Stable Sexaquark: Dark Matter predictions, constraints and lab detection



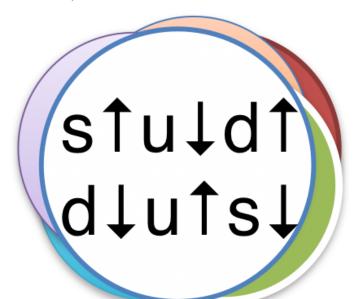
Glennys R. Farrar New York University

Stable Sexaquark, GF arXiv:1708.08951 uds-DM, GF arXiv:1805.03723 Earth's DM atmosphere, Neufeld, GF, McKee Ap.J. 2018 Low-Velocity DM limits, Wadekar & GF arXiv:1903.12190 Non-Perturbative Direct Detection Limits, Xu & GF in prep DM solution to 7Li problem, GF, Galvez & Xu in prep

Stable Sexaquark Hypothesis

https://en.wikipedia.org/wiki/Numeral_prefix

^{a b} Sometimes Greek *hexa*- is used in Latin compounds, such as *hexadecimal*, due to taboo avoidance with the English word *sex*.



Q=0, B=2 Spin-0 scalar m ~ 1.7-2 GeV

Sexaquark is unique among multi-quark states:

Fermi statistics is compatible with a <u>totally symmetric</u> spatial wave function AND

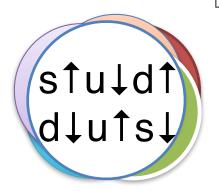
Color: singlet

- Flavor: singlet

Spin: singlet (scalar)

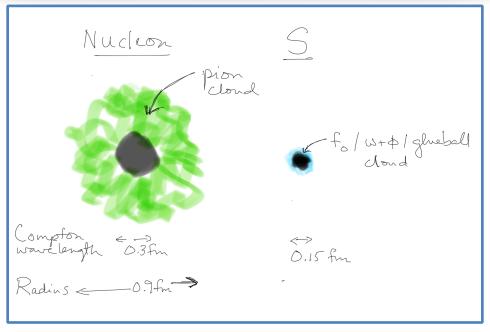


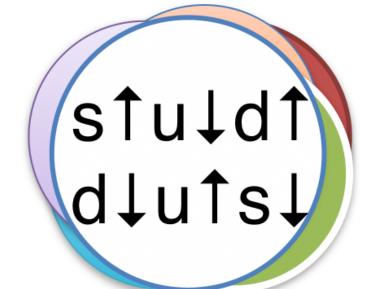




S

VERY DEEPLY BOUND, VERY COMPACT





Q=0, B=2 Spin-0, scalar m ~ 1.7-2 GeV

Crucial fact: S does not couple to pions

- → radius of S much smaller than usual hadrons
- → hard to produce S with hadrons

Stable Sexaquark Hypothesis

- QCD predicts significant binding Beane+13 Lattice QCD $(m_q = 850 \text{ MeV})$ $(m_q = 850 \text{ MeV})$

- Experimental searches exclude m_S > 2GeV
- > S is STABLE!
 - decay is doubly weak for m_S 1382-2054 MeV
 - S & nuclei absolutely stable if m_S 1875-1876 MeV (D→Se+ν; S→ppe-e-νν)
 - stability of nuclei and $\tau_{S} > \tau_{Universe}$ m_S favors: 1750 2000 MeV

S would not have been discovered at accelerators because it is <u>elusive</u>

GRF, Stable Sexaquark, arXiv:1708.08951v2

- Many negative searches, but all are inapplicable. They either*:
 - looked for H-dibaryon through decays (but S is stable)
 - restricted to mass > 2 GeV (but m_S < 2 GeV)
 - required $\Lambda\Lambda$ fusion in hypernuclei (but S- $\Lambda\Lambda$ interconversion is small)
- S is similar to (the much more copious) neutron
- Wavefunction overlap with baryons is very small. Extremely rare fluctuation required for $S \Leftrightarrow \Lambda\Lambda$; $S \Leftrightarrow NN$ is still smaller by G_{F^4} suppressed=>
 - nuclei can be stable ($\tau > 10^{29} \, \text{yr}$) even for m_S > 2 m_p
 - hard to produce in fixed target experiments
 - _ hard to breakup into 2 baryons
- Best places to make it: Heavy Ion Collision, Upsilon Decay



Experimental Searches

- Require M > 2 GeV:
 - Gufstafson+ FNAL1976: Beam-dump + tof Limit on programmon of neutral stable strongly interacting particle with mass > 2 GeV.
 - Carroll+ BNL 1978: No narrow missing mass peak ab ve GeV in pp -> K K X
- Require H-dibaryon decay:
 - Badier+ NA3 1986
 - Bernstein+ FNAL 1988: Limit \ productio of neutral with 10-8 < τ < 2 x10-6 s
 - Belz+ BNL 1996: H -/-: Λ > τΣ \ [c.f., issue raised by L...
 - Kim+ Belle 2013 no narrow resonance in ΥΛΛΚ
- Limit from production in doubly-strange hypernuclei:

Ah. + bive 2001 Takanashi+ KEK 2001

Search Six-Que States

A. S. arro, T.-H. C. ng, L. Johnson, T. F. Kycia, K. K. Ki,
L. S. tenberg, and M. D. Marx
whaven National Laboratory, Upton, New York 11973

and

R. ester, R. C. Webb, and M. S. Witherell Princeton University, Princeton, New Jersey 08540 (Received 26 July 1978)

c have searched the missing-mass spectrum of the reaction $pp \to K^+K^+X$ for a narrow squark resonance in the mass range 2.0-2.5 GeV/ c^2 . No narrow structure was obsected. Upper limits for the production cross section of such a state depend upon mass and vary from 30 to 130 nb.

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29 APRIL 1996

Search for the Weak Decay of an H Dibaryon

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*Ceceived 8 December 1995)

We have searched for a neutral H dibaryon decaying via $H \to \Lambda n$ and $H \to \Sigma^0 n$. Our search has yielded two candidate events from which we set an upper limit on the H production cross section. Normalizing to the inclusive Λ production cross section, we find $(d\sigma_H/d\Omega)/(d\sigma_\Lambda/d\Omega) < 6.3 \times 10^{-6}$ at 90% C.L., for an H of mass ≈ 2.15 GeV/ ϵ^2 , [S0031-9007(96)00050-6]

VOLUME 87, NUMBER 13

PHYSICAL REVIEW LETTERS

24 SEPTEMBER 200

Production of AAH Hypernuclei

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(Received I May 2001) published 5 September 2001)

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An experiment demonstrating the production of double- Λ hypernuclei in (K^-, K^+) reactions on ${}^9\mathrm{Be}$ was carried out at the D6 line in the BNL alternating-gradient synchrotron. The technique was the observation of pions produced in sequential mesonic weak decay, each pion associated with one unit of strangeness change. The results indicate the production of a significant number of the double hypernucleus $_{\Lambda}^{\mathrm{AH}}$ and the twin hypermuclei $_{\Lambda}^{\mathrm{AH}}$ Hand $_{\Lambda}^{\mathrm{AH}}$ The relevant decay chains are discussed and a simple model of the production mechanism is presented. An implication of this experiment is that the existence of an S=-2 chargory more than a few MeV below the Λ mass is unlikely.

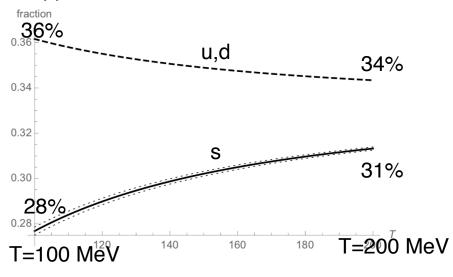
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Nature makes Sexaquark Dark Matter when Quark-Gluon Plasma → Hadrons @ T~150 MeV

GRF: uds-DM, arXiv:1805.03723

- Lattice QCD: crossover transition as T decreases gradually 160 to 140 MeV
 - T > 160 MeV: $u, \bar{u}, d, \bar{d}, s, \bar{s}, gluons$; NO vacuum condensates
 - T < 140 MeV: pions, kaons, p, \bar{p} , ...; <q \bar{q} > & <GG> condensates
- u,d,s abundances determined by temperature & quark masses:

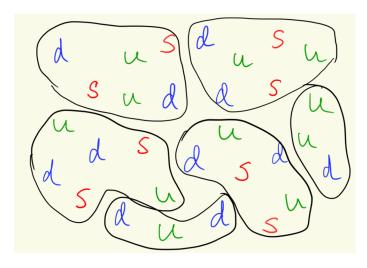
 $m_u = 2.118(38) \text{ MeV}$ $m_d = 4.690(54) \text{ MeV}$ $m_s = 92.52(69) \text{ MeV}$



DM to (left-over) baryon ratio

• If DM has u,d,s in equal numbers (sexaquark DM &/or strange quark nuggets)

$$\frac{\Omega_{DM}}{\Omega_b} = \frac{y_b \,\kappa_s \, 3f_s}{1 - \kappa_s \, 3f_s}$$



- y_b = (DM mass in units of m_p) / (baryon number of DM) ≈ 1
- f_s = fraction of quarks that are s
- 3 f_s: number uds per unit baryon # , 0.964 to 0.948 for T=160-140 MeV.
- κ_s : efficiency of uds → DM (Boltzmann, from hyperon and S masses)

$$\kappa_s(m_S, T) = \frac{1}{1 + (r_{\Lambda,\Lambda} + r_{\Lambda,\Sigma} + 2r_{\Sigma,\Sigma} + 2r_{N,\Xi})}$$

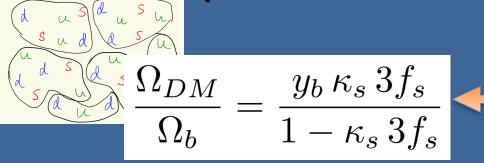
$$r_{1,2} \equiv \exp[-(m_1 + m_2 - m_S)/T]$$

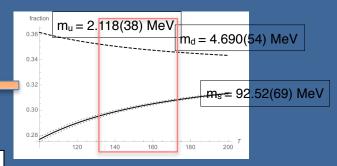
- Baryogenesis requirement shifts a bit:

$$\eta_{\rm tot} = \eta(1 + \Omega_{DM}/(y_b\Omega_b)) \approx 4.1 \times 10^{-9}$$

Prediction: $\Omega_{\rm DM}$ / $\Omega_{\rm b}$ = 4.5 ± 1

 $(\Omega_{\rm DM} / \Omega_{\rm b} \text{ observed} = 5.3 \pm 0.1)$





$$\kappa_s(m_S, T) = \frac{1}{1 + (r_{\Lambda, \Lambda} + r_{\Lambda, \Sigma} + 2r_{\Sigma, \Sigma} + 2r_{N, \Xi})}$$

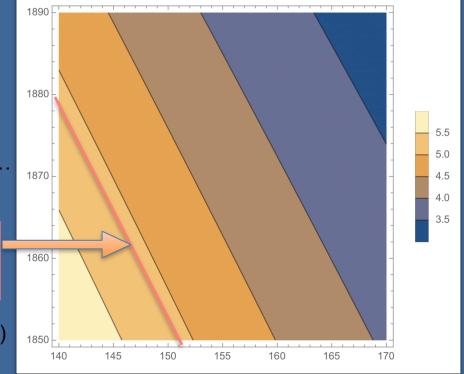
 $r_{1,2} \equiv \exp[-(m_1 + m_2 - m_S)/T]$

Prediction is *correct AND accurate* to ~20% for entire range (uncertainties cancel)

Prediction also applies to strange quark nuggets...

 $\Omega_{\rm DM}$ / $\Omega_{\rm b}$ = 5.3 ± 0.1

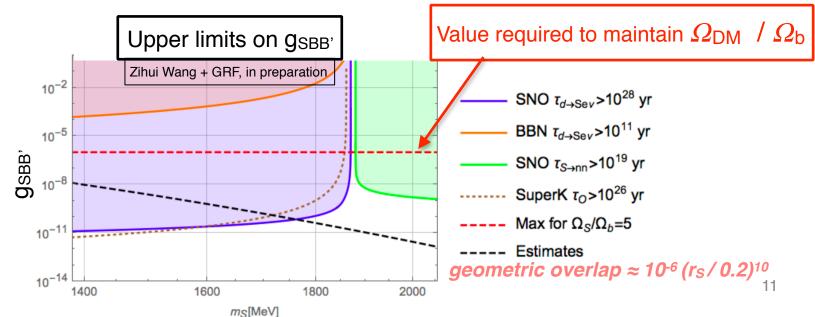
(Criticism of KT invalid bc they assumed S↔BB')



SDM survival in the hadronic phase

(effective coupling $g_{SBB'} = \langle S \mid H_{int} \mid BB' \rangle$)

- decay must be doubly weak: $m_p + m_e + m_A = 2054 \text{ MeV} > m_S > 1382 \text{ MeV} = m_d m_K$
- $m_S > 2 m_n$: $S \rightarrow nn$ in SNO (for Earth's DM atmosphere see Neufeld, GF, McKee 2018) SNO counted ~ 7k n's per year with 0.18 efficiency \Rightarrow $\tau_{S \rightarrow nn} > 10^{19} \text{ yr}$
- $m_S + m_e < m_d \ (m_S < : d \to S e^+ \nu)$
 - primordial deuterium abundance: τ_d→s_{eν} > 10¹¹ yr
 - SNO e spectrum: $\tau_{d} \rightarrow se_{\nu} > 10^{28} \text{ yr}$



GeV DM with Yukawa Interactions (X.Xu & GRF in prep)

$$V(r) = -\frac{\alpha}{r}e^{-m_{\phi}r}$$

(1) attractive Yukawa potential

$$m_{\phi} \sim 1 \text{ GeV} \quad \alpha \sim 1$$

- (2) Born approximation fails, must solve Schrödinger equation exactly
- (3) cross section depends only on dimensionless combos

$$a \equiv \frac{v}{2\alpha} \qquad b \equiv \frac{2\alpha\mu}{m_{\phi}}$$

Highly non-trivial A and velocity dependence →

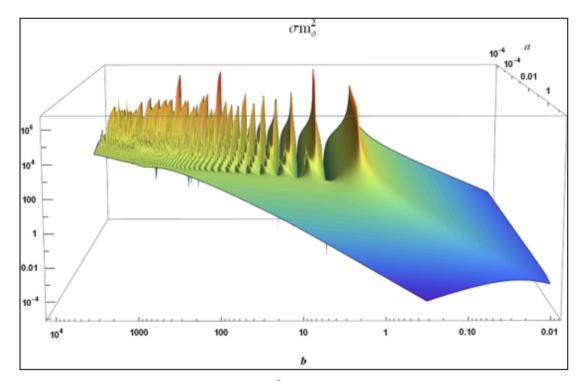
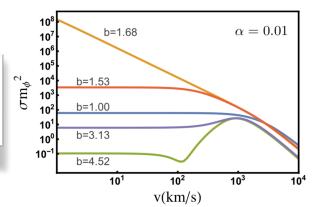
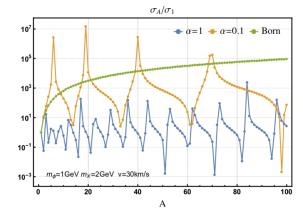
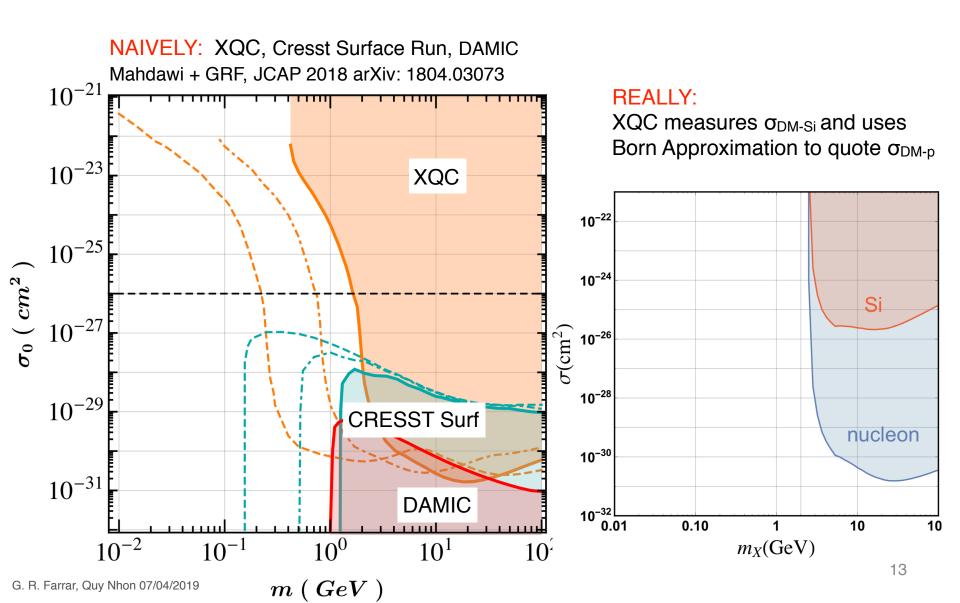


Fig 1: 3D plot of σm_{ϕ}^2 in the (a,b) plane; b increases to the left and a decreases toward the back.

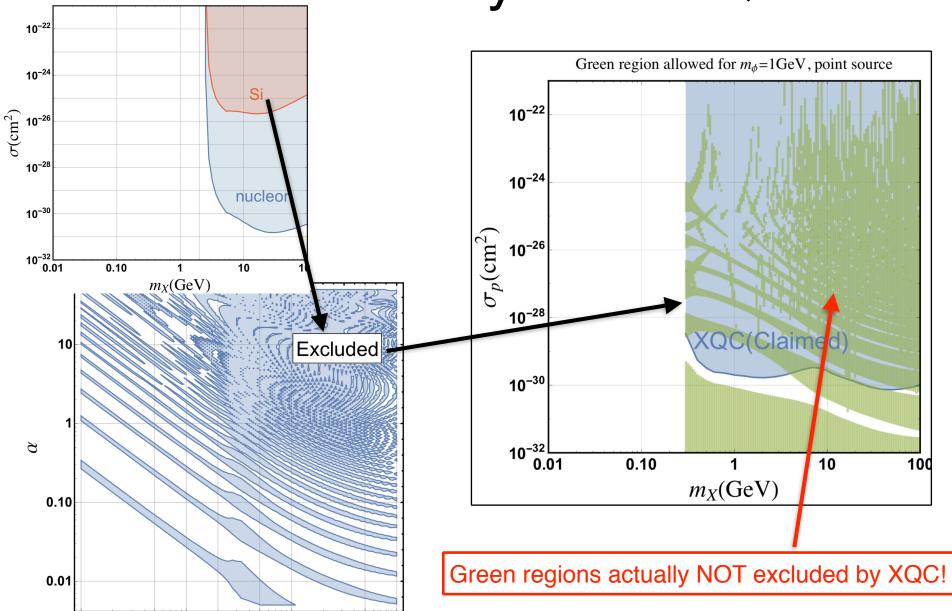




Must re-interpret direct detection expts



Correct Analysis of XQC



50

100

0.5

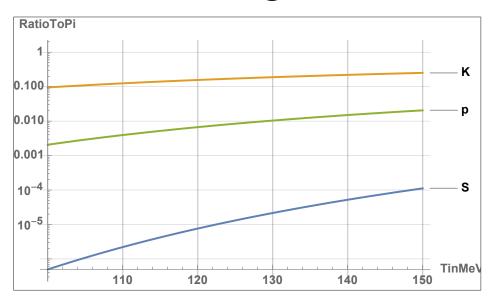
 $m_X(\text{GeV})$

Sexaquark Discovery Strategies

- S itself: neutral, generally "missing"
- Apparent lack of Baryon# and Strangeness conservation:
 - missing $B = \pm 2$ goes with missing $S = \mp 2$
 - inclusive: maximizes event rate, hermetic detector; ID!
 - Statistical correlation sufficient; do not have to ID everything.
 - Most important is to accurately distinguish K[±] from p/p
- Reconstruct missing mass, e.g.:
 - $\Upsilon \rightarrow \Lambda \Lambda \bar{S}$ (+ pions) $M_{S^2} = (p_Y p_{\Lambda 1} p_{\Lambda 2} \sum p_{\pi i})^2$
 - · exclusive: big penalty in statistics, but gain from mass neak
 - LHC: $\overline{S} + N -> \overline{\Lambda} K^+ \cdots M_{S^2} = (p_{\overline{\Lambda}} + p_{K_+ \dots} p_N)^2$
 - compromise: potentially a sweet spot (tbd)



S,S from cooling fireball at LHC?



- Fantasy: perfect equilibration → N_S/N_B = 2.5 net excess S's ©

- Reality (?):
 - no B excess in central region → no S excess over S̄
 - S,S annihilate to maintain equilibrium, till freeze out →
 - $N_{S+\bar{S}} \approx 10^{-4} N_{\pi}$ → $E_{Smiss} \approx 10^{-4} (M_S/E_{\pi}) E_{\pi tot}$... 1 ppm missing E $\stackrel{\frown}{\otimes}$
- Can a statistical correlation be established between missing
 - $B = \pm 2$ & missing $S = \mp 2$? (question of ID quality: ALICE???)

More S discovery strategies

- Time-of-flight (SHiP?): must distinguish from neutron. Rate depends on σ_{prod} σ_{int} .
- Second exponential in interaction length distribution.
- Heavy ion collisions:
 - correlation between missing B = ± 2 & missing S = ∓ 2 →
 missing | B-S | = 4 (also for pp and Y decay)
 - "Missing energy" (not much) need hermetic detectors
- Snolab nuclei: d -> S e+ ν sin θ_C^4 x GIM suppression x G_{F^4} , τ > 10^{+28} yr (ms < ~1875 MeV)

ln sum...

- There may a stable S= uuddss
 - Unique, symmetric structure ⇒ other hadrons don't provide guidance
 - mass is not driven by chiral symmetry breaking (unlike baryons)
 - lattice QCD => binding; null expts for unstable S suggests S is stable
 - S may be waiting to be discovered in existing **Y**-decays or LHC experiments... mass can be accurately measured in exclusive reactions
- If S is stable, it is an excellent Dark Matter candidate
 - No-parameter derivation of correct Dark Matter to baryon ratio
 - Semi-conductor based direct detection expts (XQC, Cresst, ...) need to be calibrated.
 - All constraints from nuclei must be reinterpreted in non-perturbative regime (c.f., Xu)
- -Astrophysics allows SDM to be constrained; remains viable so far....