Stealth dark matter and gravitational waves

David Schaich (University of Liverpool)

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Work in progress with the Lattice Strong Dynamics Collaboration
Exploring the range of possible phenomena in strongly coupled field theories
Overview

Stealth dark matter
Attractive and viable composite dark matter model

Exploring gravitational waves from first-order transition

Stealth dark matter motivational review

4-flavor SU(4) lattice phase diagram

Gravitational wave prospects
Dark matter

Consistent gravitational evidence from kiloparsec to Gpc scales

\[
\frac{\Omega_{\text{dark}}}{\Omega_{\text{ordinary}}} \approx 5 \quad \text{... not } 10^5 \text{ or } 10^{-5}
\]

\[\rightarrow\] non-gravitational interactions with standard model
Composite dark matter

Early universe
Deconfined charged fermions $\rightarrow$ non-gravitational interactions

Present day
Confined neutral ‘dark baryons’ $\rightarrow$ no experimental detections
Stealth dark matter

SU(4) dark sector with four moderately heavy fundamental fermions

Lightest scalar ‘baryon’ is stable dark matter candidate

Direct detection

Symmetries

\[ \rightarrow \text{electric polarizability} \]

is leading interaction

Collider searches

**Charged** ‘meson’ Drell–Yan

rules out shaded region
First-order confinement transition $\rightarrow$ stochastic background

$\rightarrow$ Lattice studies of stealth dark matter phase transition
Phase diagram expectations

Pure-gauge transition is first order

Becomes stronger as $N$ increases

First-order transition persists for sufficiently heavy fermions

How heavy is sufficient for SU(4)?

Using $N_F = 4$ unrooted staggered fermions

gauge action with both fundamental & adjoint plaquette terms
The lattice phase diagram game

Fermion masses \( m = 0.05, 0.067, 0.1, 0.2 \) (and pure gauge)

\[
\times
\]

Temporal extents \( N_T = 4, 6, 8, 12 \)

\[
\times
\]

Aspect ratios \( L/N_T = 2, 3, 4, 6, 8 \)

\[
\times
\]

Scan coupling \( \beta_F \) to sweep temperatures high \( \rightarrow \) low and low \( \rightarrow \) high

\[= 985 \text{ ensembles and counting} \quad [5,000–50,000 \text{ MD time units per ensemble}]\]
The lattice phase diagram game

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Scan coupling $\beta_F$ to sweep temperatures high $\rightarrow$ low and low $\rightarrow$ high

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Pure gauge checks: Bulk and thermal transitions

Try to avoid bulk transition for small $N_T$  → use $\beta_A = -\beta_F / 4$

Still need $N_T > 4$ for clear separation between bulk & thermal transitions
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Pure gauge checks: Order of thermal transition

Two peaks in Polyakov loop magnitude histogram $\rightarrow$ first-order transition ✔

Hysteresis not clearly visible even in pure-gauge case
Dynamical results: Still looks first order

Pure-gauge & dynamical susceptibilities show same behavior

\[ \rightarrow \] evidence for first-order transition with \( m \geq 0.1 \)

Fundamental fermions explicitly break \( Z_N \) \[ \rightarrow \] don’t see two peaks in histograms
What does $m \geq 0.1$ mean?

**How heavy is sufficient for SU(4)?**

**Spectrum measurements**

Zero-temp. $24^3 \times 48$ ensembles around each transition

$\rightarrow M_P/M_V = 0.80(3) \text{ for } m = 0.1$

$\rightarrow M_P/M_V = 0.91(1) \text{ for } m = 0.2$

Previous work considered $0.55 \leq M_P/M_V \leq 0.77 \rightarrow \text{ now adding } m = 0.05$
From first-order transition to gravitational wave signal

First-order transition $\rightarrow$ gravitational wave background will be produced

How do we predict its features?

Four key parameters

Transition temperature $T_\ast \lesssim T_c$

Vacuum energy fraction from **latent heat**

Bubble nucleation rate (transition duration)

Bubble wall speed

arXiv:1504.07263
Next step: Latent heat $\Delta \epsilon$

First-order transition $\rightarrow$ gravitational wave background will be produced

How do we predict its features?

Vacuum energy fraction

$$\alpha \approx \frac{30}{4N(N^2 - 1)} \frac{\Delta \epsilon}{\pi^2 T_*^4}$$

Latent heat $\Delta \epsilon$

is change in energy density at transition

**VERY PRELIMINARY**
Recapitulation and outlook

Stealth dark matter
Attractive and viable composite dark matter model
Exploring gravitational waves from first-order transition

Gravitational wave observatories will add to constraints from collider searches and direct detection experiments

SU(4) confinement transition appears first order for $M_P/M_V \gtrsim 0.8$, smaller masses underway

Next steps are latent heat, etc., for signal prediction
Thank you!

Lattice Strong Dynamics Collaboration
Especially Graham Kribs, Ethan Neil, Enrico Rinaldi

Funding and computing resources
Backup: Thermal freeze-out for relic density

Requires non-gravitational DM–SM interactions

\[ \text{DM} \leftrightarrow \text{SM} \text{ for } T \gtrsim M_{DM} \]

\[ \text{DM} \rightarrow \text{SM} \text{ for } T \lesssim M_{DM} \rightarrow \text{rapid depletion of } \Omega_{DM} \]

Hubble expansion

\[ \rightarrow \text{dilution} \rightarrow \text{freeze-out} \]

2 → 2 scattering relates coupling and mass, 200\(\alpha\) \approx \frac{M_{DM}}{100 \text{ GeV}}

Strong \(\alpha \sim 16\) \rightarrow ‘natural’ \(M_{DM} \sim 300 \text{ TeV}\) (smaller for 2 → n scattering)
Backup: Two roads to natural asymmetric dark matter

Relate dark matter relic density to baryon asymmetry

\[ \Omega_D \approx 5 \Omega_B \]
\[ \implies M_D n_D \approx 5 M_B n_B \]

\[ n_D \sim n_B \implies M_D \sim 5 M_B \approx 5 \text{ GeV} \]

High-dim. interactions relate baryon\# and DM\# violation

\[ M_D \gg M_B \implies n_B \gg n_D \sim \exp\left(-M_D/T_s\right) \quad T_s \sim 200 \text{ GeV} \]

EW sphaleron processes above \( T_s \) distribute asymmetries

Both require non-gravitational interactions with known particles
Backup: Confirming thermal transition

Fix \( m \cdot N_T \approx 0.8 \quad \rightarrow \quad \text{transition moves to} \quad \beta_F \to \infty \quad \text{as} \quad N_T \to \infty \quad \checkmark