rightarrow 0 \)

**Direct experimental constraints**

**EW confinement phase**

**WIMP Freeze-out**

- \( 10^{15} \text{ GeV} \)
- \( 100 \text{ GeV} \)
- \( 1 \text{ GeV} \)
- \( 1 \text{ MeV} \)

**Electroweak (EW) Force**

- At normal strength: \( \langle \phi \rangle \ll M/g \)
- Much stronger: \( \langle \phi \rangle \sim M/g \)

This causes EW confinement (analogous to QCD)
Prior work on EW confinement

• Historical work:
  

• One work[1] explored cosmological implications of an early EW confinement phase
  
  - Coupling strength is linked to the vev of a scalar field, $\phi$, undergoing a phase transition in the early universe

  \[
  \mathcal{L} \supset -\frac{1}{2} \frac{1}{g_{\text{eff}}^2} \text{Tr}(W_{\mu\nu} W^{\mu\nu}) \quad \frac{1}{g_{\text{eff}}^2} = \left( \frac{1}{g^2} - \frac{\langle \phi \rangle}{M} \right) \quad \text{Energy scale parameter: } M > \text{TeV}
  \]

  • Agnostic to phase transition specifics

Main takeaways from [1]

- Strong EW force causes quark and lepton doublets to confine into pion-like objects
  
  - Confinement causes spontaneous flavor symmetry breaking: \( \text{SU}(2N_f) \rightarrow \text{Sp}(2N_f) \)
    
    - Massless GSBs*: \( (4N_f^2 - 1) - (2N_f^2 + N_f) = 2N_f^2 - N_f - 1 = 65 \)
    
    - One massive pseudo-GSB (\( \eta' \) analog)

- Loop induced corrections from gauge interactions + Yukawas give 58/65 “pions” masses

- Confinement breaks SM gauge symmetry: \( \text{SU}(3)_C \times \text{U}(1)_Y \rightarrow \text{SU}(2)_C \times \text{U}(1)_Q \)
  
  - 4 massless gauge bosons + 5 massive gauge bosons

Our work throws a WIMP-like DM particle into the mix

Our DM candidate is a pair of vector-like $SU(2)_L$-charged Weyl fermions

- SM quantum numbers $SU(3)_C \times SU(2)_L \times U(1)_Y = \{1, 2, \pm 1/2\}$ with mass $m_{\text{DM}}$

\[
\mathcal{L}_\chi = i\chi_1^\dagger \bar{\sigma}^\mu D_\mu \chi_1 + i\chi_2^\dagger \bar{\sigma}^\mu D_\mu \chi_2 + m_{\text{DM}} \chi_1 \chi_2 + \text{h.c.}
\]

During EW confinement, $\chi_1$ and $\chi_2$ confine with SM quarks and leptons into bound states

- These are analogous to mesons and baryons of QCD
- The lightest of these states are mesons: $\Pi$ and $\eta'$

In analogy with chiral perturbation theory, we collect these into a complex antisymmetric scalar field $\Sigma_{ij}$ where $i,j = 1, \ldots, 2N_f$
Confinement details

- Confinement spontaneously breaks flavor symmetry $SU(2N_f) \to Sp(2N_f)$
  - Follows intuition from chiral symmetry breaking in QCD and confirmed with lattice simulations
  - Encoded by $\Sigma_{ij}$ obtaining a vev $(\Sigma_0)_{ij}$ satisfying $\Sigma_0^+\Sigma_0 = \Sigma_0\Sigma_0^+ = 1$

- Neglecting other SM gauge interactions and Yukawa couplings we get $2N_f^2 - N_f - 1$ massless Goldstone bosons (GSBs) and 1 massive pseudo-GSB, analogous to the $\eta'$ of QCD.
Confinement details

\[ \mathcal{L}_{\text{IR}} \supset \frac{f^2}{4} \text{Tr} \left[ D_\mu \Sigma^\dagger D^\mu \Sigma \right] + \Lambda_\text{W}^3 \text{Tr} \left[ M \Sigma + \Sigma^\dagger M^T \right] + \kappa \Lambda_\text{W}^2 f^2 \text{Re} \left[ \det \Sigma \right] + \Delta \mathcal{L} \]

\[ \Delta \mathcal{L} = C_G \Lambda_\text{W}^2 f^2 \frac{g_s^2}{16\pi^2} \sum_{a=1,2,3} \text{Tr} \left[ L^a \Sigma^\dagger L^a \Sigma \right] + C_A \Lambda_\text{W}^2 f^2 \frac{e_Q^2}{16\pi^2} \text{Tr} \left[ Q \Sigma^\dagger Q \Sigma \right] \]
\[ + C_W \Lambda_\text{W}^2 f^2 \frac{g_s^2/2}{16\pi^2} \sum_{\pm} \sum_{i=1,2} \text{Tr} \left[ L^{i \pm} \Sigma^\dagger L^{i \pm} \Sigma \right] + C_Z \Lambda_\text{W}^2 f^2 \frac{e_Q^2}{16\pi^2} \frac{s_Q^2 c_Q^2}{2} \text{Tr} \left[ J \Sigma^\dagger J \Sigma \right] \]

- \( \Delta \mathcal{L} \) gauge corrections from SU(3)\(_C\) and U(1)\(_Y\) explicitly break SU(2\(_{N_f}\)) giving some GSBs masses

- Confinement breaks SU(3)\(_C\) \times U(1)\(_Y\) \rightarrow SU(2)\(_C\) \times U(1)\(_Q\) eating some of the massless GSBs

\[ \Sigma = \exp \left[ i \frac{\eta'}{\sqrt{N_f f}} \right] \exp \left[ \sum_a 2i \frac{\Pi^a X^a}{f} \right] \Sigma_0 \]

\( X^a \) generators of the broken symmetry

SU(2\(_{N_f}\))/Sp(2\(_{N_f}\)), \( a : 1, \ldots, 2N_f^2 - N_f - 1 \)
Unbroken $\chi$ charge

- $\mathcal{L}_{\text{IR}}$ is invariant under an unbroken $U(1)_\chi$, convenient to organize the pions by their charges

$$\Sigma \xrightarrow{U(1)_\chi} \Sigma' \approx \Sigma + i\theta_\chi (Q_\chi \Sigma + \Sigma Q_\chi) + \ldots \quad Q_\chi = \text{diag}(0, \ldots, 0, 1, -1)$$

- Expanding $\Sigma$ to first order implies

$$\Pi_b \rightarrow \Pi_b + i\theta_\chi \delta\Pi_b \quad \delta\Pi_b = 2\Pi_a \text{Tr}[[Q_\chi, X_a], X_b]$$

- We can then construct linear combinations of the pion fields with definite $U(1)_\chi$ charge

$$\Pi^\pm_1 := \frac{1}{\sqrt{2}}(\Pi_5^{\text{mass}} \mp i\Pi_8^{\text{mass}}) \quad \Pi^\pm_2 := \frac{1}{\sqrt{2}}(\Pi_6^{\text{mass}} \mp i\Pi_7^{\text{mass}}) \quad \Pi^\pm_3 := \frac{1}{\sqrt{2}}(\Pi_9^{\text{mass}} \mp i\Pi_{12}^{\text{mass}}) \quad \Pi^\pm_4 := \frac{1}{\sqrt{2}}(\Pi_{10}^{\text{mass}} \mp i\Pi_{11}^{\text{mass}})$$
Pion masses and remaining gauge symmetries

Gauge charges

<table>
<thead>
<tr>
<th>η'</th>
<th>U(1)Q</th>
<th>SU(2)C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>±1</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

4 SM pions

2 SM/DM pions

2 SM/DM pions

4 SM/DM pions

1 SM pion

1 DM pion

Masses

\[ C_G = C_A = C_Z = -1, \ C_W = 1, \ \kappa = 1, f = 65 \text{ TeV} \]

\[ \eta' = 0.8, \ e_0 = 0.5, \ s_0 = 0.3 \]

\[ \eta' = 0.1, \ e_0 = 0.01, \ s_0 = 0.01 \]

\[ M_{0,10,11,12} \]

\[ M_{5,7} \]

\[ M_{5,8} \]
Deriving pion interactions

• We are interested in reactions which deplete the DM density i.e. $\Pi_{\text{DM}} \Pi_{\text{DM}} \rightarrow \Pi_{\text{SM}} \Pi_{\text{SM}}$

$$\mathcal{L}_{\text{IR}} \supset \frac{f^2}{4} \text{Tr} \left[ D_\mu \Sigma^\dagger D^\mu \Sigma \right] + \Lambda^3_{W} \text{Tr}[M \Sigma + \Sigma^\dagger M^T] + \kappa \Lambda^2_{W} f^2 \text{Re}[\text{det} \Sigma] + \Delta \mathcal{L}$$

• Transforming into definite DM charge basis implies we want $\Pi^+ \Pi^- \rightarrow \Pi^0 \Pi^0$

• For the benchmarks chosen we can safely neglect annihilation to gauge bosons

• We calculate the velocity averaged effective cross-section, taking into account coannihilation
  • We assume non-relativistic, s-wave scattering

• We then use this in solving the Boltzmann equation for the final co-moving number density of $\Pi_{\text{DM}}$
WIMP freeze-out in this scenario

- Freeze-out happens while $\chi_1$ and $\chi_2$ are confined in pion form
  - Lightest pion containing $\chi$ survives freeze-out: $\Pi_{\text{DM},1}$ (mass = $m_1$)
  - Calculate $\Omega_{\Pi_{\text{DM},1}} h^2$ numerically taking into account possible coannihilation

- After freeze-out, EW confined phase ends and pions deconfine
  - Entropy dump from deconfinement is negligible which prevents further freeze-out of the $\chi$'s

- In general, $m_{\Pi_{\text{DM},1}} > m_{\text{DM}}$ so we adjust the relic abundance accordingly

$$\Omega_{\chi} h^2 = \frac{m_{\text{DM}}}{m_1} \Omega_{\Pi_{\text{DM},1}} h^2$$
Parameter scan

• Under some minimal assumptions: $m_{DM} < \Lambda_W$ and $f = \frac{1}{4\pi}\Lambda_W$

• Performed a parameter scan in $\left[ \log_{10}\left( \frac{m_{DM}}{\text{GeV}} \right), \log_{10}\left( \frac{f}{\text{GeV}} \right) \right]$

• Using the log-likelihood as the objective function

$$\ln L = -\frac{1}{2} \left[ \frac{\Omega_{\chi} h^2 (m_{DM}, f) - \Omega_{PDG} h^2}{\Delta \Omega h^2} \right]$$

$$\Omega_{PDG} h^2 \pm \Delta \Omega h^2 = 0.1200 \pm 0.0012 [1]$$

\[ \langle \sigma_{\text{eff}} v \rangle \approx (1.5 \text{ to } 2) \times 10^{-11} \text{ GeV}^{-2} \left( \frac{m_{\text{DM}}}{5 \text{ TeV}} \right) \left( \frac{65 \text{ TeV}}{f} \right)^3 \]
Reminder: $\chi_{1,2}$ are $SU(2)_L$-doublets with hypercharge with full strength $Z$-boson couplings $\Rightarrow$ trouble, but...

- Avoided if there is a small Majorana mass $m_M \ll m_{DM}$ today\textsuperscript{[1]}

- Can be induced by a dimension 5 interaction with the Higgs

\[ \mathcal{L}_{\Delta M} = \frac{1}{M_1} (H^\dagger \chi_1)(H^\dagger \chi_1) + \frac{1}{M_2} (H\chi_2)(H\chi_2) + h.c. \]

- No effect on freeze-out for sufficiently large mass scales

Other experimental constraints

LHC bounds
- Analogous signature to charginos
- No constraints for $m_{DM} > 420$ GeV\textsuperscript{[1]}
- Likely out of reach for future colliders

Indirect detection
- Might be in reach of future gamma ray observatories

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Main takeaway

What did this alternate cosmological history get us?

• Maintains the correct DM relic abundance
• Increases the possible mass range of DM
• Restores some freedom to WIMP models
Conclusion

- Considering alternate cosmological histories is important and can be advantageous
- Modification to cosmological history can help restore the WIMP miracle
- Not ruled out by current experiments

Questions?
• Because of the many possible combinations of \{a, b, c, d\} we perform the calculation of \( \Pi_a \Pi_b \rightarrow \Pi_c \Pi_d \) numerically via Python.

• The code calculates \( \Omega_x h^2 \) for each parameter space point \((f, m_{DM})\) and compares it to PDG value.

• Parameter scan done with ULYSSES with a PyMultiNest back-end.

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