Dark matter in the standard model?

Helena Kolešová

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Joint work with Torsten Bringmann (University of Oslo)

COST Advanced School on Physics of Dark Matter and Hidden Sectors: from Theory to Experiment

Dark Matter Particle in QCD

Glennys R. Farrar, Zihui Wang (王子汇), and Xingchen Xu (许星辰)
Center for Cosmology and Particle Physics, Department of Physics, New York University, NY, NY 10003, USA[*]

(Dated: July 22, 2020)

We report on the possibility that the Dark Matter particle is a stable, neutral, as-yet-undiscovered hadron in the standard model. We show that the existence of a compact color-flavor-spin singlet $uuddss$ (Sexaquark, S) with mass of order $2\,m_p$ is compatible with current knowledge and that, if it exists, the S is a very attractive DM candidate. The S interacts with baryons primarily via a Yukawa interaction of coupling strength α_{SN}, mediated by exchange of the flavor-singlet superposition of the ω and ϕ vector mesons, denoted V, having mass ≈ 1 GeV. We emphasize the need to distinguish between S-nucleon scattering amplitudes which are of a hadronic scale, and S breakup amplitudes which are dynamically suppressed and many orders of magnitude smaller, akin to the weak interaction level. We use SNOlab and other data to obtain the most stringent constraints on the effective vertex for breakup, $\tilde{g}$, from the stability of DM and nuclei. The relic abundance of S Dark Matter (SDM) is established when the Universe transitions from the quark-gluon plasma to the hadronic phase at ≈ 150 MeV and is in remarkable agreement with the observed $\Omega_{DM}/\Omega_b = 5.3 \pm 0.1$; this is a no-free-parameters result because the relevant parameters are known from QCD. Survival of this relic abundance to low temperature requires $\tilde{g} \lesssim 2 \times 10^{-6}$, comfortably compatible with theory expectations and observational bounds. To analyze bounds on SDM we must solve the Schroedinger equation to determine the cross section, σ_A, for S scattering on nucleus A. Depending on α_{SN}, the true cross section can be orders of magnitude larger or smaller than given by Born approximation; this requires a reanalysis of observational limits. We use direct detection experiments and cosmological constraints to determine the allowed region of α_{SN} for the mass range relevant to SDM. If the S-nucleon interaction is attractive and strong enough, DM-nucleus bound states will form. For a range of allowed values of α_{SN}, we predict exotic nuclear isotopes at a detectable level with mass offset ≈ 2 amu. Dedicated study of this mass-offset range, for a wide range of elements, is warranted. We argue that the neutron-star equation of state and SN1987a cooling are not constraining at this time, but could become so in the future when better understood. Finally, we discuss strategies for detecting the sexaquark in accelerator experiments. This is surprisingly difficult and experiments to date would not have discovered it. The most promising approaches we identify are to search for a long-interaction-length neutral particle component in the central region of relativistic heavy ion collisions or using a beam-dump setup, and to search for evidence of missing particle production characterized by unbalanced baryon number and strangeness using Belle-II or possibly GLUEX at J-Lab.

arXiv:2007.10378v1 [hep-ph] 20 Jul 2020

I. INTRODUCTION

A successful model for dark matter (DM) must predict the observed relic DM density and ideally also provide a natural explanation for the observed DM to baryon ratio, Ω_{DM}/Ω_b= 5.3±0.1 [1]. It must be compatible with cosmological and astrophysical constraints on structure formation and DM interactions and not alter or interfere with the successful predictions of primordial nucleosynthesis. The DM interactions with normal matter must also satisfy direct detection bounds and constraints from laboratory and geophysical experiments, and must be compatible with observed properties of galaxies, neutron stars, white dwarfs, supernovae, and other astrophysical objects.

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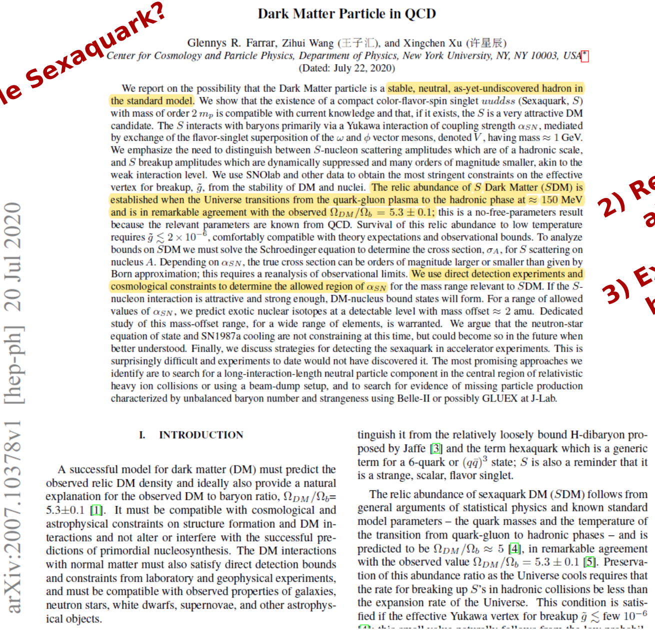
The relic abundance of sexaquark DM (SDM) follows from general arguments of statistical physics and known standard model parameters – the quark masses and the temperature of the transition from quark-gluon to hadronic phases – and is predicted to be $\Omega_{DM}/\Omega_b \approx 5$ [4], in remarkable agreement with the observed value $\Omega_{DM}/\Omega_b = 5.3 \pm 0.1$ [5]. Preservation of this abundance ratio as the Universe cools requires that the rate for breaking up S's in hadronic collisions be less than the expansion rate of the Universe. This condition is satisfied if the effective Yukawa vertex for breakup $\tilde{g} \lesssim$ few 10^{-6}



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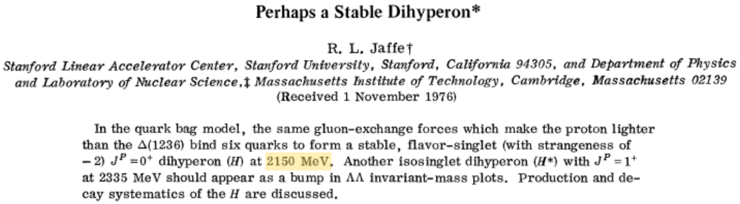
1) Stable Sexaquark?

2) Relic abundance?

3) Experimental bounds?

Not a completely new idea...



Perhaps a Stable Dihyperon*

R. L. Jaffe†

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Department of Physics and Laboratory of Nuclear Science,‡ Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 1 November 1976)

In the quark bag model, the same gluon-exchange forces which make the proton lighter than the Δ(1236) bind six quarks to form a stable, flavor-singlet (with strangeness of -2) $J^P = 0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H^*) with $J^P = 1^+$ at 2335 MeV should appear as a bump in ΛΛ invariant-mass plots. Production and decay systematics of the H are discussed.

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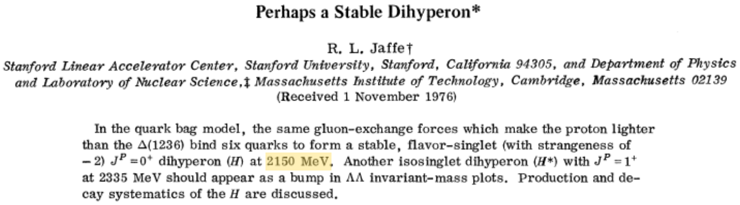

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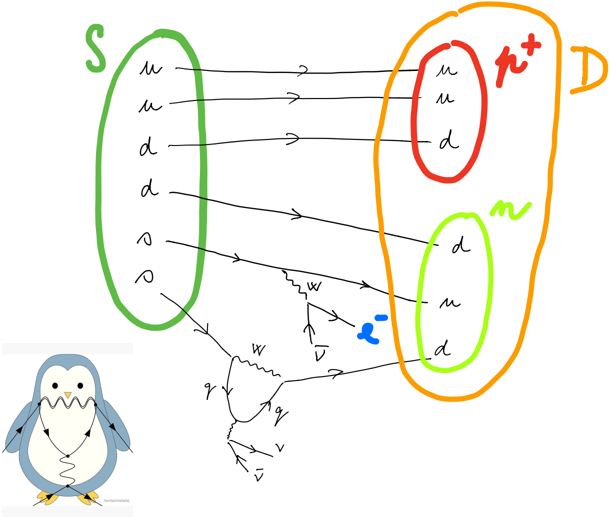
- Experimental searches for a *H*-dibaryon without any success
- Lattice studies inconclusive

SEXAQUARK
(*S*=-2, *I*=0)

S=*uuddss*

- singlet with respect to color, flavor, spin
- $m_S < m_D + m_e = 1876.1\,\mathrm{MeV} \Rightarrow S$ absolutely stable
- $m_S < m_p + m_e + m_\Lambda = 2054.5\,\mathrm{MeV} \Rightarrow S$ decays through a doubly-weak interaction, lifetime possibly longer than the age of the Universe
  ($p = uud$, $n = udd$, $\Lambda = uds$, $2m_p = 1876.5\,\mathrm{MeV}$, $2m_\Lambda = 2231.4\,\mathrm{MeV}$)



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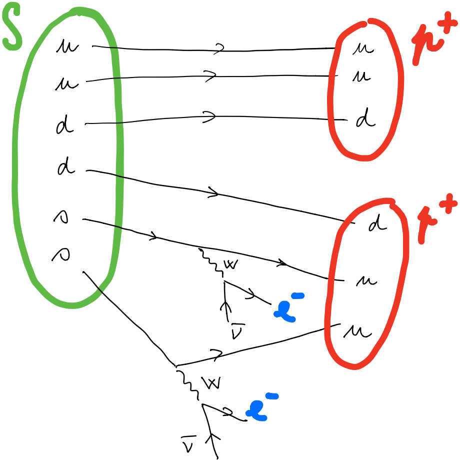

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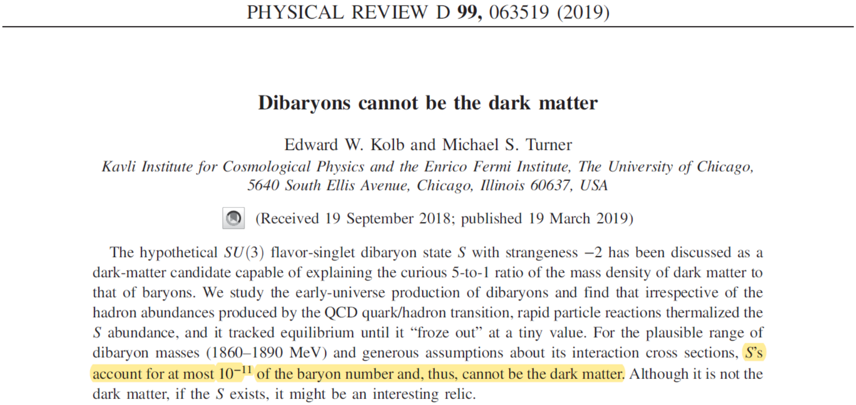
Sexaquark as a dark matter candidate?



PHYSICAL REVIEW D **99,** 063519 (2019)

Dibaryons cannot be the dark matter

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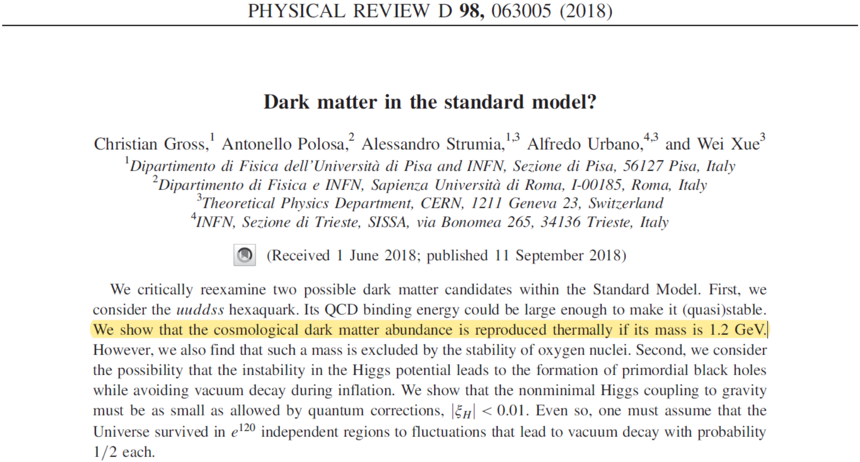
(Received 19 September 2018; published 19 March 2019)

The hypothetical $SU(3)$ flavor-singlet dibaryon state S with strangeness −2 has been discussed as a dark-matter candidate capable of explaining the curious 5-to-1 ratio of the mass density of dark matter to that of baryons. We study the early-universe production of dibaryons and find that irrespective of the hadron abundances produced by the QCD quark/hadron transition, rapid particle reactions thermalized the S abundance, and it tracked equilibrium until it "froze out" at a tiny value. For the plausible range of dibaryon masses (1860–1890 MeV) and generous assumptions about its interaction cross sections, S's account for at most 10^{-11} of the baryon number and, thus, cannot be the dark matter. Although it is not the dark matter, if the S exists, it might be an interesting relic.

Sexaquark as a dark matter candidate?



PHYSICAL REVIEW D **98,** 063005 (2018)

Dark matter in the standard model?

Christian Gross,[1] Antonello Polosa,[2] Alessandro Strumia,[1,3] Alfredo Urbano,[4,3] and Wei Xue[3]
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[2]*Dipartimento di Fisica e INFN, Sapienza Università di Roma, I-00185, Roma, Italy*
[3]*Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*
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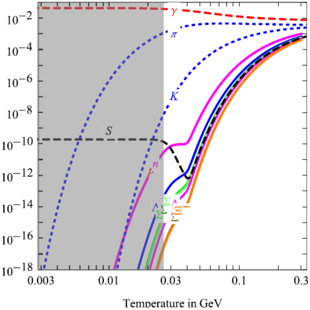
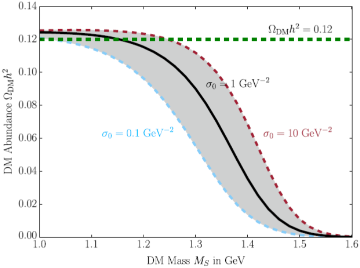
(Received 1 June 2018; published 11 September 2018)

We critically reexamine two possible dark matter candidates within the Standard Model. First, we consider the *uuddss* hexaquark. Its QCD binding energy could be large enough to make it (quasi)stable. We show that the cosmological dark matter abundance is reproduced thermally if its mass is 1.2 GeV. However, we also find that such a mass is excluded by the stability of oxygen nuclei. Second, we consider the possibility that the instability in the Higgs potential leads to the formation of primordial black holes while avoiding vacuum decay during inflation. We show that the nonminimal Higgs coupling to gravity must be as small as allowed by quantum corrections, $|\xi_H| < 0.01$. Even so, one must assume that the Universe survived in e^{120} independent regions to fluctuations that lead to vacuum decay with probability 1/2 each.

Sexaquark relic abundance à la Gross et al.





- Requiring $2\mu_b = \mu_S$ and taking into account the measured baryon-antibaryon asymmetry, equilibrium abundances can be calculated
- Key assumption: sexaquarks in thermal equilibrium with baryons (b, b') after the QCD phase transition via

$$bb' \leftrightarrow SX$$

(X: mesons or a photon)

Sexaquark relic abundance à la Farrar et al.

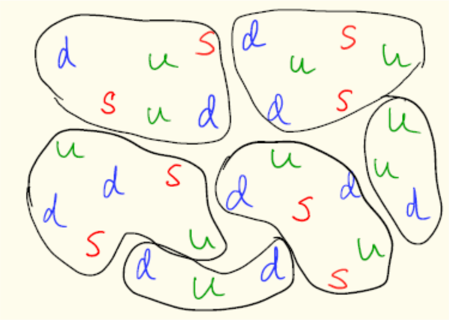
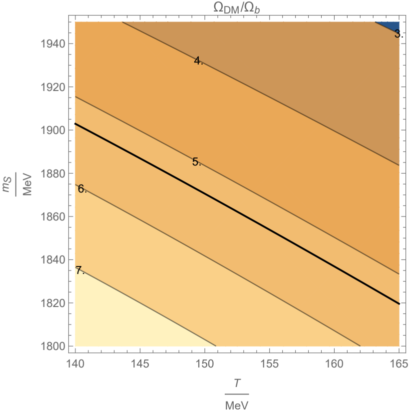


FIG. 1: Schematic illustration of how the deficit of s quarks relative to u, d quarks, $\approx 15\%$ at the transition temperature, leads to residual baryons.

- S breakup rate so small that the ratio of DM and baryon abundances fixed already at hadronization! ($\sigma_0 \sim 10^{-17}\,\mathrm{GeV}^{-2}$)
- s quark abundance straight before the hadronization + probability that S is formed depending on $m_S \Rightarrow \Omega_{DM}/\Omega_b$

Sexaquark relic abundance à la Farrar et al.



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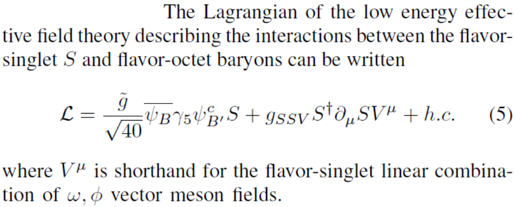
Sexaquark interactions à la Farrar et al.



The Lagrangian of the low energy effective field theory describing the interactions between the flavor-singlet S and flavor-octet baryons can be written

$$\mathcal{L} = \frac{\tilde{g}}{\sqrt{40}} \overline{\psi_B} \gamma_5 \psi^c_{B'} S + g_{SSV} S^\dagger \partial_\mu S V^\mu + h.c. \tag{5}$$

where V^μ is shorthand for the flavor-singlet linear combination of ω, ϕ vector meson fields.

- S as a flavor singlet does not couple to pions ⇒ much more compact ⇒ much smaller “wavefunction overlap” with hadrons ⇒ small $\tilde{g}$ expected
- For $\tilde{g} \lesssim 10^{-6}$ the sexaquarks freeze out straight after the hadronization

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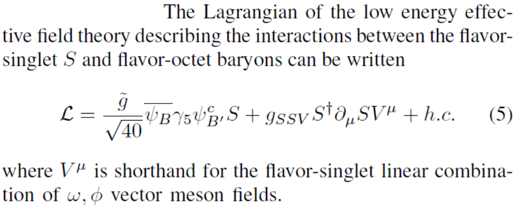

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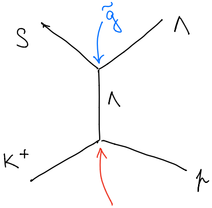
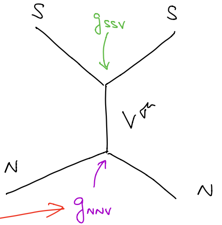
- For $\tilde{g} \lesssim 10^{-6}$ the sexaquarks freeze out straight after the hadronization
- Yet, S can interact with nucleons rather strongly via vector meson exchange!

$$\boxed{\mathcal{L} = \frac{\tilde{g}}{\sqrt{40}} \overline{\Psi}_B \gamma_5 \Psi^c_{B'} S + g_{SSV} S^\dagger \partial_\mu S V^\mu + h.c.}$$

S breakup × S-N interaction



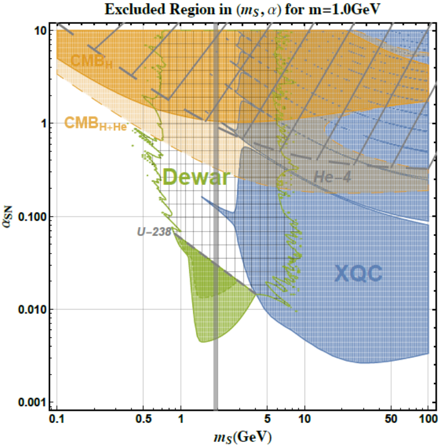


one-boson-exchange model

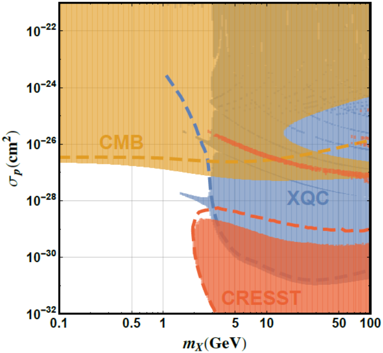
$$\boxed{\alpha_{SN} \equiv \frac{g_{NNV}\, g_{SSV}}{4\pi}}$$

Bounds on S-N interactions à la Farrar et al.

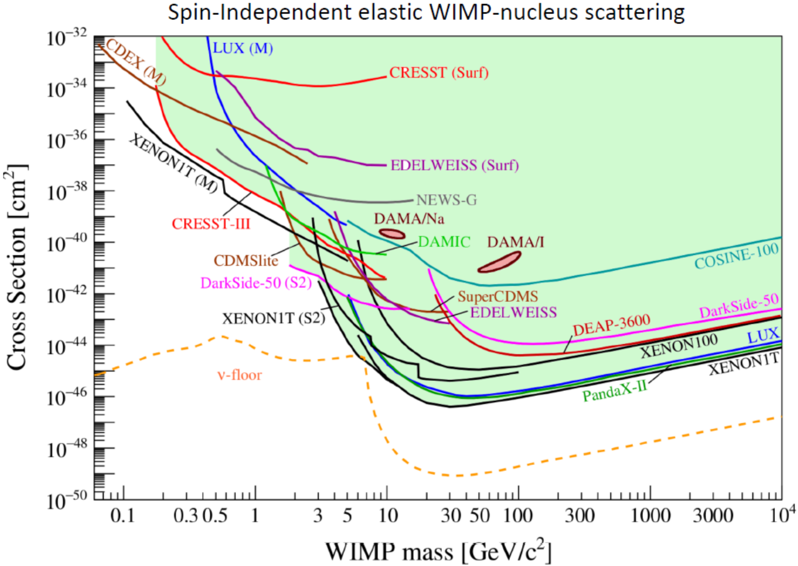
[Farrar, Wang, Xu - arXiv:2007.10378]



[Xu,Farrar - arXiv:2101.00142]



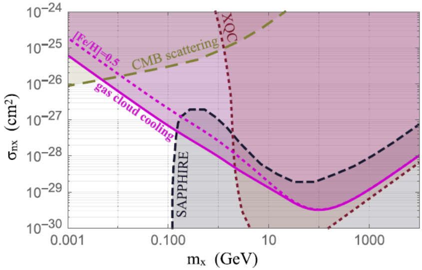
[talk of Sergey Burdin]



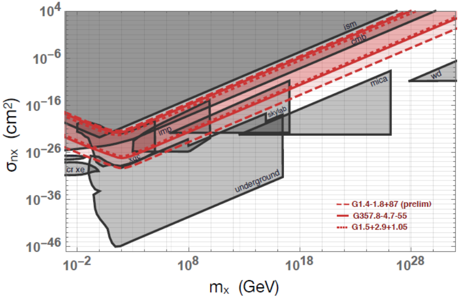
APPEC Committee Report (arXiv:2104.07634)

Closing the window for strongly interacting dark matter?

[Bhoonah et al., PRL 121 (2018)]



[Bhoonah et al., Phys.Rev.D 100 (2019)]



Conclusions

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Thank you for your attention!

Any comments welcome!