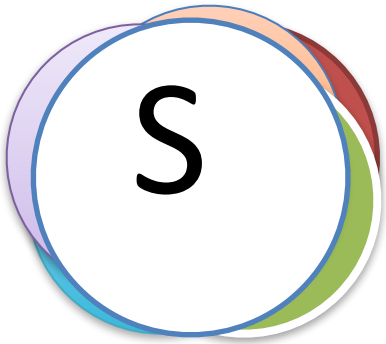
Sexaquark Dark Matter and Heavy Ion Collisions



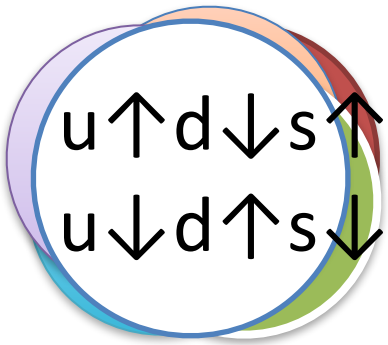
Glennys R. Farrar

New York University

Stable Sexaquark, arXiv:1708.08951v2 [hep-ph]
uds-DM, arXiv:1805.03723v2 [hep-ph]
Dark Matter Particle in QCD, GF, X. Xu & Z. Wang, arXiv:2007.10378 [hep-ph]
Earth's DM atmosphere, Ap.J. 2018 (Neufeld,GF,McKee)
Resonant Scattering between Dark Matter and Baryons: Revised Direct Detectio
(Xingchen Xu + GRF, arXiv: 2101.00142)
Sexaquark Mass from QCD Sum Rules (Zihui Wang and GRF, in prep)

ECT* Workshop on Heavy Ions and New Physics
May 20-21, 2021, Trento, IT

Sexaquark as Dark Matter



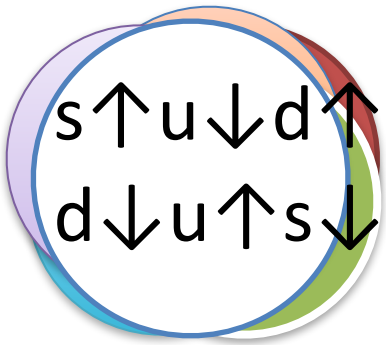
S

- *Properties of sexaquark (S)*
  - *new Sum Rule calculation of mass*
- *How could we have missed a stable particle made of quarks?*
- ***Dark-Matter to Ordinary-Matter:*** Ω_{DM} / Ω_b
- *[BBN with SDM, neutron star Mass-Radius M. Shahrbaf+21]*
- *Constraints on SDM (direct detection, CMB…)*
- ***Discovering a stable sexaquark in the lab*** ***BEST APPROACH IS Heavy Ion Collisions***

Stable Sexaquark Hypothesis

Same quark content as H-dibaryon* (Jaffe 1977), but different physics: **not a loosely bound di-Λ!**

*mass ~ 2150 MeV in bag model — decays in 10^{-10} s



S

(Most-Attractive Channel)³

Color singlet
Flavor singlet
Spin singlet (scalar)

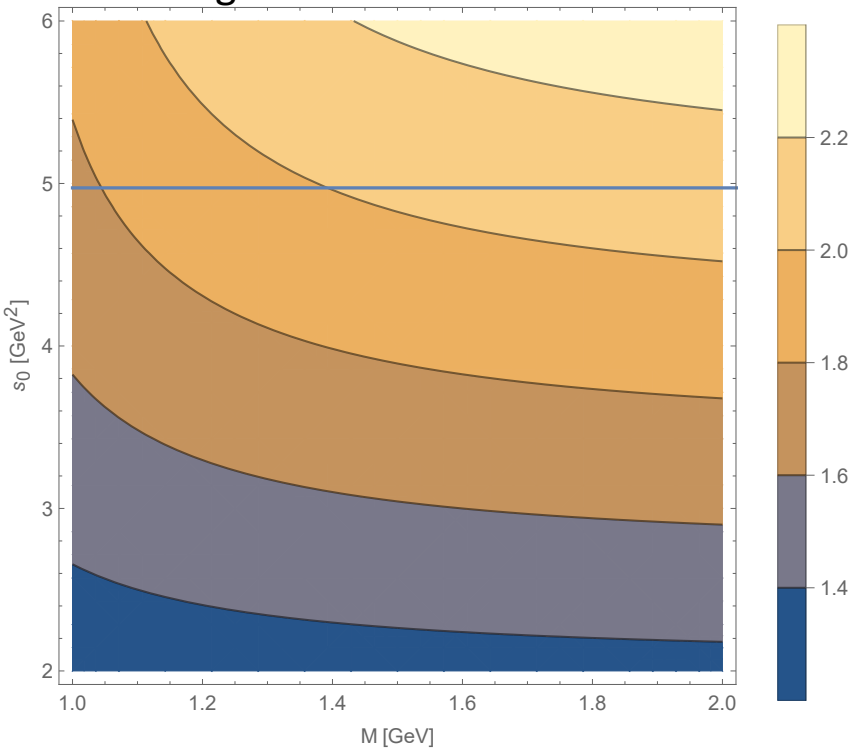
S may be tightly bound.

If $m_S \lesssim 2$ GeV ➜ S is STABLE

New Sum Rule Analysis (LO)

Zihui Wang (NYU) & GF, paper in prep

- Previous results
  - Kodama+1994: $m_S \approx 2\, m_\Lambda = 2230$ MeV (implicitly assumed no binding!)
  - Azizi+2020: $m_S \approx 1200$ MeV (took same threshold as for N)
  - Lattice (with 850 MeV quarks): 80 MeV binding
- Analysis parameters
  - $\sqrt{s_0}$ ~ continuum threshold (2 m_Λ)
  - M Borel parameter
  - $\langle \bar{q}q \rangle$ from fitting hadron masses
  - m_s from lattice QCD fits
- LO result: M_S = 1.8 - 2 GeV
  - Stable enough for DM
  - compatible with search limits!



Stable Sexaquark Hypothesis

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

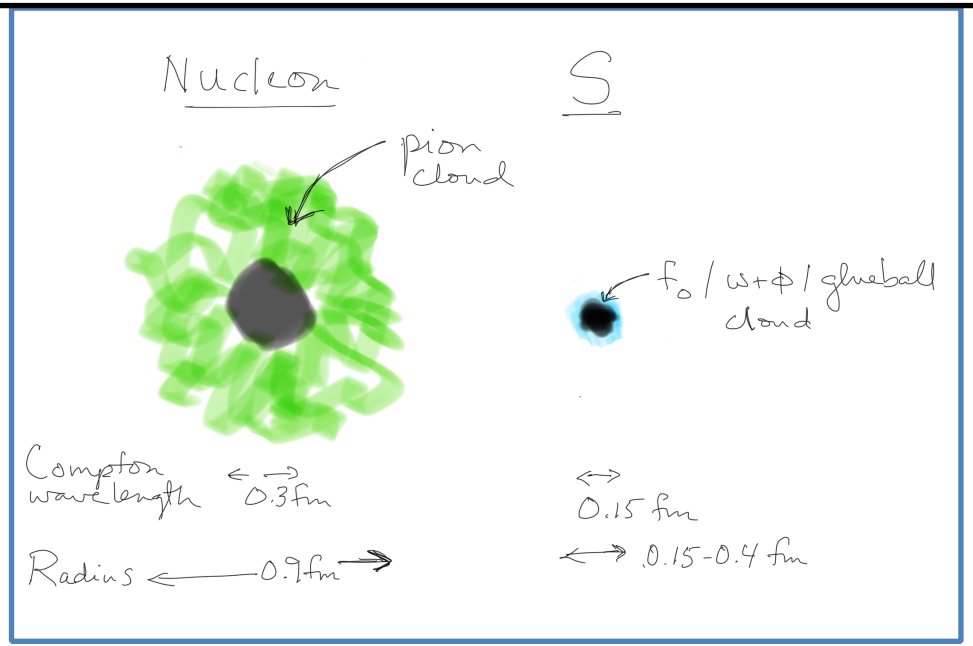
6	sexa-[19]	–	sen-[20]	sext-[21]	hex-[22]	hexakis- hexaplo- hexad- e.g. hexahedron	hect-[23] hectaio-	shat-

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

Crucial fact:

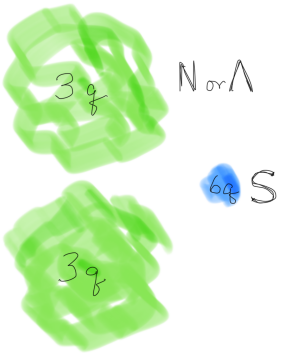
S does not couple to pions => may be much smaller than usual hadrons;

triple-diquark hard to produce with hadrons



S would not have been discovered at accelerators because it is elusive

- **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 ΛΛ fusion in hypernuclei (but SΛΛ overlap is small)
- **S is similar to** (the much more copious) **neutron**
- **Wavefunction overlap with baryons is very small.** Extremely rare fluctuation is required to dissociate S ⇔ ΛΛ*; S ⇔ NN is G_F^4 smaller & GIM suppressed ⇒
  - $g_{eff,SBB} \approx 10^{-6}\,(r_S / 0.2)^{10}$
  - nuclei can be stable ($\tau > 10^{29}$ yr) even for $m_S > 2\ m_p$
  - **hard to produce** in fixed target experiments & **hard to break-up**



- S scatters with nucleons via ϕ_0 exchange (m ≈ 1 GeV) ⇒

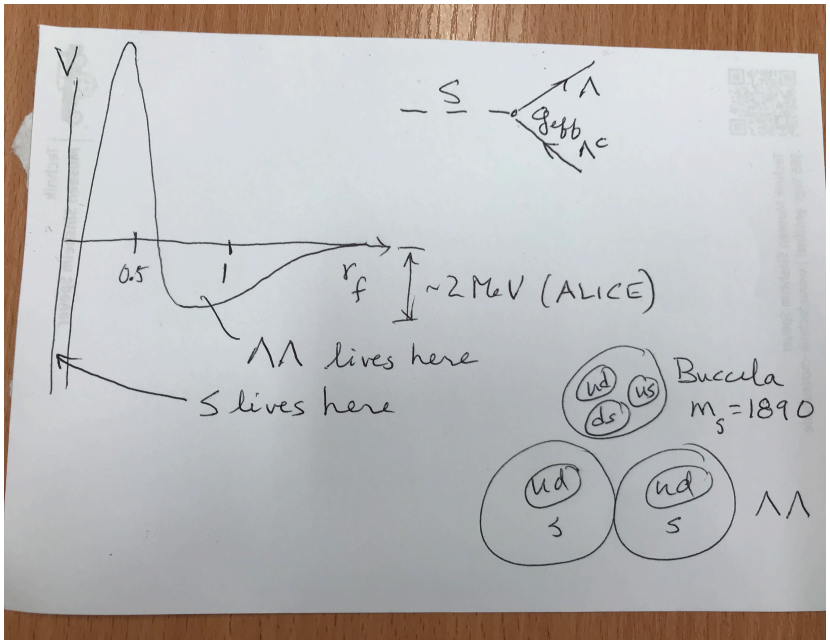
$$V(r) = \frac{\alpha}{r}\, e^{-r\, m_\phi}$$

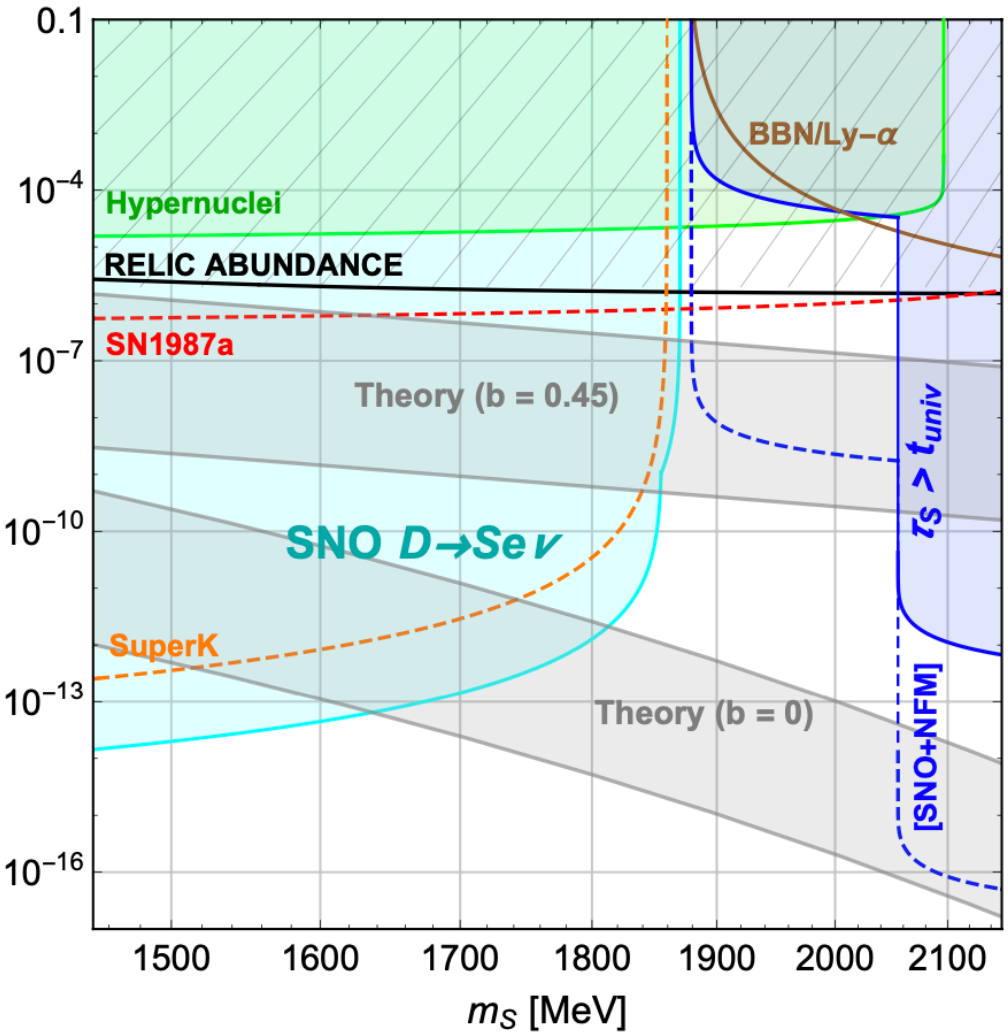
α : 0.01 - 1

*apart from BaBar

Effective Yukawa coupling S➜ΛΛ g_{eff}

- deuteron stability (GRF + Z. Wang, in prep)
- DM stability





H Experimental Searches

- Require M > 2 GeV:
  - Gufstafson+ FNAL1976 : Beam-dump + tof *Limit on production of neutral stable strongly interacting particle with mass > 2 GeV.*
  - Carroll+ BNL 1978: No narrow missing mass peak above 2 GeV in pp -> K K X
- Require H-dibaryon decay:
  - Badier+ NA3 1986
  - Bernstein+ FNAL 1988: Limit on production of neutral with $10^{-8} < \tau < 2 \times 10^{-6}$ s
  - Belz+ BNL 1996: H -> Λ n or **Σ** n [c.f., issue raised by Littenberg]
  - Kim+ Belle 2013: no narrow resonance in Υ -> Λ p K
- Limits from production in doubly-strange hypernuclei:
  - Ahn+ BNL 2001
    Takahashi+ KEK 2001

NOT APPLICABLE to S!

Search for Six-Quark States

A. R. Carroll, I-H. Chiang, R. A. Johnson, T. F. Kycia, K. K. Li, L. S. Littenberg, and M. D. Marx
Brookhaven National Laboratory, Upton, New York 11973

and

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

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

VOLUME 76, NUMBER 18 PHYSICAL REVIEW LETTERS 29 APRIL 1996

Search for the Weak Decay of an *H* Dibaryon

J. Belz,[6,*] R. D. Cousins,[3] M. V. Diwan,[5,†] M. Eckhause,[8] K. M. Ecklund,[5] A. D. Hancock,[8] V. L. Highland,[6,‡] C. Hoff,[8] G. W. Hoffmann,[7] G. M. Irwin,[5] J. R. Kane,[8] S. H. Kettell,[5,†] J. R. Klein,[4,§] Y. Kuang,[8] K. Lang,[7] R. Martin,[8] M. May,[1] J. McDonough,[7] W. R. Molzon,[2] P. J. Riley,[7] J. L. Ritchie,[7] A. J. Schwartz,[4] A. Trandafir,[6] B. Ware,[7] R. E. Welsh,[8] S. N. White,[1] M. T. Witkowski,[8,||] S. G. Wojcicki,[5] and S. Worm[7]
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[2]*University of California, Irvine, California 92717*
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[8]*College of William and Mary, Williamsburg, Virginia 23187*
(Received 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/c^2. [S0031-9007(96)00050-6]

VOLUME 87, NUMBER 13 PHYSICAL REVIEW LETTERS 24 SEPTEMBER 2001

Production of $^{\ \ 4}_{\Lambda\Lambda}$H Hypernuclei

J. K. Ahn,[13] S. Ajimura,[10] H. Akikawa,[7] B. Bassalleck,[9] A. Berdoz,[2] D. Carman,[2] R. E. Chrien,[1] C. A. Davis,[8,14] P. Eugenio,[2] H. Fischer,[3] G. B. Franklin,[2] J. Franz,[3] T. Fukuda,[15] L. Gan,[4] H. Hotchi,[12] A. Ichikawa,[7] K. Imai,[7] S. H. Kahana,[1] P. Khaustov,[2] T. Kishimoto,[10] P. Koran,[2] H. Kohri,[10] A. Kourepin,[6] K. Kubota,[12] M. Landry,[8] M. May,[1] C. Meyer,[2] Z. Meziani,[11] S. Minami,[10] T. Miyachi,[12] T. Nagae,[5] J. Nakano,[12] H. Outa,[5] K. Paschke,[2] P. Pile,[1] M. Prokhabatilov,[6] B. P. Quinn,[2] V. Rasin,[6] A. Rusek,[1] H. Schmitt,[3] R. A. Schumacher,[2] M. Sekimoto,[5] K. Shileev,[6] Y. Shimizu,[10] R. Sutter,[1] T. Tamagawa,[12] L. Tang,[4] K. Tanida,[12] K. Yamamoto,[7] and L. Yuan[4]
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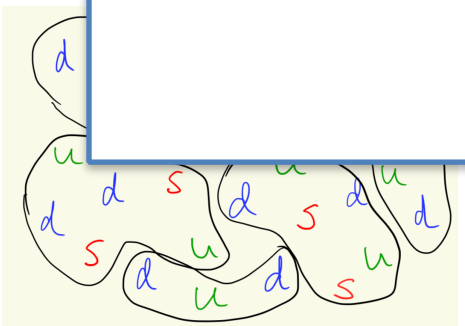
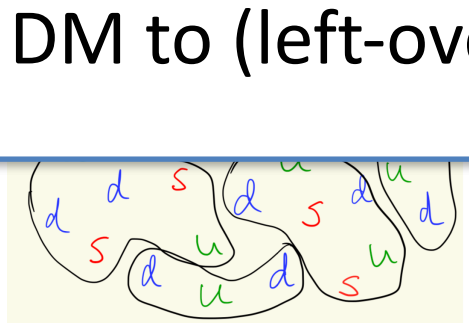
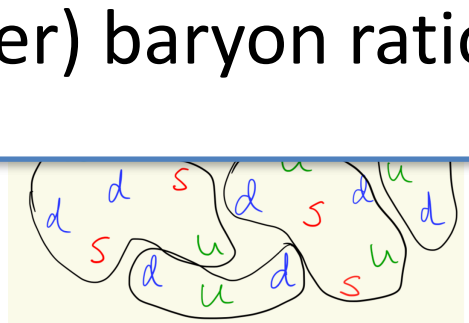
(Received 14 May 2001; published 5 September 2001)

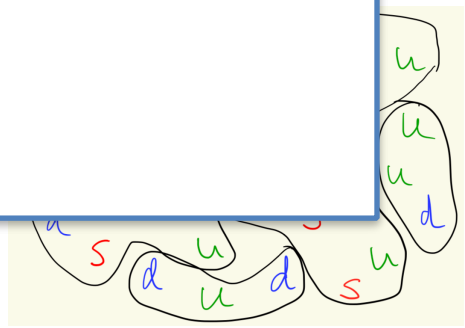
An experiment demonstrating the production of double-Λ hypernuclei in (K^-, K^+) reactions on ^{9}Be was carried out at the D6 line in the BNL alternating-gradient synchrotron. The technique was the observation of pions produced in sequential mesonic weak decay, each pion associated with one unit of strangeness change. The results indicate the production of a significant number of the double hypernucleus $^{\ \ 4}_{\Lambda\Lambda}$H and the twin hypernuclei $^{\ \ 4}_{\Lambda}$H and $^{\ \ 3}_{\Lambda}$H. 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 $S = -2$ dibaryon more than a few MeV below the ΛΛ mass is unlikely.

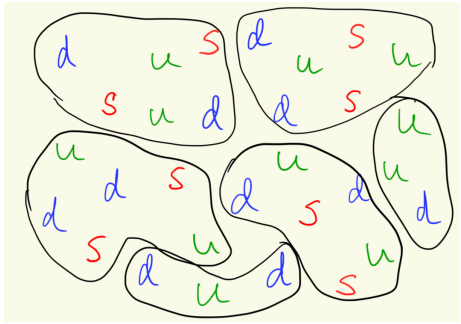
DM to (left-over) baryon ratio



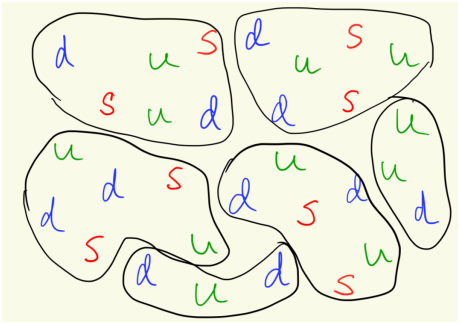




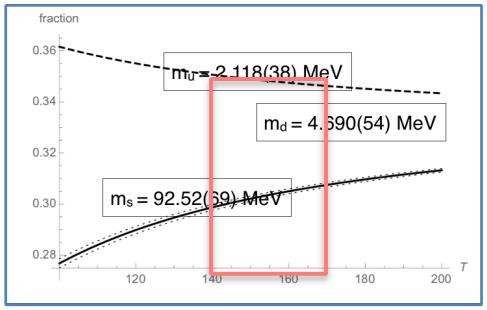




- ***Hypothesis: DM has u,d,s in equal numbers***
  (sexaquark DM, strange quark nuggets (Witten,1984))



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



- $y_b \equiv$ DM mass/m_p (≈ 2)
- $f_s \equiv$ fraction of quarks that are s
- $3 f_s$ is number uds per unit baryon # — 0.964 to 0.948 for T=160-140 MeV.
- κ_S is efficiency of uds ➜ DM (Boltzmann, w hyperon and S masses)

$$\kappa_s(m_S,T) = \frac{1}{1+(r_{\Lambda,\Lambda}+r_{\Lambda,\Sigma}+2r_{\Sigma,\Sigma}+2r_{N,\Xi})} \qquad \boxed{r_{1,2} \equiv \exp[-(m_1+m_2-m_S)/T]}$$

Correct relic density - no free parameters!

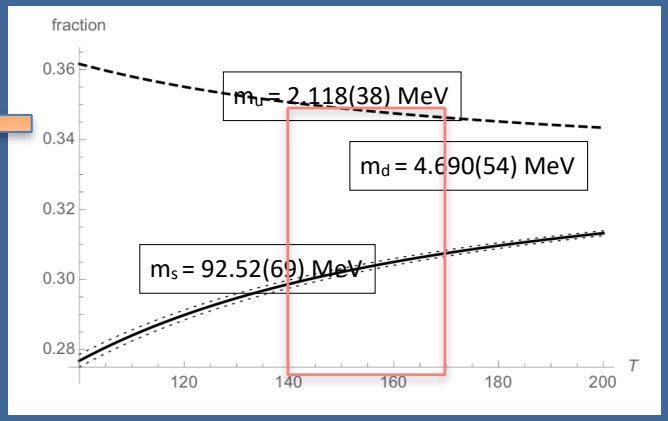
determined by *stat mech , quark masses* &
temp of *QGP-hadronization transition*

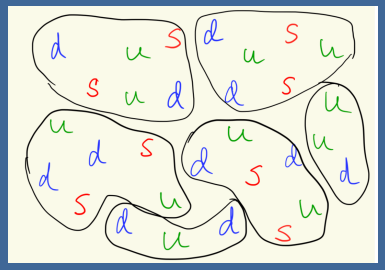
more accurate treatment would include evolution of <qq̄> with T

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

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

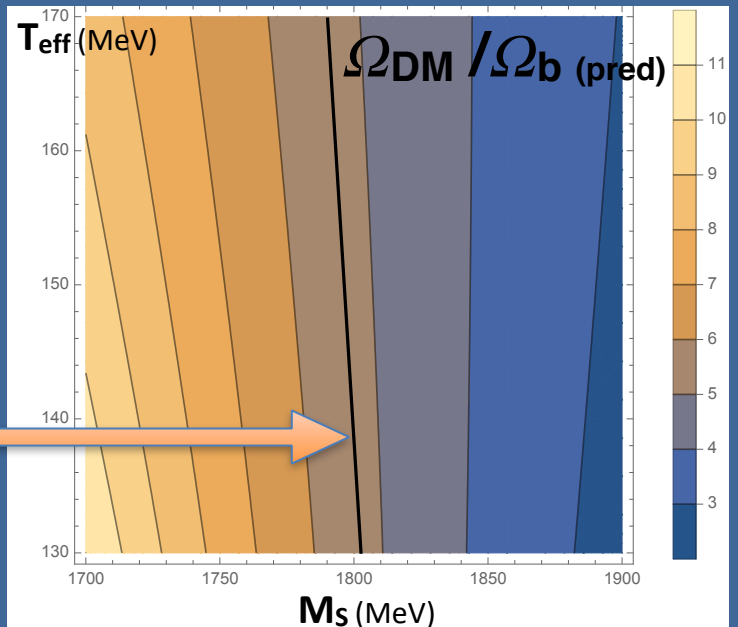
$$r_{1,2} \equiv \exp[-(m_1+m_2-m_S)/T]$$





$\Omega_{DM}\ /\ \Omega_{b\ (pred)} = 3\text{-}10$

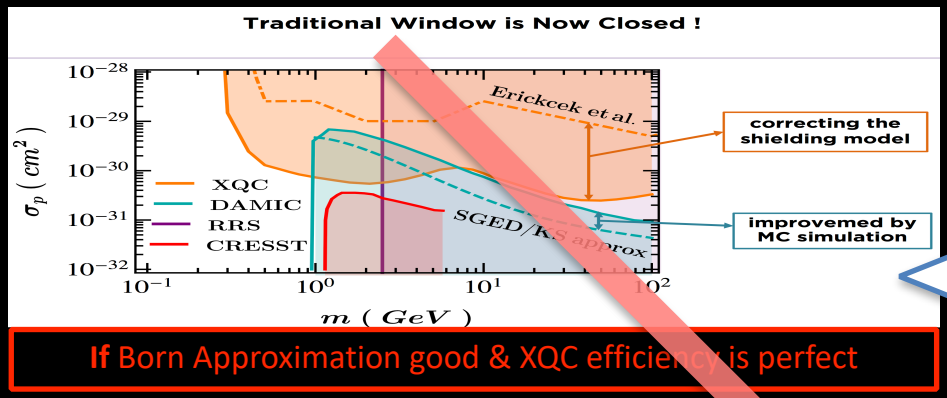
$\Omega_{DM}\ /\ \Omega_{b\ (obs)} = 5.3 \pm 0.1$



Kolb+Turner, Gross et al, did not account for S-BB suppression

Stable S as Dark Matter

10^{-26} -10^{-25} cm^2



Closing the window on ~GeV Dark Matter with moderate (~μb) interaction with nucleons

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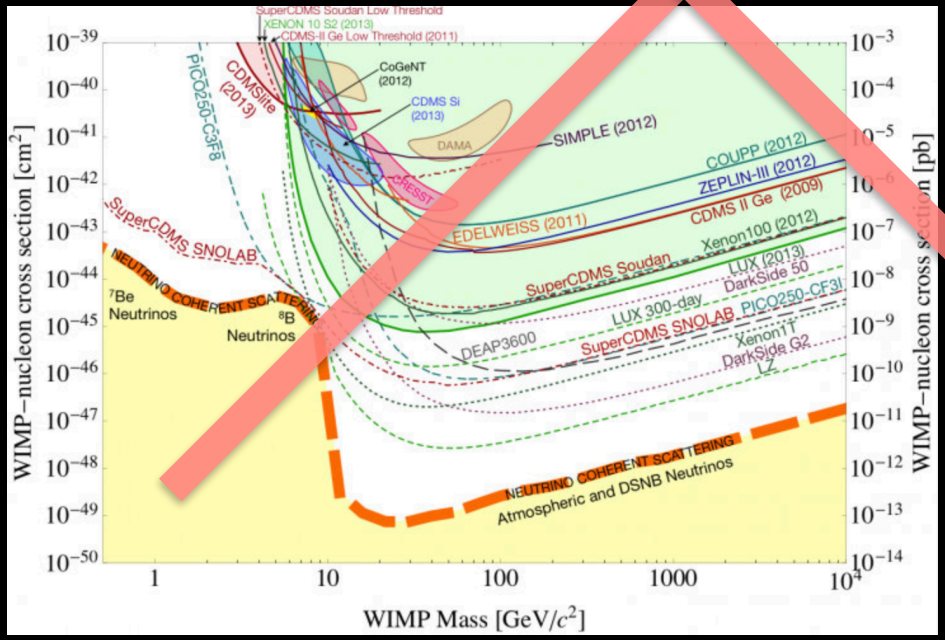
Abstract. We improve limits on the spin-independent scattering cross section of Dark Matter on nucleons, for DM in the 300 MeV – 100 GeV mass range, based on the DAMIC and XQC experiments. Our results close the window which previously existed in this mass range, for a DM-nucleon cross section of order ~ μb, assuming the standard velocity distribution.

Shielded (e.g. underground) detectors are not sensitive (energy loss)



Constraints on DM-hadron Interaction

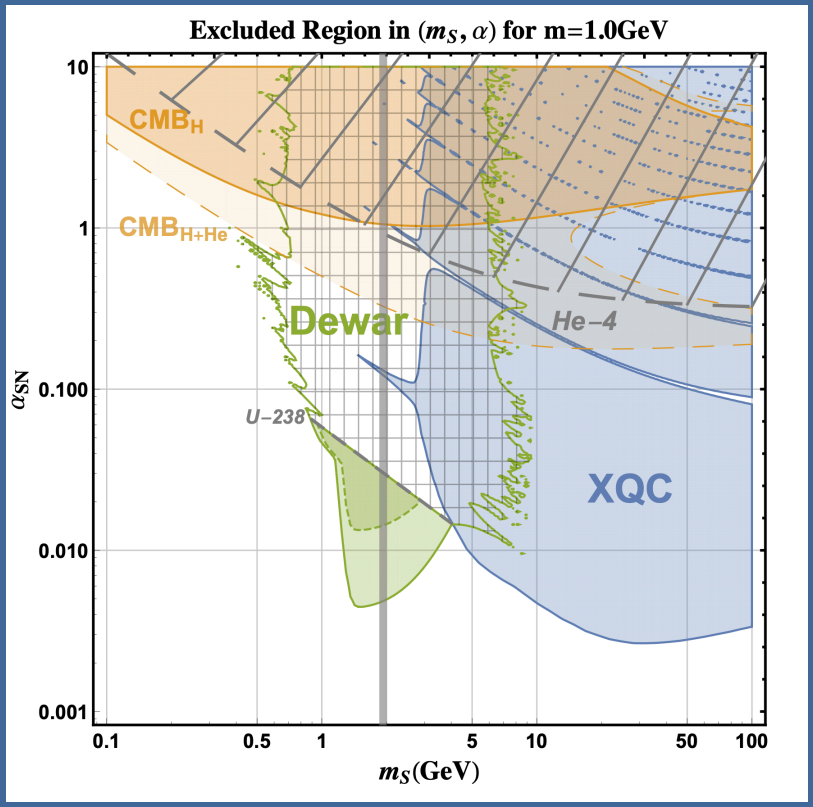
(Xingchen Xu & GRF, to appear shortly)

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

m_ϕ = 1 GeV (flavor-singlet **ω-φ** combo), sourced by p or A

- Non-perturbative in general
  - **Born approximation generically fails badly**
  - must reanalyze "standard" DM limits
- **CMB: $\alpha_{SN} < 0.3$** for $m_S = 2\, m_p$
- potential limit from dewars & exotic nuclei search

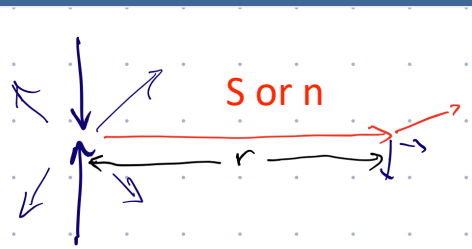
, **$\alpha_{SN} < 0.03$**

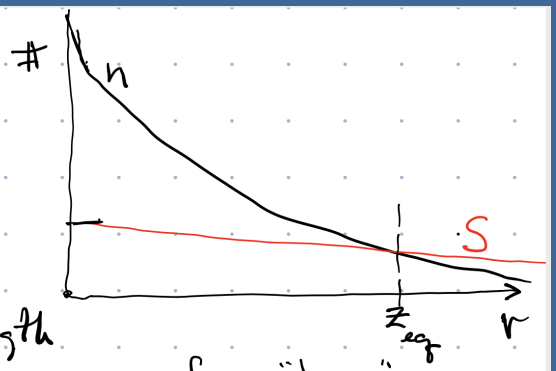


Sexaquark Discovery Strategies

- Apparent lack of B and S conservation:
  - **missing B = ± 2 + missing S = ∓ 2**
    - *inclusive: maximizes event rate, hermetic detector; ID!*
    - *Statistical correlation sufficient; do not have to ID everything.*
    - *Must have excellent particle ID*
- Reconstruct missing mass, e.g.:
  - $\Upsilon \rightarrow \Lambda \Lambda \bar{S}$ (+ pions) $M_S^2 = (p_\Upsilon - p_{\Lambda 1} - p_{\Lambda 2} - \Sigma\, p_{\pi i})^2$
    - *exclusive: big penalty in statistics, but gain from mass peak*
  - LHC: $\bar{S} + N \rightarrow \bar{\Lambda}\ K^+ \cdots$ $M_S^2 = (p_{\bar{\Lambda}} + p_{K^+ \ldots} - p_N)^2$
    - *compromise: potentially a sweet spot (tbd — seems too much bkg)*
- Interaction after beam dump; SHIP? "Missing energy" in HIC— seems too little to detect reliably
- Second exponential in interaction length
- Central HIC optimal because production is reliably predicted

Detection via scattering





$\lambda \equiv$ "inelastic" scat length
detectable scattering, removes from "beam"

$$\left.\frac{dN}{dz}\right|_n = \left.\frac{dN}{dz}\right|_S \frac{R\lambda_s e^{-z/\lambda_n}}{\lambda_n e^{-z/\lambda_s}}$$

$\lambda_s \gg \lambda_n$

$$\Rightarrow z_{eq} \approx \lambda_n \ln\left[R\frac{\lambda_s}{\lambda_n}\right]$$

$\lambda^{int}_{n,Pb} = 9.64$ cm [9.78 for Fe]

$m_S = 2m_p$ + thermal prod $\Rightarrow R \approx 30$ [up to 10^6 in non-thermal]

$$\lambda_s^{int} \approx \left(\frac{\alpha_{NN}}{\alpha_{SN}}\right)^2 \lambda_n^{int}$$

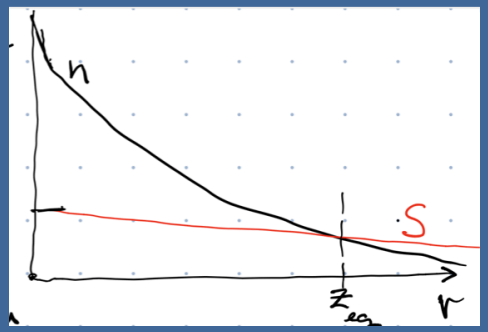
α = Yukawa coupling;
CMB $\Rightarrow \alpha_{SN} < 0.2$

$$z_{eq} = 2\,m + 0.1\,m\left[2\ln\left(\frac{\alpha_{SN}}{0.01}\right) + \ln\frac{R}{300}\right]$$

feasible addition to LHC detectors???

Central?

more forward?



REQUIREMENTS

- enough absorber (~2m) to reduce n bkg
- distinguish scattering of neutral primary (n,S) from decay of neutral (r dependence)
- low noise, to reach low interaction level

TO-DO

- model scattering to find
  - optimal cut on inelasticity
  - optimal detector position
- ⇒ preliminary detector requirements

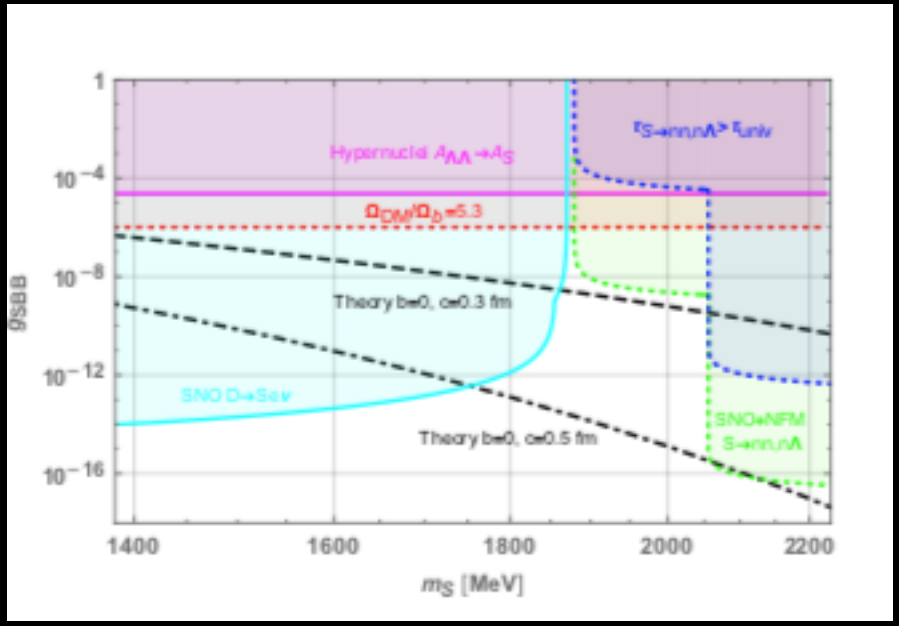
$$z_{eq} = 2\,m + 0.1\,m \left[2 \ln\left(\frac{\alpha_{SW}}{0.01}\right) + \ln\frac{R}{300} \right]$$

oversimplified "λ"

In sum…

- ***There may a tightly bound 6-quark state*** **S= uuddss**
  - **Unique, symmetric structure:**
    - Most Attractive Channel ⇒ deepest binding
    - other hadrons don't give guidance
  - ***S naturally absolutely or effectively stable***
- ***Stable S is excellent Dark Matter candidate***
  - **Correct Dark Matter to baryon ratio (no free parameters!)**
  - **Compatible with all constraints (NS, direct detection, CMB…)**
- ***S best searched for in Heavy Ion experiments***
  - **measure neutral "interaction length"**
  - **S-induced interactions should equal n-induced at ~ 2 m.**
  - **CONTACT ME IF YOU'RE INTERESTED in designing. SNOWMASS LoI; now needs details!** (GF, Beacham, deRoeck, Echenard, Feng, Haas, Lowette, Unger)

Backup Slides



$\Upsilon \to \Lambda\Lambda\bar{S}$ & $\bar{\Lambda}\bar{\Lambda}S$

High Energy Physics – Experiment

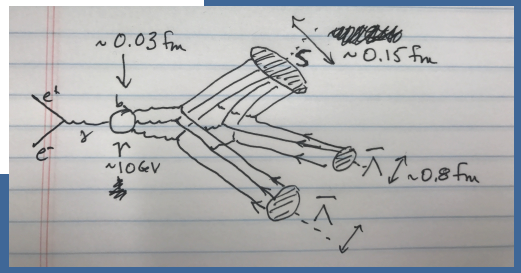
Search for a Stable Six-Quark State at BABAR

Bertrand Echenard (on behalf of The BABAR Collaboration)

(Submitted on 10 Oct 2018)

Recent investigations have suggested that the six-quark combination uuddss could be a deeply bound state (S) that has eluded detection so far, and a potential dark matter candidate. We report the first search for a stable, doubly strange six-quark state in Upsilon -> S anti-Lambda anti-Lambda decays based on a sample of 90 million Upsilon(2S) and 110 million Upsilon(3S) decays collected by the BABAR experiment. No signal is observed, and 90% confidence level limits on the combined Upsilon(2S,3S) -> S anti-Lambda anti-Lambda branching fraction in the range (1.2-1.4)x10^-7 are derived for m_S < 2.05 GeV. These bounds set stringent limits on the existence of such exotic particles.

Comments: 7 pages, 4 figures, submitted to Phys. Rev. Lett
Subjects: **High Energy Physics – Experiment (hep-ex)**
Report number: BABAR-PUB-18/009, SLAC-PUB-17335
Cite as: arXiv:1810.04724 **[hep-ex]**
(or arXiv:1810.04724v1 **[hep-ex]** for this version)



- BaBar: ***exclusive*** BF[$\Upsilon(2S,3S) \to \Lambda\Lambda\bar{S} + \bar{\Lambda}\bar{\Lambda}S$] *< 1.4 x 10^{-7}*
  - 2 x 10^8 events; main backgrounds $\Upsilon(2S,3S) \to \Lambda\Lambda\bar{\Lambda}\bar{\Lambda} + X$ & noise in E-cal
- Predicted ***inclusive*** BF [$\Upsilon(ggg) \to (\bar{S}$ or $S + X)$] ~ 2.7 x 10^{-7} (GRF arXiv:1708.08951)
  - SU(18) (color-flavor-spin) singlet: 5.4 10^{-4} ; α_s^3 ; $(1/2)^5$

  Exclusive Penalty:
  - start with biggest exclusive 3-body channel: BF[$\Upsilon(2S,3S) \to \phi$ K K] = 2 x 10^{-6}
  - penalty of $S+\bar{S}$ relative to ϕ : 6 x 10^{-5}
- Predict Exclusive BF [$\Upsilon(ggg) \to \Lambda\Lambda\bar{S} + \bar{\Lambda}\bar{\Lambda}S$] ~ *10^{-11}*

$\Upsilon \to \Lambda \Lambda \bar{S}$ & $\bar{\Lambda} \bar{\Lambda} S$

High Energy Physics – Experiment

Search for a Stable Six-Quark State at BABAR

BaBar exclusive limit far from constraining — need inclusive or semi-inclusive search

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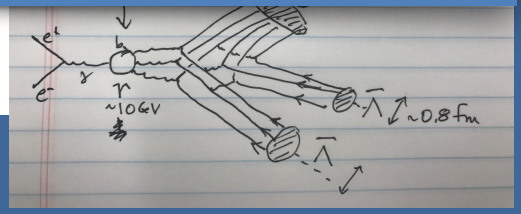

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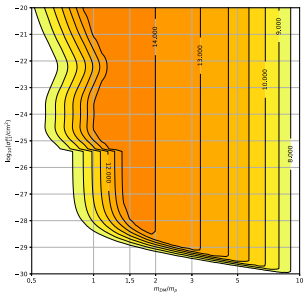
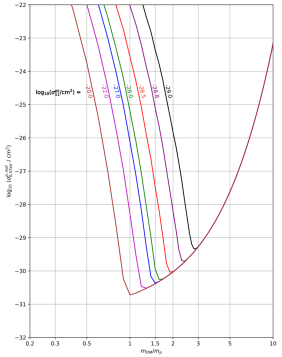
Cosmology & structure formation

- DM-baryon interaction: momentum transfer => *slight drag on DM during structure formation*
  - Dvorkin, Blum, Kamionkowski (2014), Gluscevic+Boddy (2017), Xu+18
    - **Ly-alpha forest: σ < ~10 mb if v-indept — no problem for S**
  - Buen-Abad, Marques-Tavares, Schmaltz (2015):
    - **momentum transfer helps reconcile H_o & σ_8**
  - Boring or an opportunity? To be determined…
- S-S self interactions + S-baryon interactions:
  - could have similar benefits as Self Interacting DM
    - core-cusp, "too-big-to-fail" & missing sub-halos problems.

Advertisement

Earth's Dark Matter Atmosphere and limits on DM-baryon interactions for $0.6 < m_{DM} < 6$ GeV

D. Neufeld, GRF & C. McKee, Ap. J. 2018

- IF
  - DM-crust cross section is large enough for capture ($\sigma \gtrsim 10^{-28}$ cm^2)
  - and ~0.6 GeV < m_{DM} < ~6 GeV
  - and Earth's atmosphere has been ~same on Gyr timescale
- THEN
  - NFM: strongest limits on many different DM-nuclei cross sections
  - limits on DM-proton scattering at TeV energies (from LHC beam)