FERMILAB-SLIDES-24-0217-T

Stealth Dark Matter

George T. Fleming

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The Big Picture

Cosmology tells us after early radiation domination, the expansion of the Universe was matter dominated until recently.

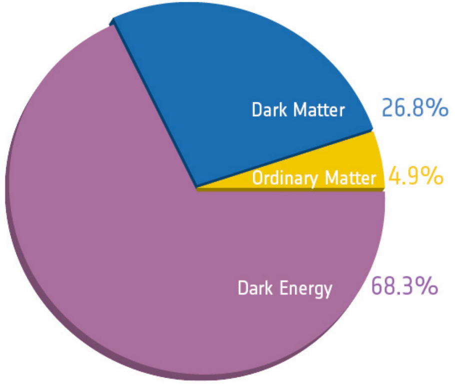
The total amount of matter density was about 6X visible matter. Dark matter exists and it is matter (i.e. massive), not radiation.

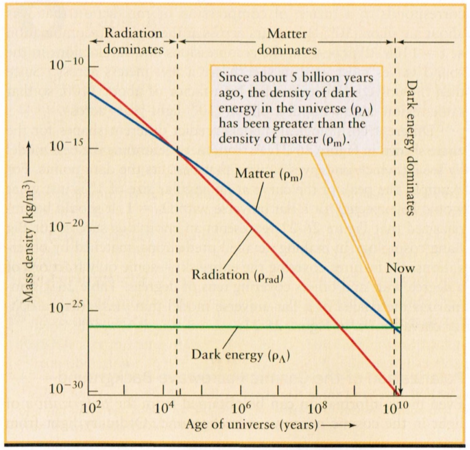
Dark matter also affects structure formation from galaxy scales (rotation curves) up to the largest scales.

In the Standard Model, two mechanisms exist to generate mass for matter: confinement and the Higgs mechanism.

Confinement is responsible for 98% of energy density of ordinary matter ρ_M and Higgs is the rest.

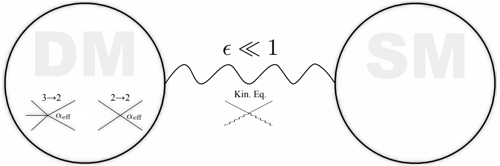
For dark matter, we need a mechanism to generate 5X energy density as normal matter. Why not start with most efficient mechanism? Dark confinement…





History of Composite Dark Matter

- In the past O(100 GeV) SUSY WIMPs were popular, with thermal freezeout based on $2 \rightarrow 2$ scattering $\langle \sigma v \rangle \sim {}^{\alpha^2}/_{M^2} \approx 1\, pb$.
- O(TeV) technibaryon dark matter was a viable alternative [Nussinov 1985, Chivukula et al 1990]. Interesting features:
  - SM charged dark quarks confined into neutral composites.
  - Novel Boltzmann-suppressed freezeout mechanism allowed for lower O(TeV) masses.
- Many other toy models of composite dark matter have been proposed. One example: Strongly-Interacting Massive Particle (SIMP).
  - “Cannibalism” Strong $2 \leftrightarrow N$ scattering dramatically alters freezeout.



Y. Hochberg et al, arXiv:1402.5143

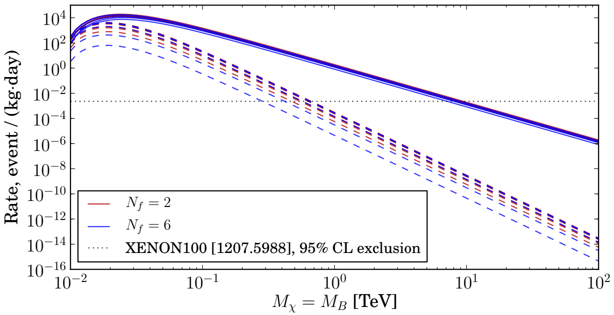
- Self-Interacting Dark Matter (SIDM) [Spergel, Steinhardt astro-ph/9909386]: Dark matter self-interaction is potentially observable in galaxy formation if ${}^{\sigma}/_{M} \lesssim O(100\ {}^{mb}/_{GeV})$.

Coupling Dark Matter to the Standard Model

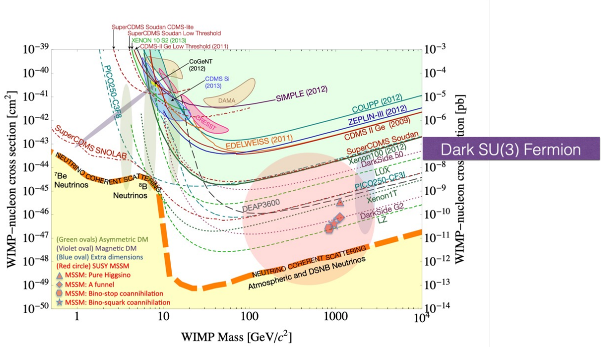
- Desirable since having both sectors in thermodynamic equilibrium in the early universe helps explain similar energy densities today: $\rho_{DM} \approx 5\, \rho_B$.
- Direct detection experiments (DM + N → DM + N) rule out tree-level Z couplings and severely limit Higgs couplings.
- Direct production at LEP and LHC place additional constraints on masses of new charged particles, generically M > 90 GeV, with stronger constraints possible depending on the model.
- Bullet cluster collision places lower bound on self-interacting dark matter. For self-interaction strengths similar to QCD nucleon, dark matter mass must be larger than 5 GeV.
- Interesting coincidence: If the dark matter mass is 5x the QCD baryon mass and the energy density is 5x the QCD baryon density, then the number densities are comparable.
  - Possibility that composite dark matter may play a role in matter-antimatter asymmetry.
- Most toy models have a hard time satisfying all these constraints, so they usually introduce an additional heavy mediator. Is it still possible to have DM charged under SM?

Illustrative Example: Dark QCD

- Suppose we had another SU(3) gauge sector with two Dirac flavors and $Q_u = {}^{2}/_{3}, Q_d = -{}^{1}/_{3}$ Is this viable? If $m_d \lesssim m_u$ the dark neutron is lightest and stable.
- But, charged states can be produced so from LEP $M_\pi > 90\ GeV$ and more stringent constraints from LHC if $\rho \to \pi\pi$ forbidden due to $\rho \to \gamma\gamma$.
- More serious: dark neutron maybe neutral but it has a magnetic moment (dim 5), charge radius (dim 6), EM polarizability (dim 7), …
- Current direct detection limits $M_B \gtrsim 1000\ TeV$. Dark neutron is hidden in neutrino fog if $M_B \gtrsim 10{,}000\ TeV$.
- Relic abundance? It's complicated: $B\bar{B} \to \pi\pi, \pi\pi\pi, \ldots$ plus $\pi\pi \to \pi\pi, \pi\pi\pi, \pi\pi\pi\pi, \ldots$ In heavy quark limit, probably too heavy to be all the dark matter, which is not the same as ruled out.



LSD Collaboration
Phys. Rev. D 88, 014502 (2013)



Lattice Strong Dynamics Collaboration

X.-Y. Jin
J. Osborn

J. Kiskis
(deceased)

G. Fleming

C. Peterson

QUANTINUUM

E. Rinaldi

A. Gasbarro*

A. Hasenfratz
E. Neil

S. Park
P. Vranas

NVIDIA

E. Weinberg

O. Witzel

V. Ayyar*
R. Brower
N. Matsumoto
E. Owen*
C. Rebbi

J. Ingoldby

C. Culver*
D. Schaich

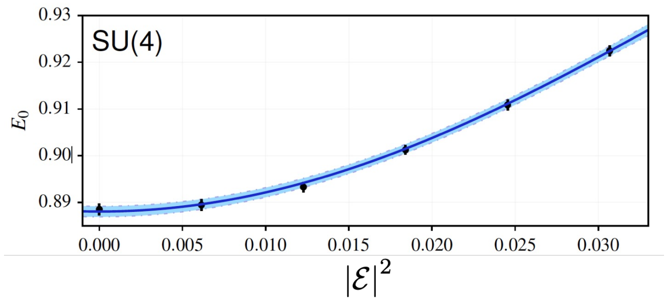
G. Kribs

T. Appelquist
K. Cushman*

Stealth Dark Matter

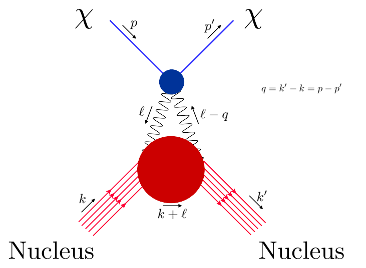
- Magnetic moment limits how light dark baryons can be. Can we eliminate it?
- G-parity with stabilize dark charged pions. Some mixing with Higgs required for decays.
- Stealth Dark Matter can solve this problem: SU(2N) gauge theory with $N_f = 4$ Dirac flavors. Global symmetry: can embed SU(2)xSU(2)xSU(2) in SU(4). Magnetic moment is zero because baryon is scalar boson. One SU(2) exact enforces zero charge radius.
- Vector-like quark masses to avoid affecting Higgs vacuum alignment. Tuneable small Higgs Yukawa couplings will lead to very small S and T contributions. Aside: W boson mass?
- Lattice Strong Dynamics Collaboration
  - Phys. Rev. D 89 (2014) 094508
  - Phys. Rev. Lett. 115 (2015) 171803
  - Phys. Rev. D 92 (2015) 075030

SU(4) Scalar Baryon Polarizability



Mass shift from external EM

$$E_0(\mathcal{E}) = M_B + 2\, C_F \mathcal{E}^2$$

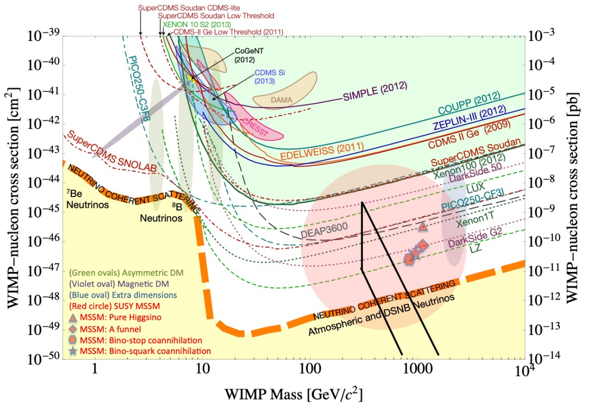


$$\sigma \propto \left| C_F\, f_F^A \right|^2$$

Nuclear Matrix Element

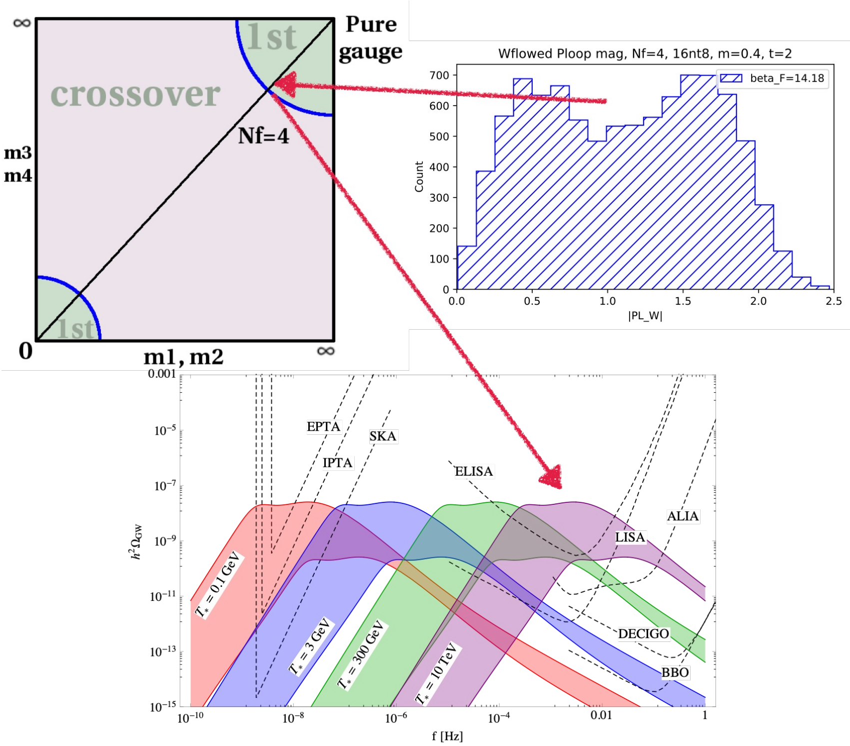
$$f_F^A = \langle A | F^{\mu\nu} F_{\mu\nu} | A \rangle$$

- Coherent DM-Nucleus Scattering
- Nuclear Matrix Element with large uncertainties: O(3)
- Direct detection possible only if $M_D < 1\, TeV$.
- Lower mass limit due to LEP bound.
- Ultimately, direct production of charged TeV-scale dark hadronic resonances possible at muon collider.



SU(4) Stealth Dark Matter and Gravity Waves

- Great talk by **Zhi-Wei Wang** in Session G on Mon, 14:00 on how to go from lattice results to gravitational wave phenomenology.
- LSD mapping phase diagram of SU(4) $N_f = 4$ theory for 1st order transitions, focusing on easier heavy quark regime.
- LSD arXiv:2006.16429, results show first order region exists when ${}^{M_\pi}/_{M_\rho} > 0.9$.
- In this heavy quark regime, LHC bounds $M_\rho > 2\,TeV$ from lack of diphoton resonance, so $T_c \gtrsim 0.4\,TeV$ which is in interesting range for LISA.
- Computation of latent heat in progress.



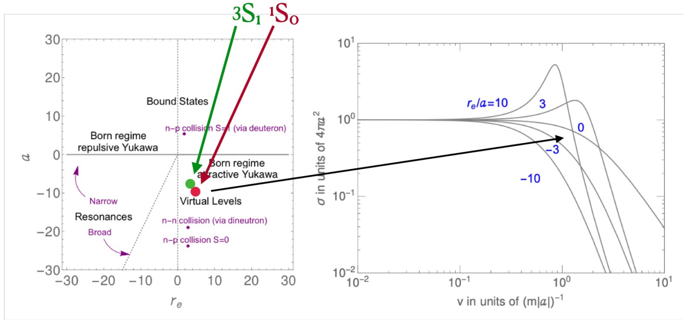
P. Schwaller, PRL **115** 181101

Fermilab

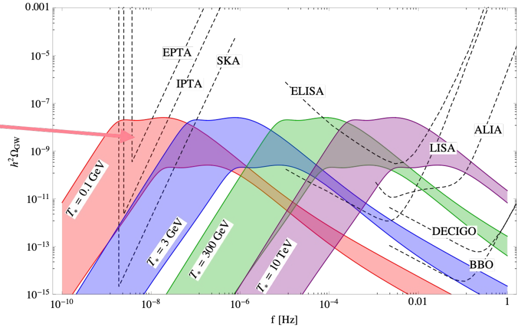
Dark Matter Self-Interactions

- CDM cosmology assumes DM not self-interacting. Bullet cluster collision sets upper limit $\sigma/m \lesssim 10$ cm^2/g, v ~ 4,800 km/s.
- Numerical simulations indicate SIDM $\sigma/m \sim 1$ cm^2/g at much lower virial velocities could help explain galaxy formation.
- In particle physics units, this is compatible with dark baryon O(1-5 GeV).
- NPLQCD results on SU(3) baryon-baryon scattering for 3 degenerate flavors.
- LSD working on SU(4) baryon-baryon scattering. Do dark bosons form dark nuclei?

NPLQCD SU(3) Nf=3 PRC 88 024003



Chu, Garcia-Cely, Murayama, JCAP 06 (2020) 043



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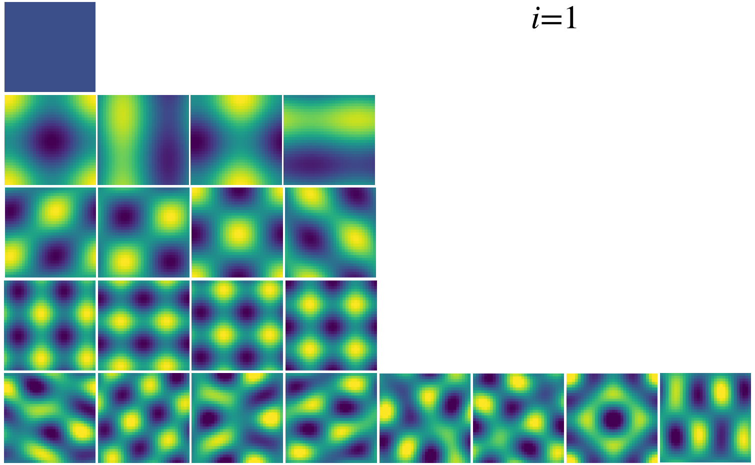
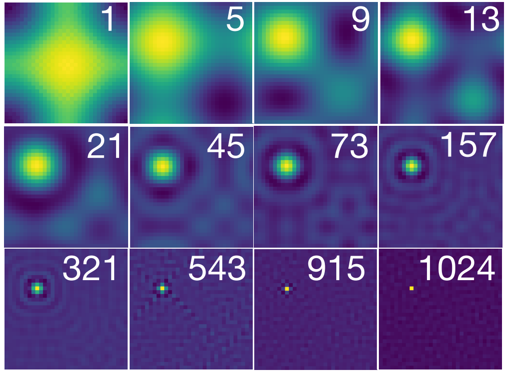
Preparing to compute SU(4) baryon-baryon scattering

LapH

$$S_{xy}(t)\, q(y,t) = \sum_{i=1}^{N_{\text{vec}}} V^{\dagger}_{x|i}(t)\, V_{i|y}(t)\;\; q(y,t)$$

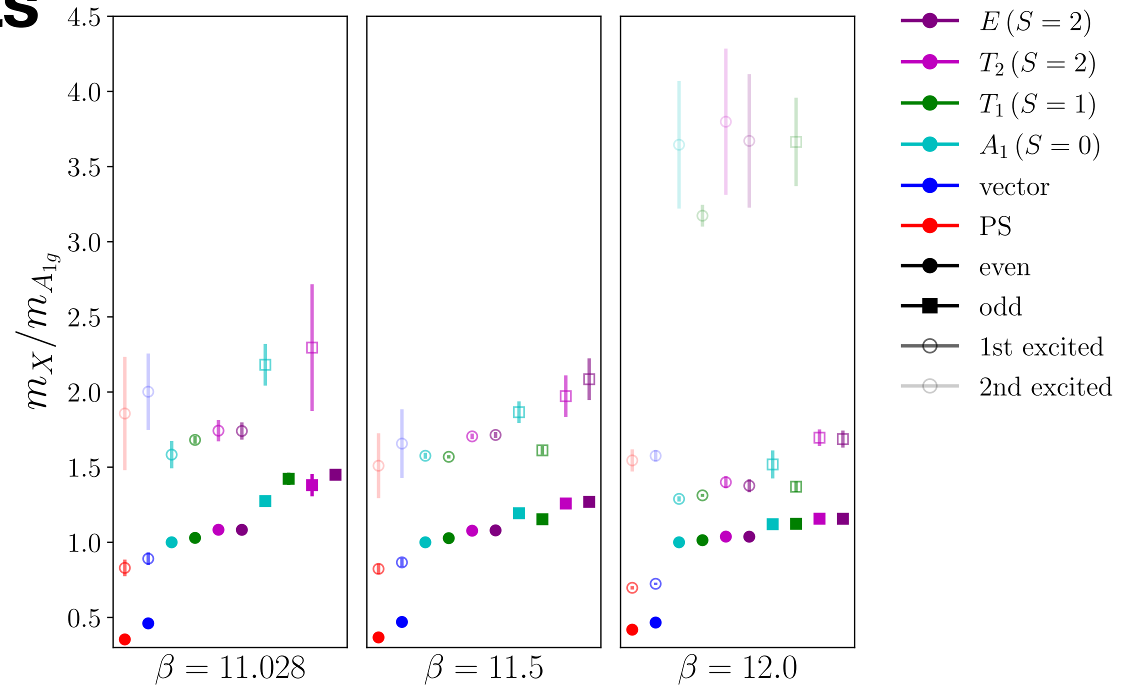




Yale

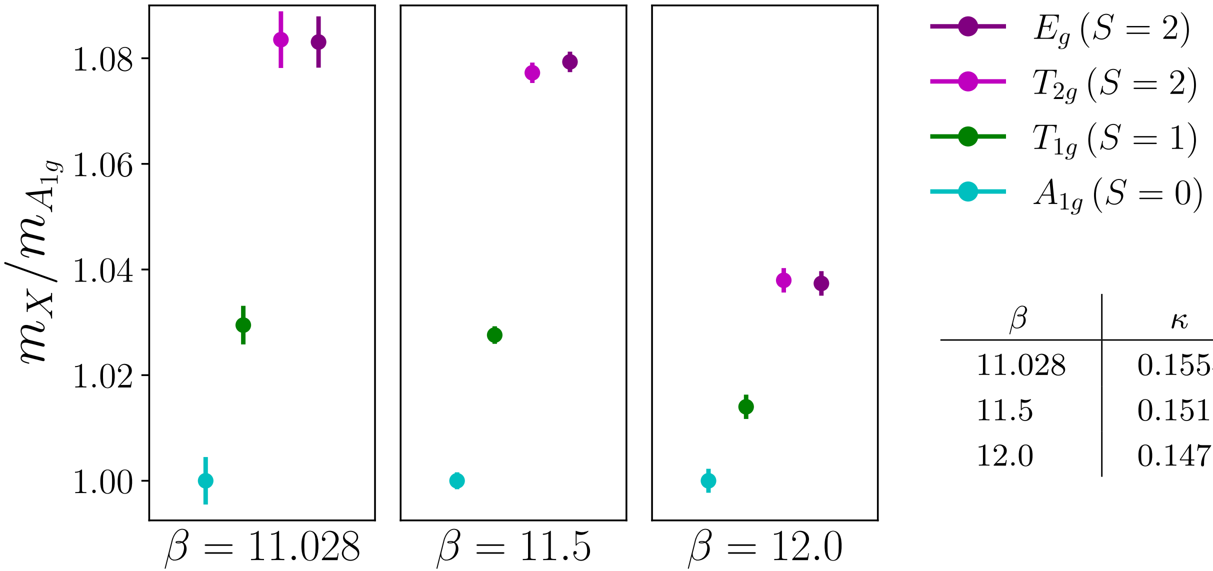
Kimmy Cushman

Final results



Yale **Kimmy Cushman**

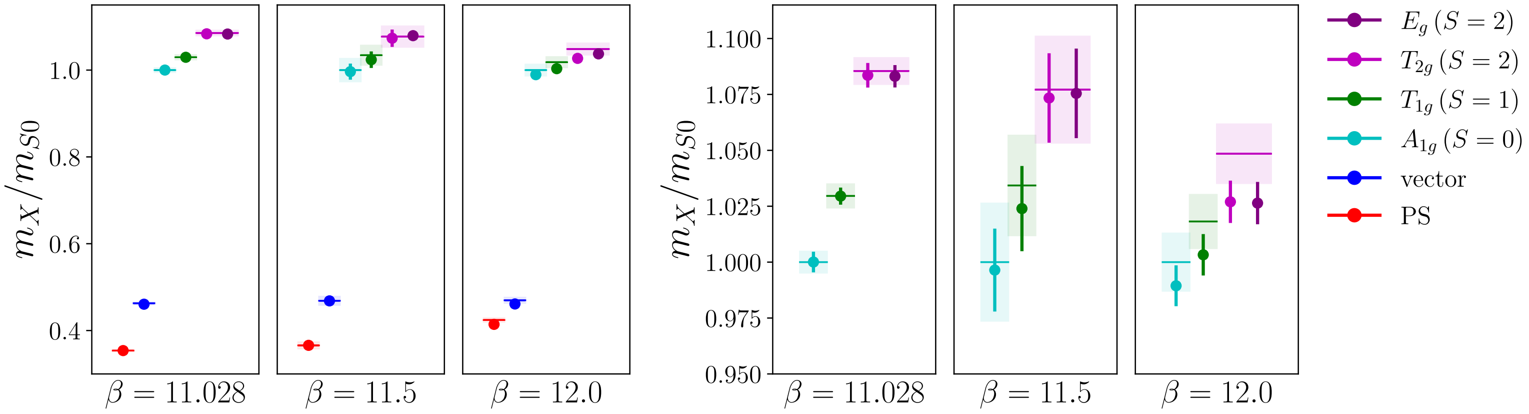
Final results



β	κ	m_{PS}/m_V
11.028	0.1554	0.764(3)
11.5	0.1515	0.781(10)
12.0	0.1475	0.891(9)

Yale Kimmy Cushman

Final results



Stealth dark matter spectrum using LapH and Irreps #1

Phys. Rev. D 89, 094508 (2014)

R.C. Brower (Boston U.), C. Culver (Liverpool U., Dept. Math.), K.K. Cushman (Yale U.), G.T. Fleming (Yale U. and Fermilab),
A. Hasenfratz (Colorado U.) et al. (Dec 12, 2023)

e-Print: 2312.07836 [hep-lat]

Yale

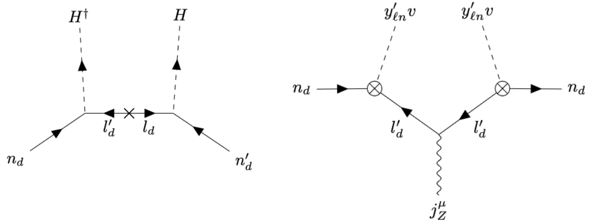
Kimmy Cushman

Hyper Stealth Dark Matter: SU(4) $N_f = 1$

- Self-interactions in Stealth Dark Matter are interesting at any mass since if the dark sector can form stable charged nuclei (dark deuteron) then the model is severely restricted.
- But Stealth Dark matter likes the confinement scale to be around a TeV or higher. To be relevant for galaxy scale physics, we need dark baryons around 5 GeV.
- Hyper Stealth Dark Matter [Vranas et al, to appear soon] is a special case where one of the flavors is neutrino-like and can only interact through mixing with heavier flavors.
- At low energies, it is effectively a dark SU(4) $N_f = 1$ theory with no spontaneous chiral symmetry breaking and no Nambu-Goldstone bosons.

	Field	$SU(N_D)$	$(SU(2)_L, Y)$	T_3	$U(1)_{\rm em}$
dark matter sector	n_d	$\mathbf{N}$	$(\mathbf{1}, 0)$	0	0
	n'_d	$\overline{\mathbf{N}}$	$(\mathbf{1}, 0)$	0	0
dark equilibration sector	l_d	$\mathbf{N}$	$(\mathbf{2}, -\frac{1}{2})$	$\begin{pmatrix} +\frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
	l'_d	$\overline{\mathbf{N}}$	$(\mathbf{2}, +\frac{1}{2})$	$\begin{pmatrix} +\frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\begin{pmatrix} +1 \\ 0 \end{pmatrix}$
	e_d	$\mathbf{N}$	$(\mathbf{1}, -1)$	0	-1
	e'_d	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1)$	0	+1

TABLE I. The dark matter and dark equilibration fermion sectors of HSDM model. Note that the heavy fields l_d, l'_d have EM charge-neutral components that can mix with the n_d after electroweak symmetry breaking. The electric charge is equal to $Q = T_3 + Y$.



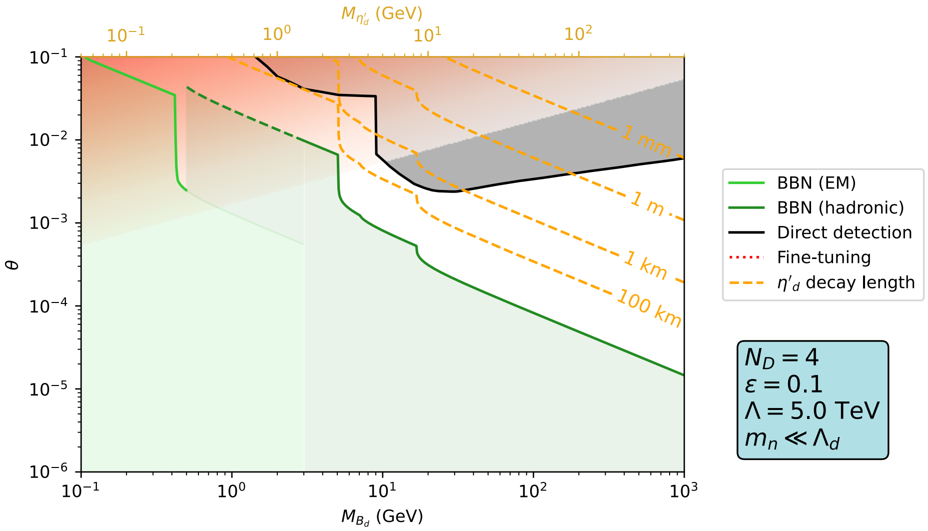
Spectrum of QCD with one flavor: A window for supersymmetric dynamics

Michele Della Morte (Southern Denmark U., CP3-Origins), Benjamin Jäger (Southern Denmark U., CP3-Origins and U. Southern Denmark, Odense, DIAS), Francesco Sannino (Southern Denmark U., CP3-Origins and U. Southern Denmark, Odense, DIAS and Naples U.), Justus Tobias Tsang (CERN and Southern Denmark U., CP3-Origins), Felix P.G. Ziegler (Edinburgh U.) (Feb 21, 2023)

Published in: *Phys.Rev.D* 107 (2023) 11, 114506 • e-Print: 2302.10514 [hep-lat]

Hyper Stealth Dark Matter, Allowed Regions

- The theory is constrained in three ways. If the effective coupling to the electroweak sector is too strong (larger values of θ), then it would have been observed in direct detection.
- If the effective coupling is too weak, then the η' meson is too long-lived and will inject energy into the Universe during BBN which is not allowed.
- A consequence of lighter M_B is lighter and potentially longer-lived η' unless θ is increased. This leads to vector-like mass terms becoming comparable to Yukawa interactions and at some point the theory looks fined-tuned.



Preliminary !!!

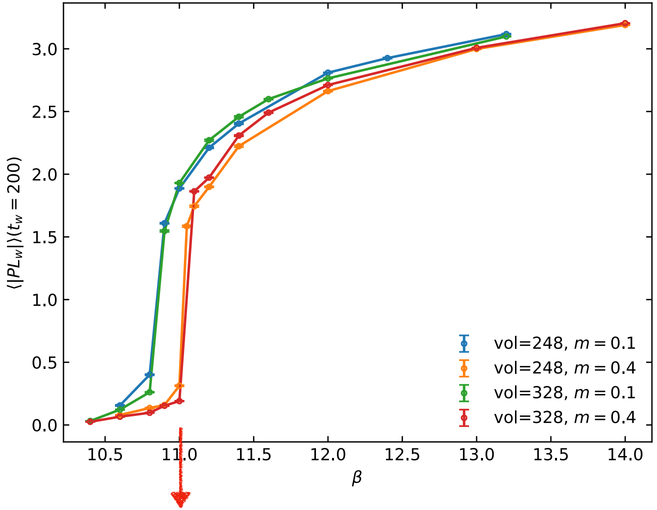
Hyper Stealth Dark Matter, Thermodynamics

- Essentially nothing is known so far about SU(N) $N_f = 1$ thermodynamics: no NG bosons, no spontaneous chiral symmetry breaking. Could it behave like a quenched theory (1st order) over the entire range of $M_{\eta'}/M\_B$? Reminder, η' is not especially light even if quark masses are set to zero.
- Two LSD LATTICE presentations: 2023 Venkitesh Ayyar, 2024 Sungwoo Park. An extension of our ongoing program of SU(4) thermodynamics for $N_f = 0, 4$.
- So far, exploring relatively heavy quark mass regime $m_q/T_c \geq 0.8$. Clear evidence for the phase transition and ongoing efforts to characterize the order of the transition.

Polyakov loop

Deconfinement transition order parameter

- β_{crit} from Wilson-flowed PL
  - Volume dependence negligible
  - $\beta_{\mathrm{crit}} \sim 10.8$ for $am = 0.1$
  - $\beta_{\mathrm{crit}} \sim 11.0$ for $am = 0.4$ and $am = \infty$ (pure gauge)



β_{crit} in $am = \infty$ (pure gauge theory)

Conclusions

- Dark quark confinement is an efficient mechanism for generating dark matter energy.
- Equilibration with the Standard Model is possible without adding additional mediator sectors: Stealth Dark Matter.
- Generically, dark matter masses O(TeV) or larger due to possibility of producing charged resonances at LHC.
- Calculating relic abundance is complicated. Any good ideas?
- A special case called Hyper Stealth Dark Matter allows for one light dark scalar baryon around 5 GeV. Self-interactions may play a role in galaxy formation.
- Dark matter nuclear physics? What changes in the nuclear spectrum when the baryons are bosons and not fermions?
- Ongoing work to identify parameter space of 1st order phase transitions and calculate quantities relevant to gravity wave phenomenology.

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