Composite Dark Matter from Strong Dynamics on the Lattice
LOI to CF1, TF05, TF08, CompF2
Lattice Strong Dynamics (LSD) Collaboration

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Dark matter (DM) theories are of paramount importance in helping guide and interpret ongoing and future experiments. Development and exploration of DM theories should be a main priority for the future. An important class of these theories features new strong dynamics producing composite DM. Here we discuss the Stealth Dark Matter (SDM) theory that we are investigating using non-perturbative lattice gauge theory methods and large-scale numerical calculations on supercomputers. This theory features a neutral DM candidate with electrically charged constituents, to explain both the similar abundances of dark and visible matter as well as the non-detection of DM in ongoing experiments. Our investigations have addressed direct-detection searches, collider experiments, and stochastic gravitational waves from a first-order phase transition in the early universe, constraining $M_{\text{DM}} \gtrsim 0.3$ TeV. Here we propose to build upon this research by exploring the new frontiers these discoveries have opened. The results of this research are verifiable and can help interpret and guide future experiments.

Background: Composite dark matter (DM) theories are a well-motivated class of potential new physics beyond the standard model [1, 2]. They are inspired by the confining gauge–fermion theory of quantum chromodynamics (QCD), which produces the massive stable protons and nuclei of the visible universe. More general SU(N) Yang–Mills gauge theories feature ‘dark gluons’ and ‘dark fermions’ confined in composite particles. Our main focus is the theory of Stealth Dark Matter (SDM) [3, 4], in which the ‘dark’ fermions couple to the standard model (SM) in order to generate the correct cosmological DM abundance. The SDM candidate is the lightest SM-singlet ‘dark baryon’, which is automatically stable on cosmological time scales due to the conservation of dark baryon number. In the high-temperature plasma of the early universe, the dark and visible sectors interact directly to produce comparable abundances, $\Omega_{\text{DM}} \approx 5\Omega_{\text{vis}}$. At the same time, the SM-singlet DM candidate has very small direct-detection cross sections, with distinctive dark-sector signatures in collider experiments.

In slightly more detail, the electrically charged dark fermion constituents generate non-perturbative form factors of the SM-singlet dark baryon, enabling direct-detection interactions through the dimension-5 magnetic moment, dimension-6 charge radius and dimension-7 electromagnetic polarizability effective operators. Direct detection can also proceed via Higgs exchange through the dark baryon’s scalar form factor. In this context it matters whether N is odd or even. In the latter case the dark baryon may be a scalar, forbidding the leading magnetic moment contribution to direct-detection cross sections. In addition, a custodial symmetry can forbid the charge radius contribution, leaving the electromagnetic polarizability contribution as an unavoidable lower bound on direct-detection signals [3, 4].

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In Ref. [5] we used numerical lattice calculations to study an SU(3) model, finding that direct-detection experiments constrain $M_{\text{DM}} \gtrsim 20$ TeV in this case. The SU(4) case is more interesting, as the smallest even-N theory with a fundamental distinction between baryons and mesons. In Ref. [6] we studied Higgs exchange for the $N = 4$ SDM theory that features both vector-like and electroweak-breaking mass terms for the fermions, finding that the former must dominate to avoid direct-detection constraints. We also computed the dark baryon's electromagnetic polarizability [3], obtaining the constraint $M_{\text{DM}} \gtrsim 0.2$ TeV from existing direct-detection searches. The steep dependence of the cross section on the dark baryon mass, $\sigma \propto 1/M_{\text{DM}}^6$, causes the predicted signal to fall below the irreducible neutrino background for $M_{\text{DM}} \gtrsim 0.7$ TeV [3]. This motivates the name "Stealth Dark Matter": Like stealth aircraft, the SDM direct-detection cross section is much smaller than its electrically charged constituents might suggest [3, 4, 7–10]. At the same time, collider searches for 'dark mesons' place a similar TeV-scale constraint on the dark baryon's mass [11].

Self-interactions and nuclear physics: An important new frontier for research on composite DM in general, and SDM in particular, is to explore the interactions between two dark baryons. Such self-interactions may resolve some apparent puzzles in astrophysical observations [12]. Lattice gauge theory calculations of the scattering cross section of two dark baryons, and of the binding energies of any bound states they may produce, are challenging but possible. These are the first steps towards exploring the possibility that bosonic SDM could produce larger 'dark nuclei' along the lines of QCD, beginning with investigations of the analogs of the QCD deuteron and di-neutron.

In this context, a key feature of SDM is that it can be analyzed with reliable and systematically improvable uncertainties through numerical lattice calculations, similar to lattice QCD. We can directly apply lattice QCD methods to analyze two-baryon scattering and bound states in SDM, with the only difference being more complicated tensor contractions due to the larger number of 'colors'. Using long-established techniques, scattering phase shifts can be measured on the lattice [13–16] and used to identify bound states (see for example Refs. [17, 18] and references therein). These SDM analyses will complement ongoing efforts around the world to analyze few-nucleon systems in lattice QCD, with the computational advantage that the 'dark pions' of SDM need not be as light as the pions of QCD, making numerical calculations considerably faster. However, care will be needed when exploring the novel physics of bosonic baryons (where results cannot reliably be estimated by rescaling QCD or applying naive dimensional analysis), making it important for theorists to maintain access to state-of-the-art supercomputers and develop efficiently scalable algorithms to exploit these resources.

Gravitational waves: SDM features a finite-temperature phase transition in the early universe, through which the state of the system changes from a high-temperature deconfined plasma of dark gluons and dark fermions to stable SM-singlet dark baryons. This property is a natural feature of the theory rather than being 'inserted' by hand. If this confinement transition was first order, it would have produced a stochastic background of gravitational waves that will be searched for by future space-based facilities [19–21]. We have begun carrying out numerical lattice calculations to investigate the confinement transition physics, beginning in Ref. [22] by determining the region of parameter space for which it is first order. Ongoing analyses will predict features of the resulting stochastic gravitational waves, which will be needed to constrain (or discover) SDM from observations at future facilities.

Variations: Finally, it will also be important to continue exploring the broad possibilities for theories of composite DM, to ensure that no experimental opportunities are overlooked or misinterpreted. Even changing the way the dark fermions of SDM interact with the SM could result in substantially different phenomenology based on the same new strong dynamics, allowing existing lattice calculations to be reused and motivating new generations of investigations. We have an active program of exploration underway, and hope to see independent contributions by others in the coming years.

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