Sexaquark Dark Matter and ways to find it

S

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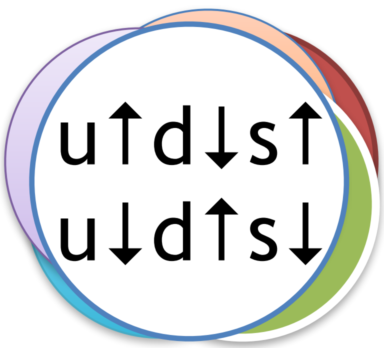
Stable Sexaquark, arXiv:1708.08951v2 [hep-ph]
uds-DM, arXiv:1805.03723v2 [hep-ph]
&
Earth's DM atmosphere, Ap.J. 2018 (Neufeld,GF,McKee)
Direct detection limits for non-perturbative DM-OM interactions (Xingchen Xu + GRF in preparation)
Sexaquark dissociation bounds (GRF+Zihui Wang, in prep)
Dark Matter - nucleus hybridization and 7Li Problem (GF+Xu, in prep)

Sexaquark as Dark Matter



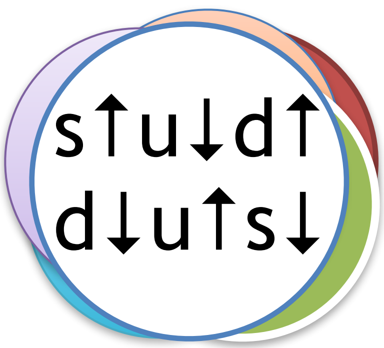
S

- *Properties of sexaquark (S)*
- *How could we have missed a stable particle made of quarks?*
- ***Dark-Matter to Ordinary-Matter:*** Ω_{DM} / Ω_b
- *BBN with SDM*
- *Constraints on SDM (direct detection, CMB…)*
- *Discovering a stable sexaquark in the lab*

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)

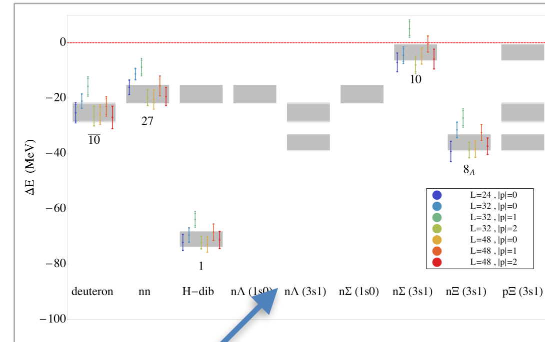
↓

$m_S \lesssim 2$ GeV

S is STABLE

Why consider $m_S \sim 2\ m_p$?

($2\ m_p$ =1.876 GeV)



- Light quarks almost massless, i.e. relativistic
  - $m_{u,d} \approx$ few MeV, m_s = 91 MeV
- S has same QNs as ground state glueball
  - $m_S \approx m_{glueball}$ +180 MeV = (1.5-1.7)+ 0.18 GeV $\lesssim 2\ m_p$
  - 3 x di-quark mass (F. Bucella: $m_S \approx$ 1890 MeV)
  - triple-singlet (color,flavor,spin): MAC, lattice, models $\Rightarrow m_S < 2\ m_\Lambda$
- Chiral symmetry breaking does not (obviously) give S mass

mass $\lesssim$ 2 GeV $\rightarrow$ $\tau > \tau_{Univ}$ or stable ($\Gamma \sim G_F^4 \times g_{eff}^2$

- $m_S < 2\ (m_p + m_e)$: S is absolutely stable
- $m_S > m_D - m_e$: nuclei are guaranteed stable ($d \nrightarrow S\ e^+ \nu$)
- $2\ m_p \pm 100$ MeV: may also be stable enough

Interesting DM candidate

G. R. Farrar,

Stable Sexaquark Hypothesis

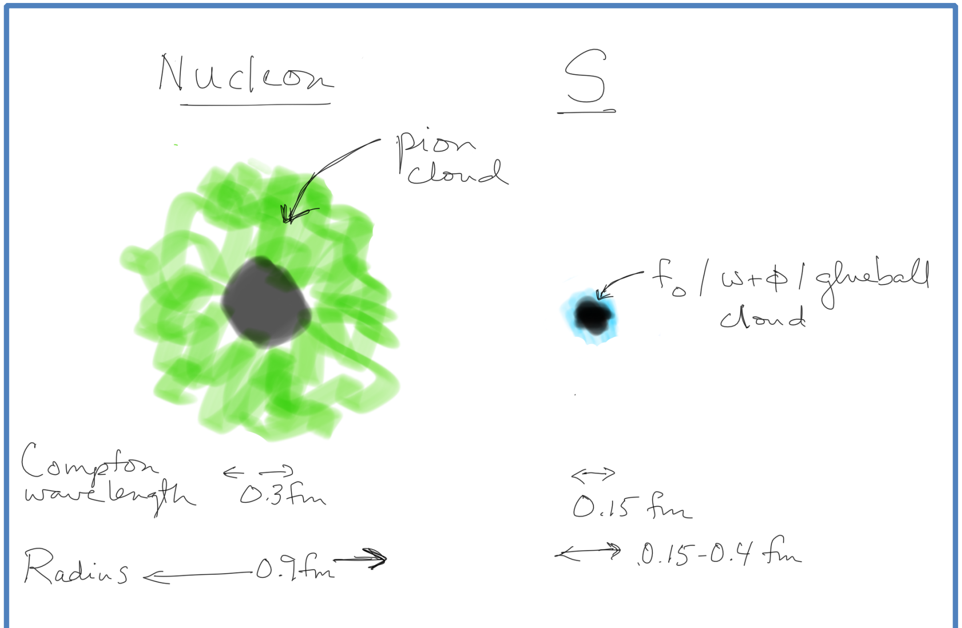
https://en.wikipedia.org/wiki/Numeral_prefix

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 => much smaller than usual hadrons => hard to produce with hadrons

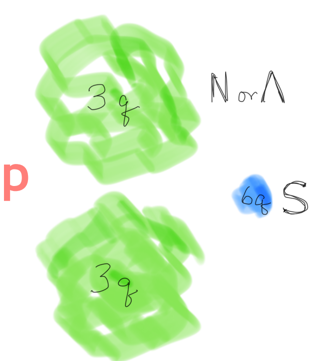


S would not have been discovered at accelerators because it is elusive

- **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) ⇒

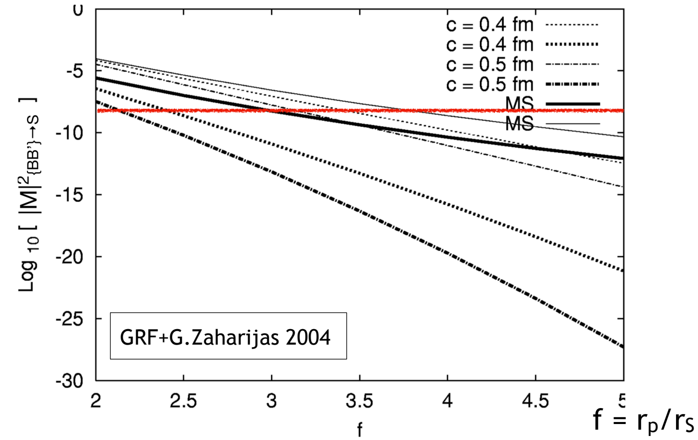
$$V(r) = \frac{\alpha}{r} e^{-r\, m_\phi}$$

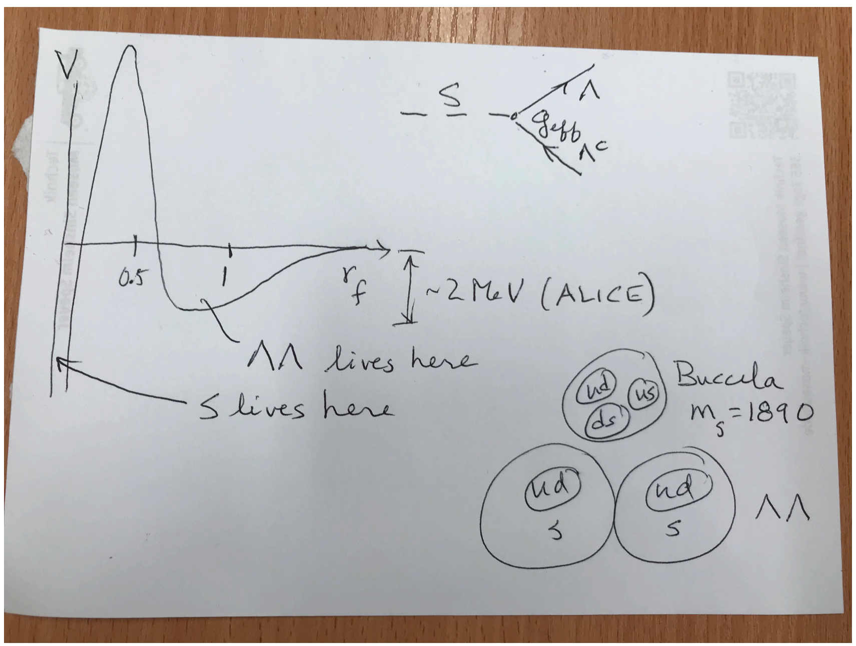
α : 0.01 - 1

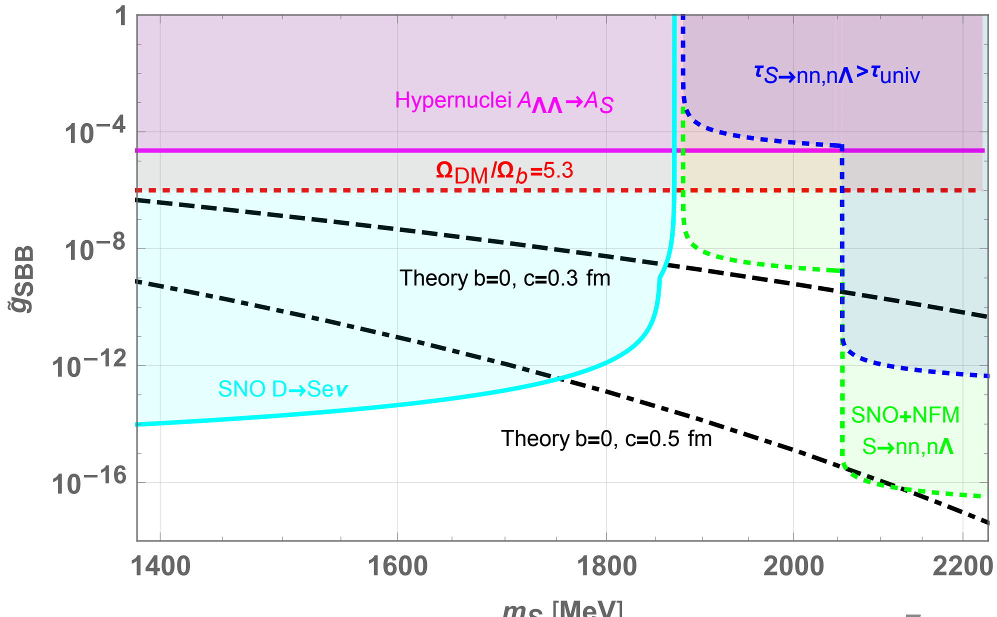
*apart from BaBar

Effective Yukawa coupling S➜ΛΛ g_{eff}

- prediction from spatial overlap only ➜
- deuteron stability (GRF + Z. Wang, in prep)
- DM stability



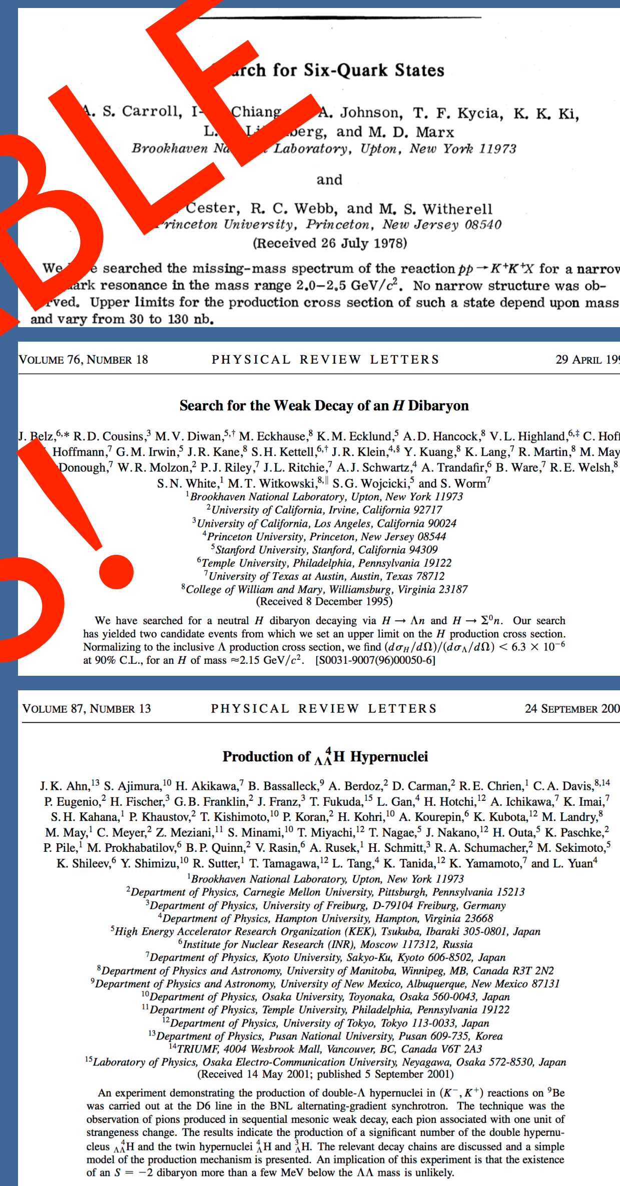




H Experimental Searches

- 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 L. Littenberg]
  - Kim+ Belle 2013: no narrow resonance in $\Upsilon \to \Lambda$ 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. S. 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

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(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

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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.

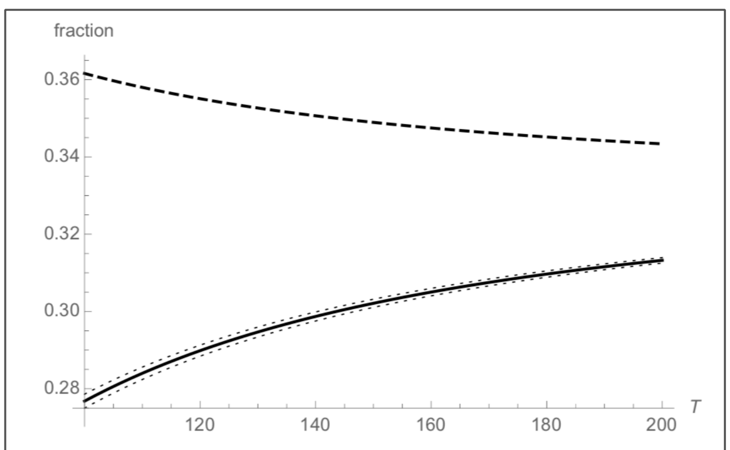
Quark-Gluon Plasma ➜ Hadrons in the Early Universe

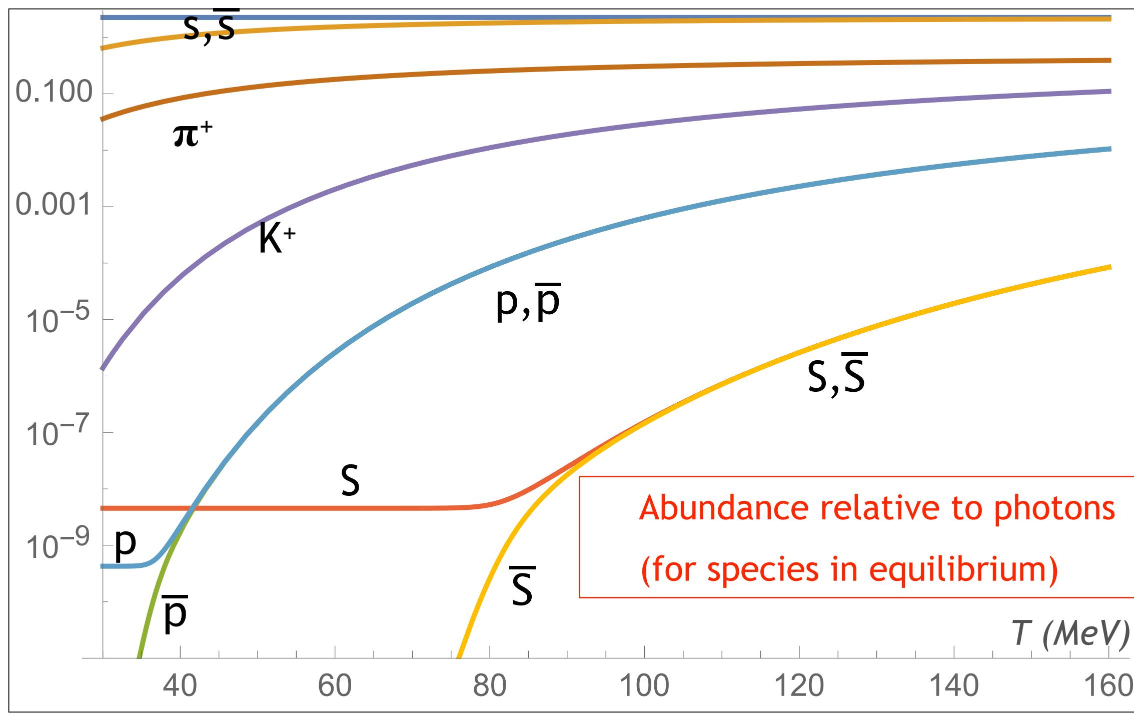
Cooling very slow: $\tau_{Hubble} \approx 10^{-5}$ s

GRF: uds-*DM*, arXiv:1805.03723v2 [hep-ph]

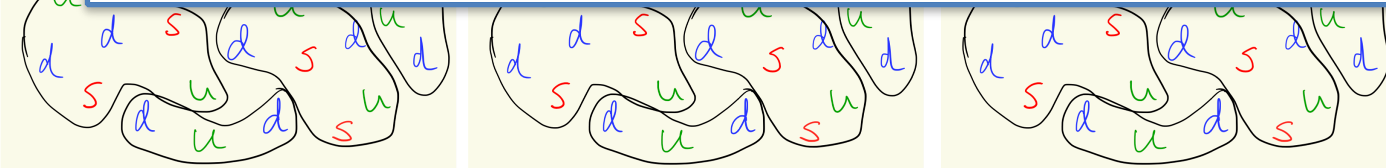
- Lattice QCD: crossover transition 160-140 MeV
  - T > 160 MeV: u,$\bar{u}$,d,$\bar{d}$,s,$\bar{s}$,gluons; NO vacuum condensates
  - T < 140 MeV: pions, kaons, p,$\bar{p}$, …; $\langle q\bar{q}\rangle$ & $\langle GG\rangle$ condensates
- Baryogenesis for the net baryon-photon ratio $\eta_{\rm tot} = \eta(1 + \Omega_{DM}/(y_b\Omega_b)) \approx 4.1 \times 10^{-9}$
- u,d,s ratio from q masses:

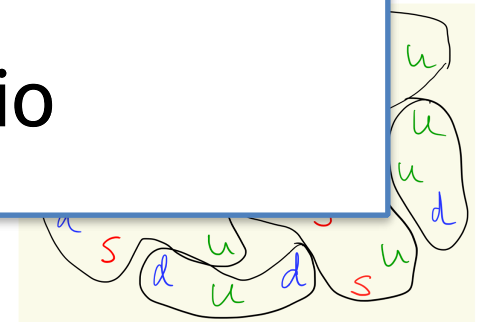
m_u = 2.118(38) MeV
m_d = 4.690(54) MeV
m_s = 92.52(69) MeV



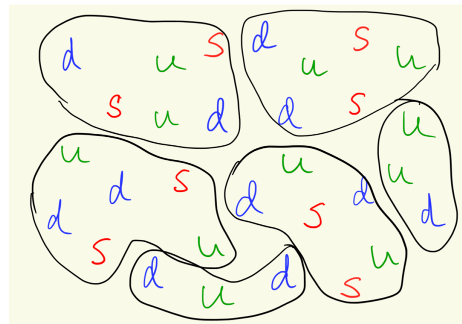


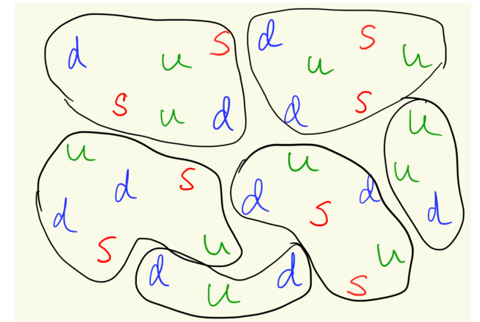
DM to (left-over) baryon ratio



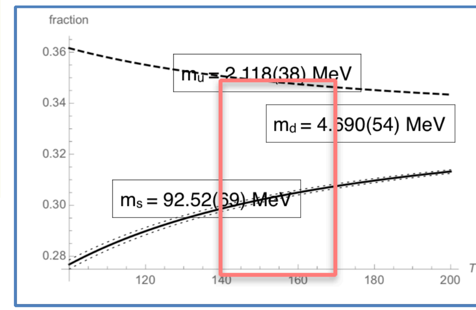


- ***Hypothesis: DM has u,d,s in equal numbers***
  (sexaquark DM, strange quark nuggets (Witten,1984))





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



- *y_b ≡ DM mass/m_p (≈ 2)*
- *f_s ≡ 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, from hyperon and S masses)*

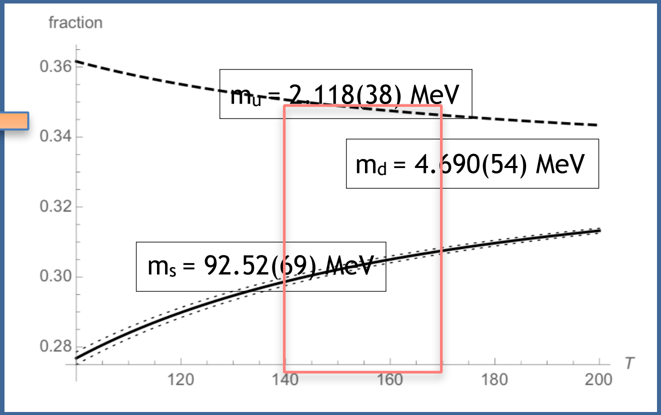
$$\kappa_s(m_S, T) = \frac{1}{1 + (r_{\Lambda,\Lambda} + r_{\Lambda,\Sigma} + 2r_{\Sigma,\Sigma} + 2r_{N,\Xi})} \qquad \boxed{r_{1,2} \equiv \exp[-(m_1{+}m_2{-}m_S)/T]}$$

Correct relic density - no free parameters!

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

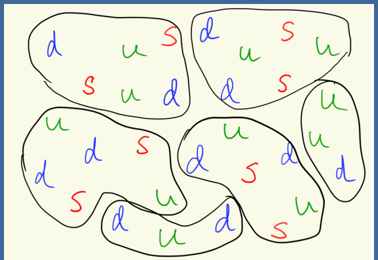
$m_S/(2m_p)$

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



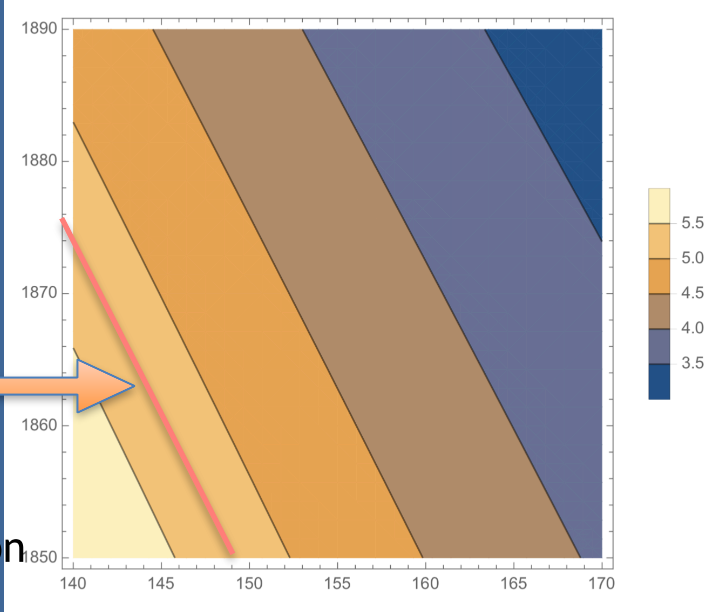
$$\kappa_s(m_S, T) = \frac{1}{1 + (r_{\Lambda,\Lambda} + r_{\Lambda,\Sigma} + 2r_{\Sigma,\Sigma} + 2r_{N,\Xi})}$$

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



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

Ω_{DM} / Ω_b (pred) = 4.5 ± 1



Ω_{DM} / Ω_b (obs) = 5.3 ± 0.1

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

Non-Perturbative DM-hadron Interactions

(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

- v/c (DM) <~ 10^{-3} 10^3 km/s (galaxy clusters), 300 km/s BBN & MW, … 1 km/s (atm & z = 17)
  - must solve Schroedinger Eqn. **Born approximation generically fails badly**
  - point source cross section depends only on combos

$$a = \frac{v}{2\alpha} \text{ and } b = \frac{2\alpha\mu}{m_\phi}$$

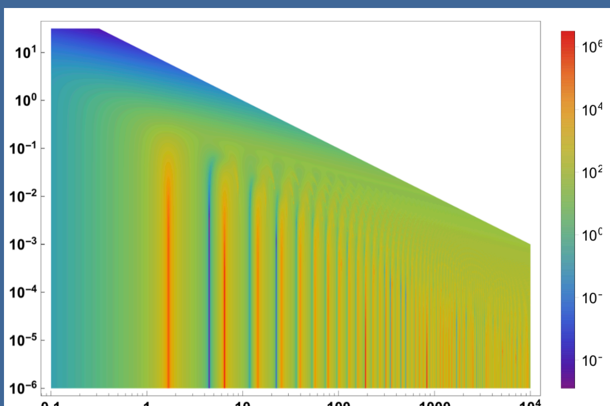


FIG. 1: $\sigma\, m_\phi^2$ as a function of $a = \frac{v}{2\alpha}$ and $b = \frac{2\alpha\mu}{m_\phi}$.

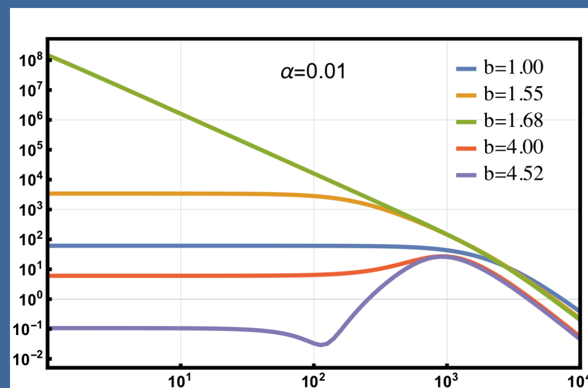


FIG. 4: $\sigma\, m_\phi^2$ versus v in km/s, for 5 values of $b = \frac{2\alpha\mu}{m_\phi}$.

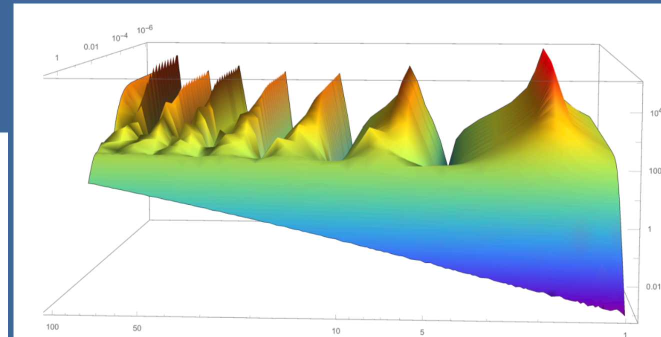


FIG. 2: 3D plot of $\sigma\, m_\phi^2$ in the a, b plane; b increases to the left and a decreases toward the back.

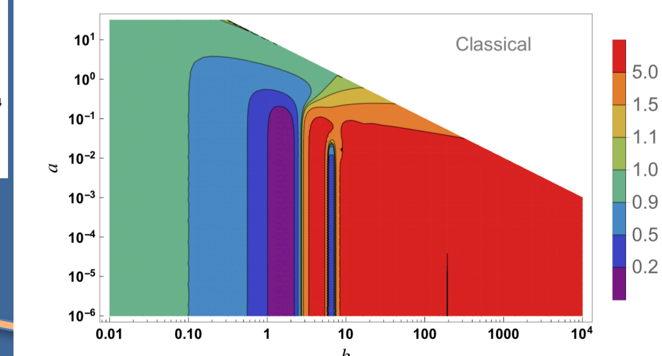


FIG. 3: Ratio of Born Approximation and Schroedinger Equation

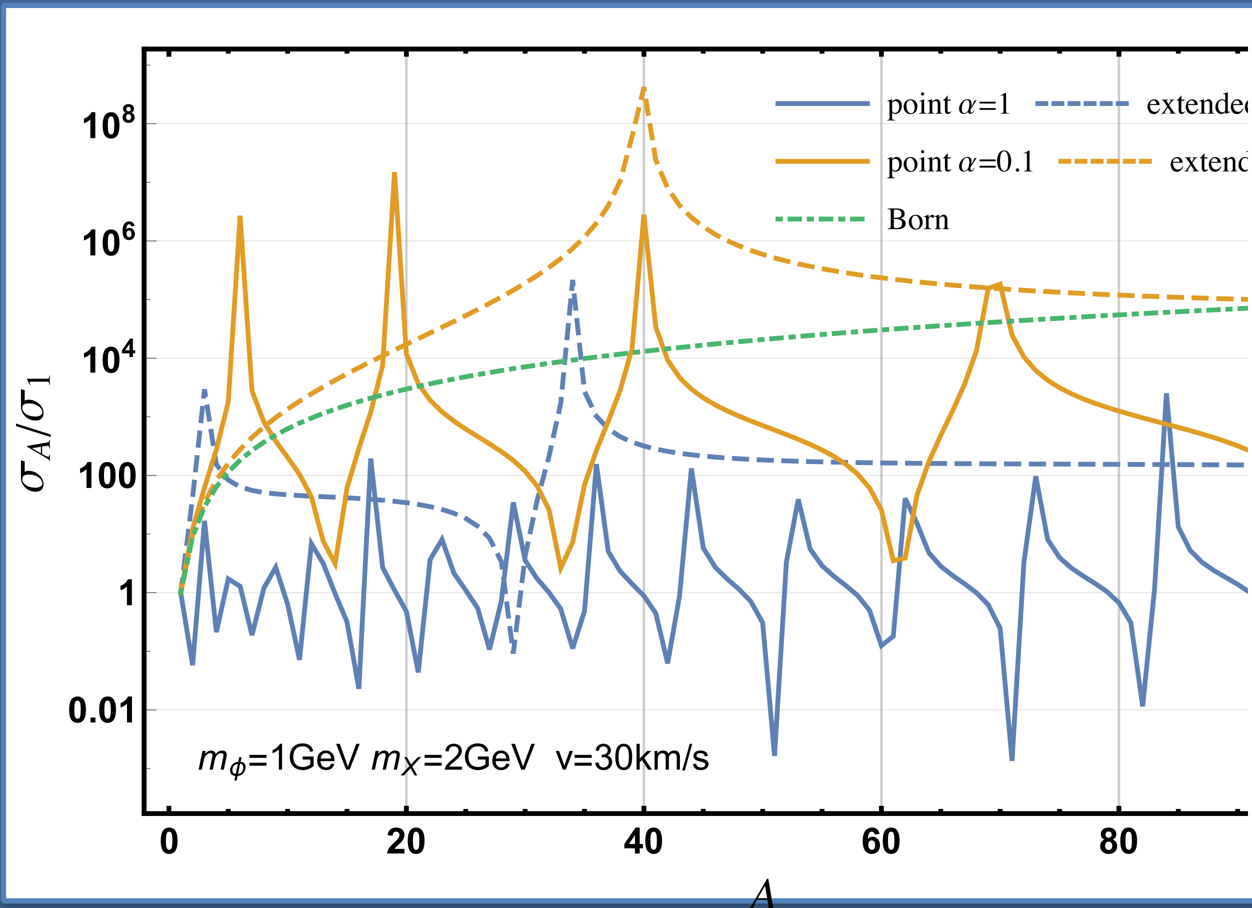
Non-Perturbative DM-baryon Interactions

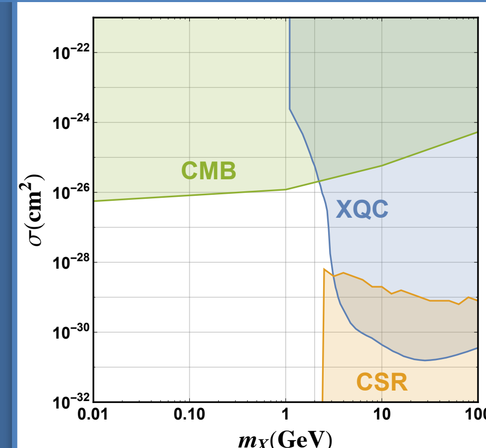
(Xingchen Xu & GRF, to appear shortly)

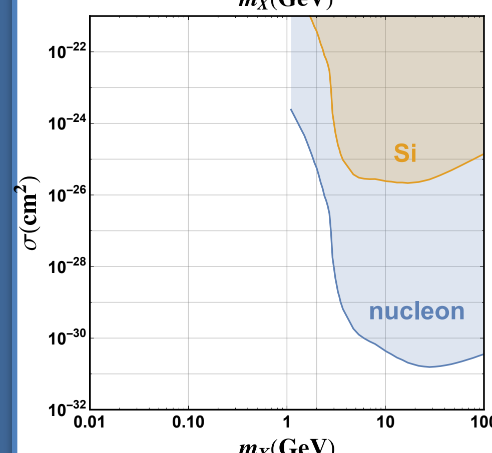
$$V(r) = \frac{\alpha}{r}\, e^{-r\, m_\phi}$$

- Must solve Schroedinger Eqn
- Born approximation fails by orders of magnitude.
- A-dependence of cross section sensitive to nuclear size.

std. form factor & Born approx relation $\sigma_A \Leftrightarrow \sigma_p$ are wrong. Analyses must be redone

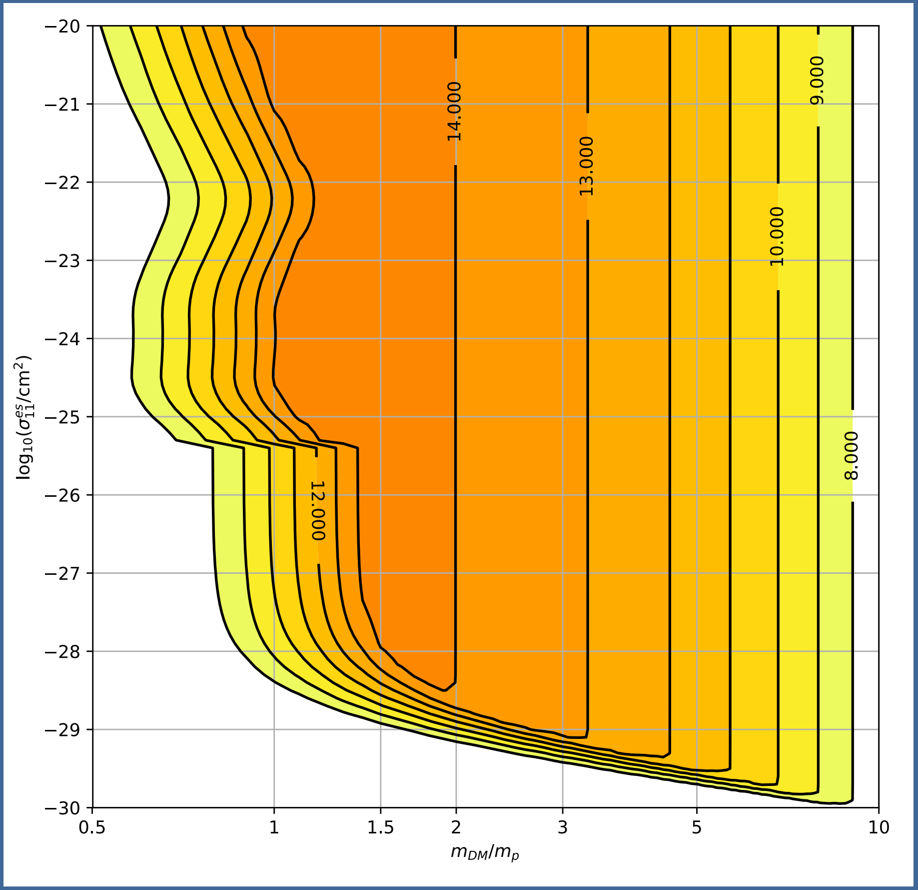




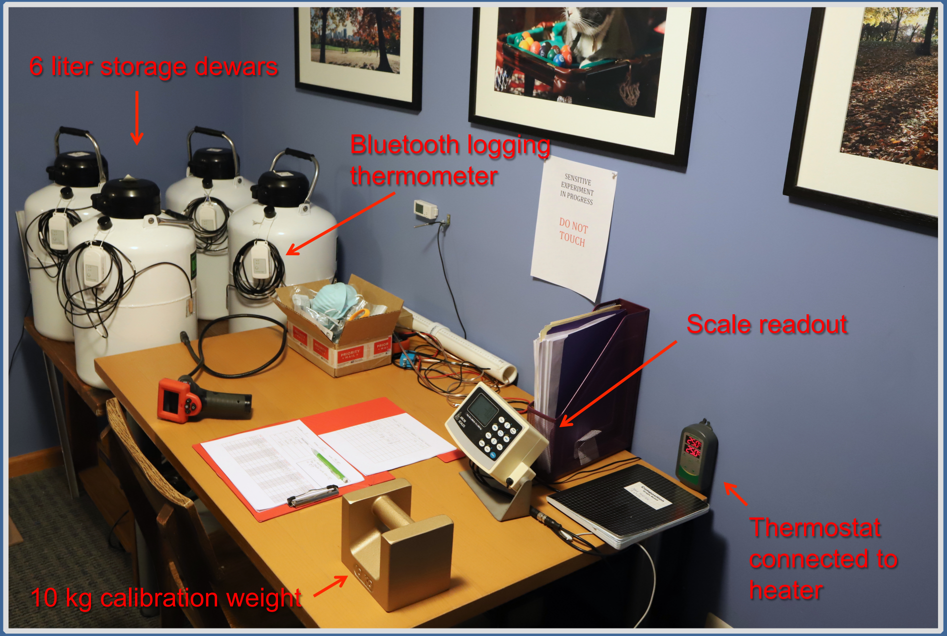


DM capture by Earth [⇒] DM atmosphere dewar & HST drag constraints

Neufeld, GRF, McKee, ApJ 2018



Neufeld, Branch-Neufeld, ApJ 2019



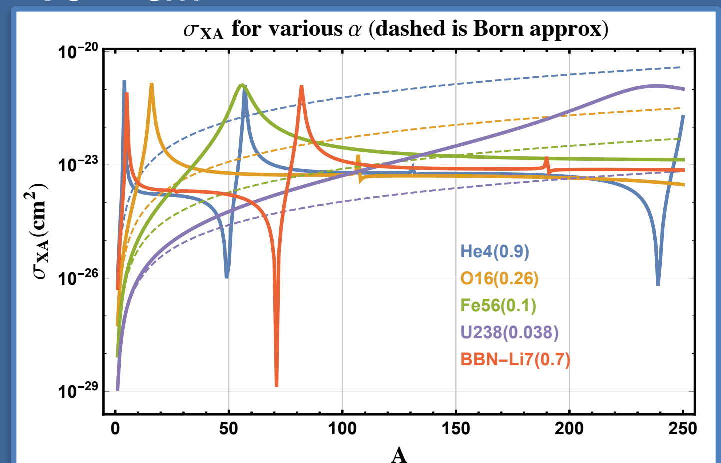
strong constraints, if DM forms atmosphere

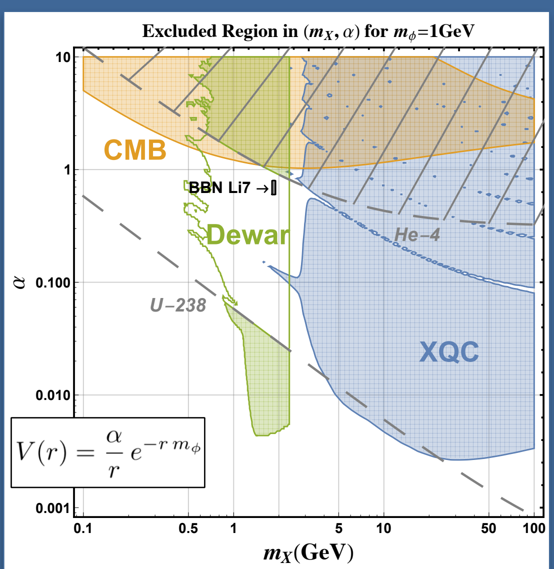
Dark Matter-Nucleus Hybridization

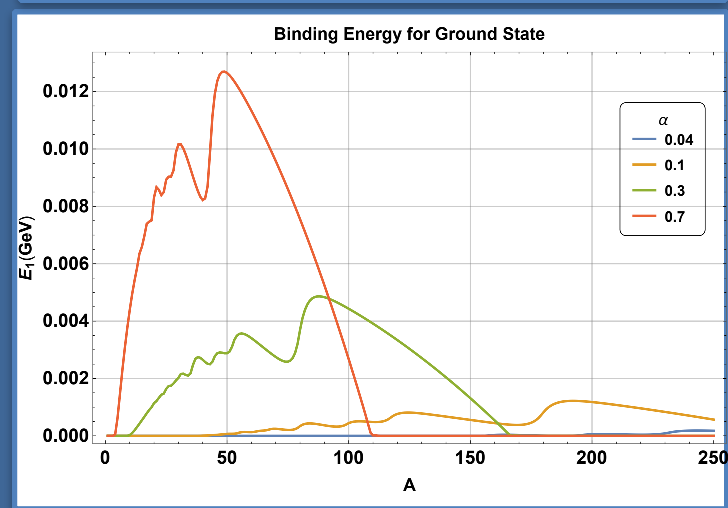
(GRF + Xingchen Xu, in prep)

- For $A > A_{res}(\alpha)$, DM-nucleus potential has bound state A_S .
- $S + A \rightarrow A^*_S \rightarrow A_S + \gamma$ like $n\, p \rightarrow d\, \gamma$ and other neutron capture
- $\lambda_{hyb} = (n_A\, \sigma_{hyb})^{-1}$ $\sigma_{hyb} = \kappa\, \sigma_{scat}$; $n_O \approx 10^{23}\ cm^{-3}$
- from neutron capture, $\kappa \approx 10^{-4}$ $\Rightarrow$

  $\lambda_{hyb} \approx 10\ m\ (10^{-4}/\kappa)\ (10^{-23}/\sigma)\ (n_O\,/n_A)$
- no DM atmosphere!
- exotic isotopes ≈ ppb



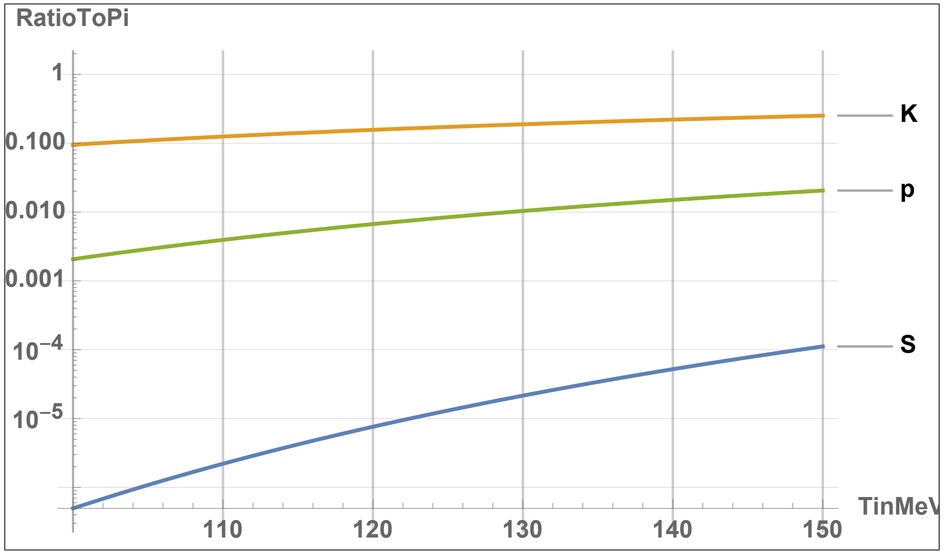




Sexaquark Discovery Strategy

- 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.*
- Reconstruct missing mass, e.g.:
  - **Υ -> Λ Λ $\bar{S}$** (+ 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 peak*
  - LHC: $\bar{S}$ + N -> $\bar{\Lambda}$ $K^+ \ldots$ $M_S^2 = (p_{\bar{\Lambda}} + p_{K^+ \ldots} - p_N)^2$
    - *compromise: potentially a sweet spot (tbd)*
- Time-of-flight => distinguish from neutron (SHiP?)
- Second exponential in interaction length
- "Missing energy" in heavy ion collisions
- Snolab nuclei: d -> S $e^+ \nu$ $\sin\theta_C^4$ x GIM suppression x G_F^4 , $\tau > 10^{+29}$ yr ($m_S <$ ~1875 MeV)

$S,\bar{S}$ from cooling fireball at LHC?

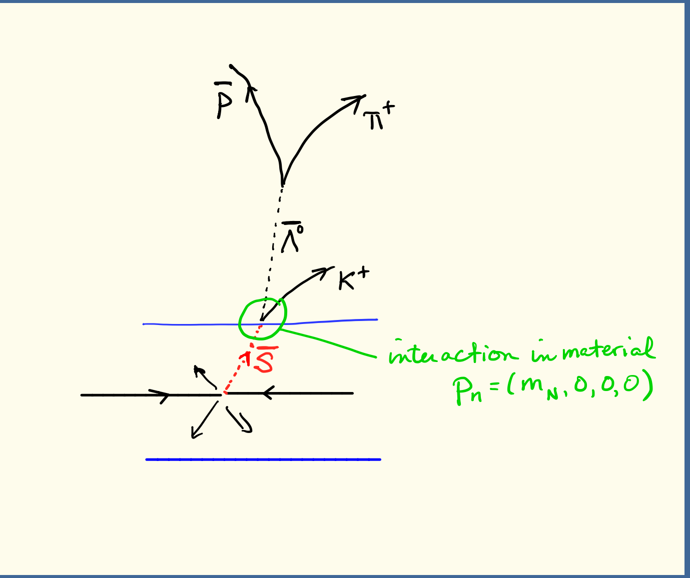


- Fantasy: perfect equilibration ➜ $N_S/N_B = 2.5$ net excess S's ☺
- Reality (?):
  - no B excess in central region ➜ no S excess over $\bar{S}$
  - $S,\bar{S}$ annihilate to maintain equilibrium, till freeze out ➜
  - $N_{S+\bar{S}} \approx 10^{-4} N_\pi$ ➜ $E_{S miss} \approx 10^{-4} (M_S/E_\pi) E_{\pi tot}$ … 1 ppm missing E ☹
- Can a *statistical* correlation be established between missing

  $B = \pm 2$ & missing $S = \mp 2$? (question of ID systematics)

LHC I.

- Statistical examination of correlation $\Delta B = \pm 2, \Delta S = \mp 2$
- 2nd exponential in scattering-length distribution of n-like interactions, due to S?
- *Distinctive needle in a haystack*
  (~few x 10^{11} events have been recorded!)

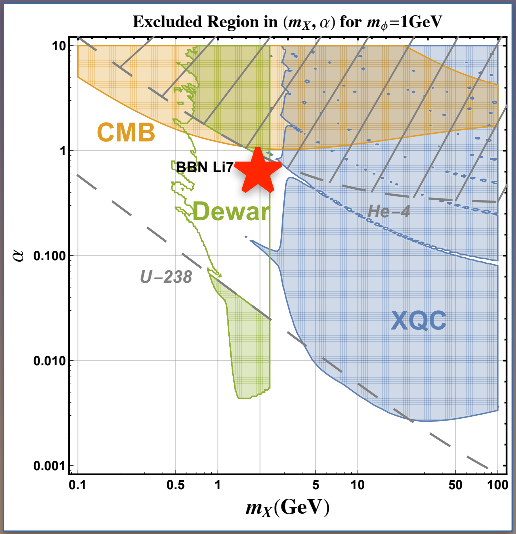


In sum…

- ***There may a tightly bound 6-quark state*** **S= uuddss**
    - **Unique, symmetric structure ⇒ other hadrons don't provide guidance**
        - Mass is not driven by chiral symmetry breaking (unlike baryons)
        - Most Attractive Channel ⇒ deepest binding
    - ***S can naturally be absolutely or effectively stable***
- ***If S is stable, it is an excellent Dark Matter candidate***
    - **No-parameter derivation of correct Dark Matter to baryon ratio**
    - **S-Be hybridization can produce exotic isotopes**

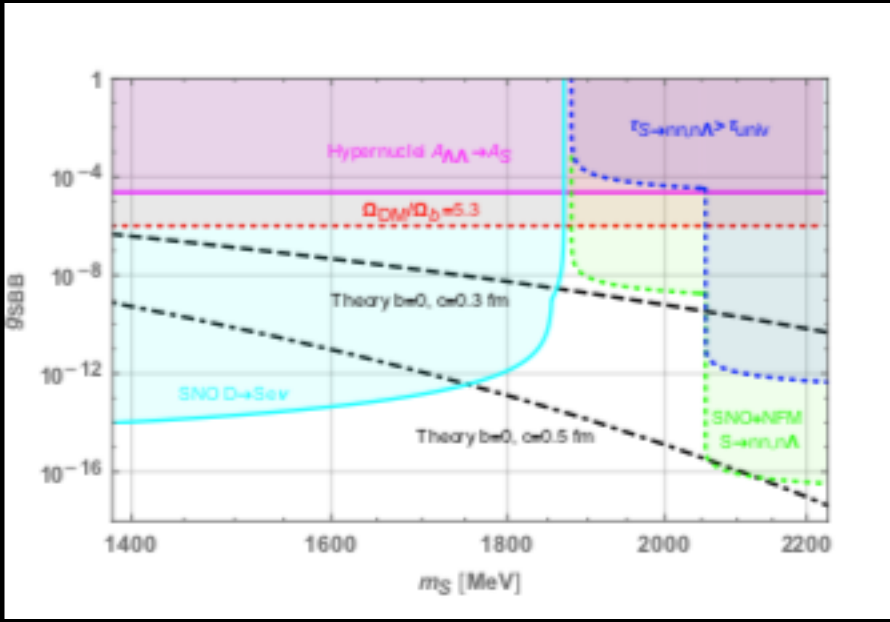
Follow-up

- ~~Search for ≈^{9}Be in Spite Plateau stars~~
- ~~Weaker Katchri-Sunyaev neutrino lines from Be→Li~~ ;-)
- Search for exotic isotopes with $\Delta m \sim +2\ m_p$ at ppb (10^{-9}) level
- Extend sensitivity of DM direct detection to lower mass
- Accelerator searches



G. R. Farrar

Backup Slides



Υ -> $\Lambda\,\Lambda\,\bar{S}$ & $\bar{\Lambda}\,\bar{\Lambda}\,S$

High Energy Physics – Experiment

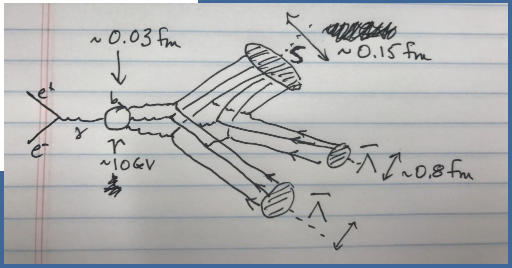
Search for a Stable Six-Quark State at BABAR

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[Υ(2S,3S) -> $\Lambda\,\Lambda\,\bar{S}$ + $\bar{\Lambda}\,\bar{\Lambda}\,S$] < *1.4 x 10^{-7}*
  - 2 x 10^8 events; main backgrounds Υ(2S,3S) -> $\Lambda\,\Lambda\,\bar{\Lambda}\,\bar{\Lambda}$ + X & noise in E-cal
- Predicted ***inclusive*** BF [Υ(ggg) -> ($\bar{S}$ 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 ; $(1/2)^5$

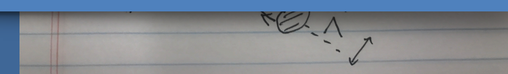
  Exclusive Penalty:
  - start with biggest exclusive 3-body channel: BF[Υ(2S,3S) -> ϕ K K] = 2 x 10^{-6}
  - penalty of S+$\bar{S}$ relative to ϕ : 6 x 10^{-5}
- Predict Exclusive BF [Υ(ggg) -> $\Lambda\,\Lambda\,\bar{S}$ + $\bar{\Lambda}\,\bar{\Lambda}\,S$] ~ *10^{-11}*

Υ -> $\Lambda \Lambda \bar{S}$ & $\bar{\Lambda} \bar{\Lambda} S$

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



- BaBar: ***exclusive*** BF[$\Upsilon(2S,3S)$ -> $\Lambda \Lambda \bar{S}$ + $\bar{\Lambda} \bar{\Lambda} S$] < *1.4×10^{-7}*
  - 2×10^{8} events; main backgrounds $\Upsilon(2S,3S)$ -> $\Lambda \Lambda \bar{\Lambda} \bar{\Lambda}$ + X & noise in E-cal
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LHC beam lifetime

- DM capture by Earth => DM atmosphere

Neufeld, GRF, McKee, ApJ2018

$\sigma_{DMp,\ inel} <\sim 10^{-30}\ cm^2$

$E_{lab} = 6.5$ TeV; $m_S \sim 2\ m_p$

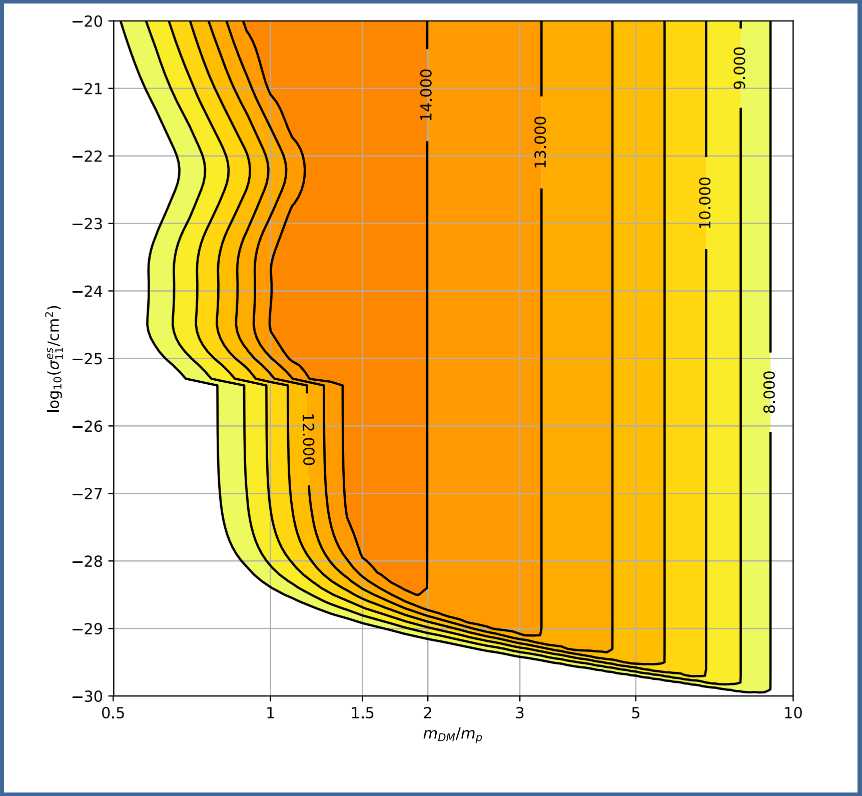


Fig. 6.— Number density of HIDM at the Earth's surface, $n_{DM}(R_\oplus)$, in the $m_{DM} - \sigma_{11}^{es}$ plane. Contours are labeled by $\log_{10}(n_{DM}/cm^{-3})$.

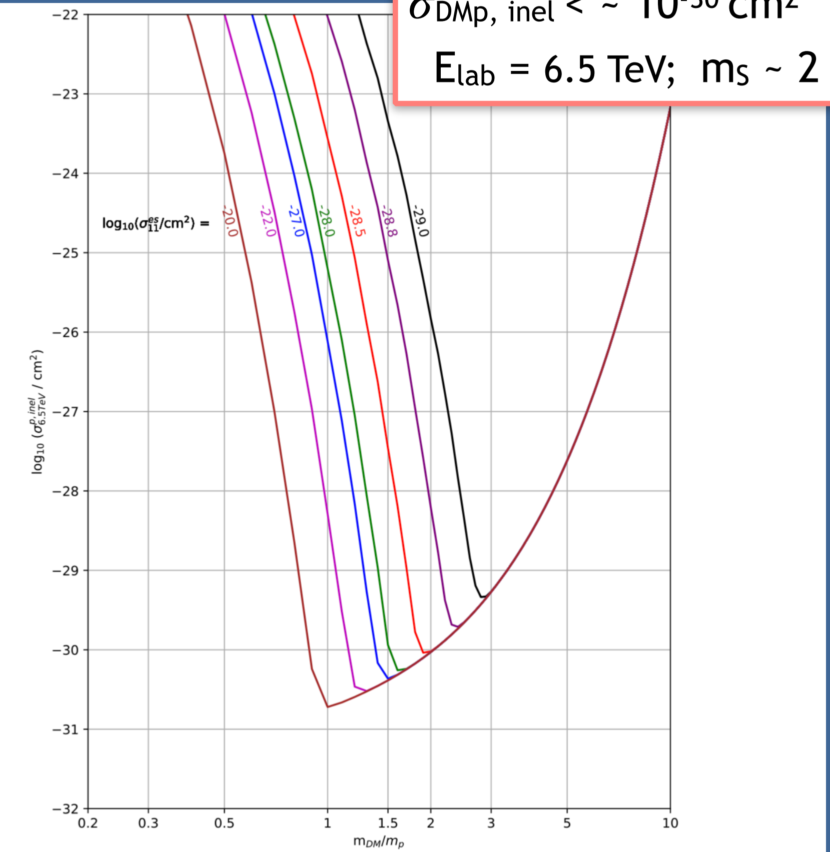
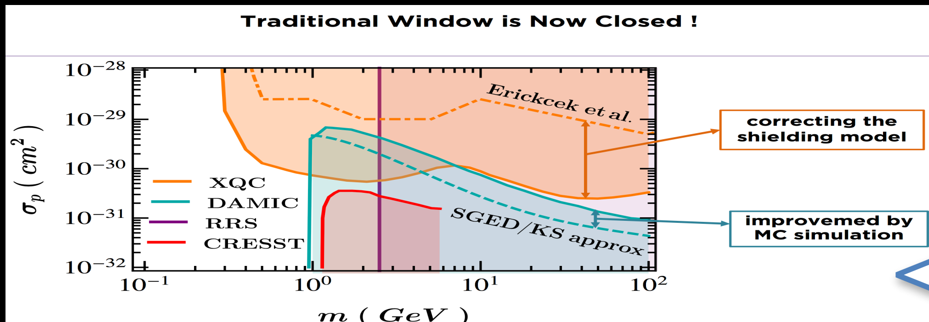


Fig. 7.— Upper limits on $\sigma_{6.5\,TeV}^{p,inel}$ implied by an LHC beam lifetime of 100 hr. Results are shown for five values of σ_{11}^{es} for which the LSS lies in the crust ($10^{-29.0}$, $10^{-28.8}$, $10^{-28.5}$, 10^{-28}, and 10^{-27} cm^2), and two values for which the LSS lies in the atmosphere (10^{-22} and 10^{-20} cm^2). The curves are labeled with $\log_{10}(\sigma_{11}^{es})$.

Stable S as Dark Matter

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



If Born Approximation good & XQC efficiency is perfect

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

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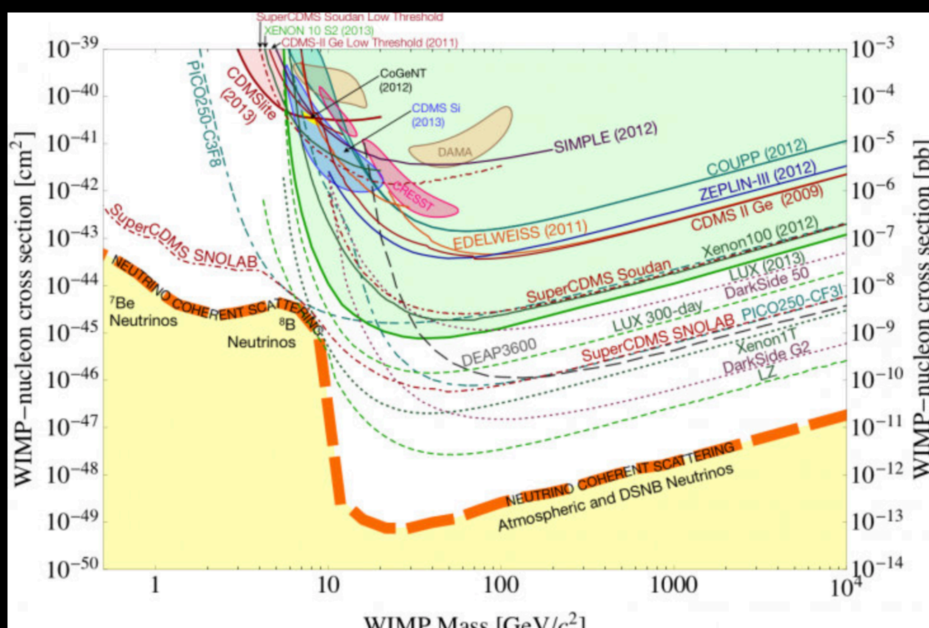
Abstract. We improve limits on the spin-independent scattering cross section of Dark Matter on nucleons, for DM in the 300 MeV – 100 GeV mass range, based on the DAMIC and XQC experiments. Our results close the window which previously existed in this mass range, for a DM-nucleon cross section of order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

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



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: $\sigma <\sim 10$ 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 (fro