Exploring Composite Dark matter with an SU(4) gauge theory with 1 fermion flavor

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Work in progress with the LSD collaboration
Dark matter

Evidence

- Galaxy rotation curves
- Weak lensing
- CMB

Dark matter features:

★ Interaction is weak: Gravitational

★ Abundance: $\Omega_{\text{Dark}} = 5 \times \Omega_{\text{SM}}$

Galaxy rotation curves point to missing dark matter

Fig. from wikipedia
Strongly coupled Composite Dark matter

- New strong sector (dark color)
  - Dark fermions and gluons
  - Stable composite particles
  - Can be dark matter
  - Coupled via Electroweak to SM particles

New confinement and chiral transitions to explore

Potential gravitational wave signal
A new strong Dark sector SU(4)

\[ SU(N_c) \]

Natural extension to SM

\[ U(1) \times SU(2) \times SU(3) \times SU(4) \]

Couple to EWK sector

Dark quarks

Composite Dark particles

- Baryons
- Mesons

The Challenge

- Massive particles that can be detected by future experiments
- No light particles that should’ve been seen by existing experiments

Explain new physics

Be consistent with observations
The model: SU(4) gauge theory with 1 flavor

1 flavor models are interesting!

- $U_V(1)$ (Dark baryon number) symmetry is preserved
- $U_A(1)$ is broken by the anomaly
- No chiral transition
- No light mesons from chiral SB

Previous 1 flavor work

SU(3) 1 flavor: Morte, Jager, Sannino, Tsang, Ziegler Phys. Rev. D 107 (2023), 114506

SU(2) 1 flavor: Francis, Hudspith, Lewis, Tulin JHEP 12 (2018) 118
SU(4) 1 flavor emerges from Hyper stealth Dark matter (HSDM) model

HSDM\(^1\)

- SU(4) gauge theory: 4 flavors of fundamental Dirac fermions
- Two couple to SU(2) and U(1)
- Two couple only to U(1)
- Mass from:
  - Vector mass terms
  - Yukawa couplings to Higgs
- Can tweak to get a mass hierarchy

\(M^u_1, M^d_1, M^d_2\)

Mass hierarchy

**Lightest baryon is charge neutral**

Similar to a QCD with neutron lightest

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\(^1\)In preparation: Fleming, Kribs, Neil, Schaich and Vranas
Lattice simulation goals

Step 1: Thermodynamics

Explore phase diagram at finite T
Identify confinement transition
Is it first order?

Observables:

- Plaquettte
- Polyakov loop
- Susceptibilities
  \[ \chi_\theta = L^3 \left[ \langle \theta^2 \rangle - \left( \langle \theta \rangle \right)^2 \right] \]

Step 2: Find the spectrum

Challenges:

- Lightest meson $\eta'$ has disconnected diagrams
- Baryon is 4-quark state
Simulation details

Wilson gauge action

Mobius domain-wall fermions

Lattice sizes: \(16^3 \times 8, 24^3 \times 8, 24^3 \times 12\)

Mass: 0.1

Domain-wall \(L_5 = 16\)

~ 350 - 1300 MDTUs (molecular dynamics time units) per run

8 GPUs per run

Gauge config generation

https://github.com/paboyle/Grid

Measurements

https://github.com/aportelli/Hadrons

Runs on Tioga AMD GPU machine at Livermore Lab

Thank you Antonin and Peter for help!
Results: Plaquette shows location of a bulk transition

Preliminary results

Jump in the Polyakov loop for $\beta \sim 10.3$

No variation with temperature ($L_t = 8, 12$)

Bulk transition: unphysical, lattice artifact
Results: Comparing Hot and Cold starts

Preliminary results

Polyakov loop : Confinement transition $\beta \in (11.0,12.0)$

<table>
<thead>
<tr>
<th></th>
<th>Hot start</th>
<th>Random gauge fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold start</td>
<td>Unit gauge field</td>
<td></td>
</tr>
</tbody>
</table>

Hot and cold starts not meeting
Can’t trust results here
Need more configurations!
Results: Confinement transition from the Polyakov loop

Preliminary results

Variation with temperature ($N_t = 8, 12$)

$$T \sim \frac{1}{a N_t}$$

As $N_t \uparrow \implies a_c \downarrow \implies \beta_c \uparrow$

Transition moves as expected

Not a bulk transition

Transition shifts to larger $\beta$ with increasing $N_t$
Next steps

- Need more configs near the transition
- Polyakov loop is noisy
- Calculate masses of lightest stable baryon and meson
- Map phase diagram for larger $m_q$

Wilson flowed observables to map transition
Challenging: $\eta'$ has disconnected contributions
Perhaps use Wilson fermions with RHMC
Summary

Hyper-stealth Dark matter : SU(4)
Studying thermodynamics of SU(4) 1 flavor
Found the region of the transition

Future direction

✦ Calculate masses of lightest stable baryon and meson
✦ Scattering
Thank you

<table>
<thead>
<tr>
<th>Location</th>
<th>Contributors</th>
</tr>
</thead>
<tbody>
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</tr>
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<td>Bern</td>
<td>Andrew Gasbarro</td>
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<td>Boston University</td>
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<td>CU Boulder</td>
<td>Ethan Neil, Anna Hasenfratz, Curtis Peterson</td>
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<td>Oliver Witzel</td>
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</tr>
<tr>
<td>Yale</td>
<td>Thomas Appelquist, Kimmy Cushman</td>
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</tbody>
</table>

Computing resources:

LLNL machines Lassen and Tioga
Backup slides
### Hyper-stealth dark matter (HSDM)

#### Fermion kinetic terms

\[
\mathcal{L} \supset \sum_{i=3,4} iF_i^\dagger \sigma^\mu D_{i,\mu} F_i + \sum_{j=u,d} \sum_{i=3,4} iF_i^j \sigma^\mu D_{i,\mu} F_i^j
\]

#### Covariant derivatives

\[
\begin{align*}
D_{1,\mu} &= \partial_\mu - ig'Y_1 B_\mu - igW_{\mu}^{a} \sigma^a \over 2 - ig_D G_{\mu}^{b} t^b \\
D_{2,\mu} &= \partial_\mu - ig'Y_2 B_\mu - igW_{\mu}^{a} \sigma^a \over 2 + ig_D G_{\mu}^{b} t^b \\
D_{3,\mu} &= \partial_\mu - ig'Y_3 B_\mu - ig_D G_{\mu}^{b} t^b \\
D_{4,\mu} &= \partial_\mu - ig'Y_4 B_\mu + ig_D G_{\mu}^{b} t^b
\end{align*}
\]

#### Flavor charge assignments

<table>
<thead>
<tr>
<th>Field</th>
<th>(SU(N_D))</th>
<th>((SU(2)_L, Y))</th>
<th>(T_3)</th>
<th>(Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F_1^u)</td>
<td>(N)</td>
<td>((2, -1/2))</td>
<td>+1/2</td>
<td>0</td>
</tr>
<tr>
<td>(F_1^d)</td>
<td>(N)</td>
<td>((2, -1/2))</td>
<td>-1/2</td>
<td>-1</td>
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<tr>
<td>(F_3^u)</td>
<td>(N)</td>
<td>((1, 0))</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(F_3^d)</td>
<td>(N)</td>
<td>((1, -1))</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>(F_4^u)</td>
<td>(N)</td>
<td>((1, +1))</td>
<td>0</td>
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<td>(F_4^d)</td>
<td>(N)</td>
<td>((1, 0))</td>
<td>0</td>
<td>0</td>
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\[Q = T_3 + Y\]
Mass terms: Vector and Yukawa

Vector-like mass terms

\[ \mathcal{L} \supset M_{12} \epsilon_{ij} F^i_1 F^j_2 - M^u_{34} F^u_3 F^d_4 + M^d_{34} F^d_3 F^y_4 + \text{h.c.} \]

Yukawa masses after EWK symmetry breaking

\[ \mathcal{L} \supset \frac{\nu}{\sqrt{2}} \left( -y^u_{14} F^u_1 F^d_4 + y^d_{14} F^d_1 F^u_4 + y^d_{23} F^d_2 F^d_3 - y^u_{23} F^d_2 F^u_3 + \text{h.c.} \right) \]

Mass eigenbasis

\[ \mathcal{L} \supset - \left[ M^u_1 \bar{\Psi}^u_1 \Psi^u_1 + M^u_2 \bar{\Psi}^u_2 \Psi^u_2 + M^d_1 \bar{\Psi}^d_1 \Psi^d_1 + M^d_2 \bar{\Psi}^d_2 \Psi^d_2 \right] \]
SDM and HSDM comparison

**SDM**

<table>
<thead>
<tr>
<th>+1</th>
<th>-1</th>
<th>+1</th>
<th>-1</th>
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2 flavors have SU(2) charges
2 flavors have hypercharge

Light charged dark pions exist

Dark baryons scale ~ TeV

**HSDM**

<table>
<thead>
<tr>
<th>0</th>
<th>-1</th>
<th>0</th>
<th>+1</th>
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2 flavors have SU(2) and hypercharge
2 flavors have hypercharge

Dark baryons scale ~ few GeV

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1. PHYSICAL REVIEW D 92, 075030 (2015)
2. PHYSICAL REVIEW LETTERS PRL 115, 171803 (2015)
3. PHYSICAL REVIEW D 103, 014505 (2021)
Want to find the order of confinement transition for SU(4)

<table>
<thead>
<tr>
<th>Number of flavors</th>
<th>Order of confinement transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure gauge(^1)</td>
<td>1(^{st}) order</td>
</tr>
<tr>
<td>1 flavor</td>
<td>?</td>
</tr>
<tr>
<td>2 flavors(^2)</td>
<td>cross-over</td>
</tr>
<tr>
<td>4 flavors(^1)</td>
<td>cross-over for low masses</td>
</tr>
</tbody>
</table>

Conjectured Columbia plot for SU(N) gauge theory

We like 1\(^{st}\) order

Potential Gravitational wave signal!

\(^1\)PHYSICAL REVIEW D 103, 014505 (2021), LSD collaboration
\(^2\)PHYSICAL REVIEW D 97, 114502 (2018), TaCo collaboration