Stable Sexaquark as Dark Matter

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Stable Sexaquark and other uds Dark Matter

How could we have missed a stable particle made of quarks?

[Hints from Astrophysics]
[Primordial Nucleosynthesis]
Dark-Matter to Ordinary-Matter ratio
[Detecting S dark matter]
Discovering a stable sexaquark in the lab
Unique among multi-quark states:

Fermi statistics is compatible with a \textit{totally symmetric} spatial wave function AND

antisymmetric (singlet) in:
- color
- flavor
- spin

totally symmetric in space

(Most-Attractive Channel)\textsuperscript{3}:

6-quark, \( Q=0, B=2 \)
- \textit{Spin-0, scalar}
- \textit{Flavor singlet}
- \( m_S < 2 \text{ GeV} \)

Same quark content as H-dibaryon\textsuperscript{*} (Jaffe 1977), but different physics: \textbf{not a loosely bound di-\( \Lambda \)!}

\textsuperscript{*}mass ~ 2150 MeV in bag model — decays in \( 10^{-10} \) s
Why consider $m_S \sim 2 m_p$?

$(2 m_p = 1.876 \text{ GeV})$

- Light quarks almost massless, i.e. relativistic
  - $m_{u,d} \approx 0, m_s = 91 \text{ MeV}$
- $S$ has same QNs as ground state glueball
  - why not $m_S \approx m_{\text{glueball}} + 180 \text{ MeV} = (1.5-1.7) + 0.18 \text{ GeV} \approx 2 m_p$
- $3 \times \text{di-quark mass} = 1.2 - 2 \text{ GeV}$

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- $m_S < 2 (m_p + m_e): S$ is absolutely stable
- $m_S > 2 (m_p - 8 \text{ MeV}): \text{nuclei are stable}$

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- triple-singlet (color,flavor,spin): MAC, lattice, almost all models $\Rightarrow m_S < 2 \Lambda$
- extensive experimental searches exclude weak-lifetime & $m > 2 \text{ GeV}$

$\Rightarrow$ bound state exists and mass $< 2 \text{ GeV}$ (τ > τ_{Univ} or stable)
Stable Sexaquark Hypothesis

Stable Sexaquark Hypothesis

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

|----|------------|----|-----------|-----------|---------|---------------------------------------|---------|-------|

**Crucial fact:**

S does not couple to pions => much smaller than usual hadrons => hard to produce with hadrons

6-quark, Q=0, B=2

**Spin-0, scalar**

**Flavor singlet**

m ~ 1.7-2 GeV

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

G. R. Farrar, LHC-LLP, Oct. 24, 2018
Stable S?

- $\tau > \tau_{\text{Univ}}$
  - $M_S < 2m_p + 2m_e = 1877.6 \text{ MeV} \Rightarrow$ absolutely stable
  - $M_S > 2m_p + 2\text{BE} = 1860 \text{ MeV} \Rightarrow$ nuclei absolutely stable
  - higher and lower mass may also work $\Gamma \sim G_F^4 \times (\text{wave function overlap})^2$

- Lattice predicts binding (Beane+13)
  - $(m_q = 850 \text{ MeV} \text{ so not realistic})$
  - 80 MeV binding

- Experiments exclude decaying S
  \[ \Rightarrow \text{ it must be STABLE ! } \quad ;-) \]
Conditions on QCD Dark Matter

✓ $\tau_{DM} > \tau_{Univ}$, cold, neutral
✓ primordial nucleosynthesis
✓ Particle must not be already excluded
  – accelerator searches
  – exotic isotopes
  – DM searches
  – indirect impacts (heating planets, helioseismology,…)
  – stability of nuclei
  – equation of state of neutron stars (and their stability)
✓ Correct relic density (for natural DM mass & size)
S has not 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 required for S ⇔ ΛΛ; S ⇔ NN is GF^4 smaller & GIM suppressed=>
  - g_{eff,SBB} ≈ 10^{-6} (r_S / 0.2)^10
  - nuclei can be stable (τ > 10^{29} yr) even for m_S > 2 m_p
  - hard to produce in fixed target experiments

*apart from BaBar

G. R. Farrar, LHC-LLP, Oct. 24, 2018
Parenthesis:
Relic Abundance of *uds* Dark Matter

Stat Mech + quark masses, $T_{QCD} \approx 150$ MeV $\Rightarrow \Omega_{SDM}/\Omega_b = 4.5 \pm 1$

**CORRECT udsDM RELIC DENSITY!** $\Omega_{DM}/\Omega_b = 5.3 \pm 0.1$

After hadronization: S excess is out-of-equilibrium abundance preserved if S’s don’t disintegrate, e.g., via $K^+ S \rightarrow \Sigma + \Lambda$

requires $g_{eff,SBB} < 2 \times 10^{-6}$

With $r_S \approx 0.2$ fm, $g_{eff,SBB}$ effective coupling is $\approx 10^{-6} (r_S/0.2)^{10} \Rightarrow S$ DOES NOT BREAKUP

Dibaryons cannot be the dark matter

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(Accepted: September 18, 2018)
Experimental searches so far

Looking for Jaffe’s H-dibaryon (same QN but assumed to be unstable and r~1 fm)

- 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 $\text{pp} \to \text{K K X}$

- 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: $\text{H} \to \Lambda n$ or $\Sigma n$ [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

G. R. Farrar, LHC-LLP, Oct. 24, 2018
Experimental Searches

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  - Kim+ Belle 2013: No narrow resonance in \(\Xi^0 -> \Lambda + K^+\)

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**Search for the Weak Decay of an H Dibaryon**


- Brookhaven National Laboratory, Upton, New York 11973

- We have searched for a neutral H dibaryon decaying via \(H \rightarrow \Lambda + H\) and \(H \rightarrow \Sigma^0\). Our search yielded two candidate events from which we set a limit on the H production cross section. Normalizing to the inclusive A production cross section, we find at a mass of \(2.5 \text{ GeV}/c^2\), \(\sigma_{H \rightarrow \Lambda + H} \times \sigma_{H \rightarrow \Sigma^0} < 2 \times 10^{-6}\) at 90 C.L.

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**Production of \(\Xi^0\) Hypernuclei**


- Brookhaven National Laboratory, Upton, New York 11973

- We have investigated the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 GeV. Using the PHENIX detector, we have measured the production of \(\Xi^0\) hypernuclei in \(p+p\) collisions at 200 Gev.
Sexaquark Discovery Strategy

- Apparent lack of B and S conservation:
  - missing $B = \pm 2$ + missing $S = \mp 2$
    - inclusive: maximizes event rate, hermetic detector; ID!

- Reconstruct missing mass, e.g.:
  - $\gamma \rightarrow \Lambda \Lambda \bar{S}$ (+ pions)  \[ M_{S^2} = (p_\gamma - p_{\Lambda 1} - p_{\Lambda 2} - \Sigma p_{\pi})^2 \]
    - exclusive: big penalty in statistics, but gain from mass peak

- LHC: \[ \bar{S} + N \rightarrow \bar{\Lambda} K^+ \cdots \quad M_{S^2} = (p_{\bar{\Lambda}} + p_K - p_N)^2 \]
  - compromise: potentially a sweet spot (tbd)

- Snolab nuclei: \[ p_n \rightarrow S e^+ \nu \quad G_F^4, \quad \tau > 10^{+29} \text{ yr} \quad (m_S < \sim 1875 \text{ MeV}) \]
\[ \Upsilon \rightarrow \Lambda \Lambda \bar{S} \text{ & } \bar{\Lambda} \bar{\Lambda} \bar{S} \]

\[ (+ \text{ pions}) \]

- \( \Upsilon \) is localized source of ggg
  \( \Rightarrow \) production of \( S \) is (relatively) enhanced

- Many \( \times 10^8 \) events collected (CLEO, BaBar, Belle)
  - detectors pretty hermetic, have good mass resolution, \( \mathcal{O}(10 \text{ MeV}) \)
  - \( \Lambda \) decays quickly to \( p \pi^- \) so easy to ID. \( c\tau = 8 \text{ cm} \)

- Can MEASURE \( m_S \) via missing mass in exclusive events
- Very clean
  - Main bkg is \( K_S K_S K_L K_L \) (+ pions)
    - \( K_S \)'s mis-ID'd as \( \Lambda \)'s and \( K_L \)'s escaping before decay: negligible for Belle
    - rare and can model accurately
    - \( K_S K_S K_L K_L \) (+ pions) is measurable, from \( K^+ K^+ K^- K^- \) (+ pions)

  - “Conspiracy” of missed particles producing \( \Delta B = \pm 2, \Delta S = \mp 2 \) very hard

**Background does not have narrow peak in missing mass!**

G. R. Farrar, LHC-LLP, Oct. 24, 2018
BaBar: exclusive $\text{BF} \left[ \Upsilon(2S,3S) \rightarrow \Lambda \Lambda \bar{S} + \bar{\Lambda} \bar{\Lambda} S \right] < 1.4 \times 10^{-7}$
- 2 x $10^8$ events; main backgrounds $\Upsilon(2S,3S) \rightarrow \Lambda \Lambda \bar{\Lambda} \bar{\Lambda} + X$ & noise in E-cal

Predicted inclusive $\text{BF} \left[ \Upsilon(3S) \rightarrow (\bar{S} \text{ or } S + X ) \right] \sim 2.7 \times 10^{-7}$ (GRF arXiv:1708.08951)
- SU(18) (color-flavor-spin) singlet: $5.4 \times 10^{-4}$; $\alpha_s^3$; $(1/2)^5$

Exclusive Penalty:
- start with biggest exclusive 3-body channel: $\text{BF} \left[ \Upsilon(2S,3S) \rightarrow \phi K K \right] = 2 \times 10^{-6}$
- penalty of S+\bar{S} relative to $\phi$: $6 \times 10^{-5}$

Predict Exclusive $\text{BF} \left[ \Upsilon(3S) \rightarrow \Lambda \Lambda \bar{S} + \bar{\Lambda} \bar{\Lambda} S \right] \sim 10^{-11}$
BaBar exclusive limit is a factor $10^4$ from being constraining — need inclusive or semi-inclusive

- **BaBar:** *exclusive* BF\[ \Upsilon(2S,3S) \rightarrow \Lambda \Lambda \bar{S} + \bar{\Lambda} \bar{\Lambda} S \] < $1.4 \times 10^{-7}$
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- **Predict Exclusive BF** [\( \Upsilon(ggg) \rightarrow \Lambda \Lambda \bar{S} + \bar{\Lambda} \bar{\Lambda} S \)] \( \sim 10^{-11} \)
LHC I.

- Low production rate \((uuddss \text{ in small vol}; \text{SU}(18) \text{ singlet})\)
- Statistical examination of correlation \(\Delta B = \pm 2, \Delta S = \mp 2\)
- **Distinctive needle in a haystack** \((\sim 10^{11} \text{ recorded events})\)

- 2nd exponential in scattering-length distribution of n-like interactions, due to S
LHC II.

- Low production rate \((uuddss \text{ in small vol} \Rightarrow )\)
  - \(g_{\text{eff, SBB}} \approx 10^{-6} (r_S / 0.2)^{10}\)
  - \(\sim 100\) particles in central tracker/event \(\times N_{11} 10^{11}\)
  - \(\sim 10\) events (worst case, hopefully, since overlap may be enhanced at larger momentum)

- Statistical examination of correlation \(\Delta B = \pm 2, \Delta S = \mp 2\) ???

- Heavy ion collisions produce more particles — feasible to reconstruct ???

- **Find a distinctive needle in a haystack** (~\(10^{11}\) recorded events)?
  - ★ \(\bar{\Sigma}\) annihilation in tracker, tag by \(\bar{\Lambda} K^+\) pointing to tracker or \(\Xi^{+,0} \rightarrow \bar{\Lambda} \pi^{+,0}, \bar{\Lambda} \rightarrow \bar{p} \pi^+\)

Rate estimate: (GRF arXiv:1708.08951)

\(\bar{\Sigma}\) Production:

- 30 charged particles with pseudo-rapidity |\(\eta| < 2.4\); \(N\) events = \(N_{11} 10^{11}\)
- \(f_{-4}^{\text{prod}} 10^{-4}\) is the \(\bar{\Sigma}\) production rate relative to all charged particles
- \(\Rightarrow N_{\bar{\Sigma}} \approx 3 f_{-4} N_{11} 10^8\)

\(\bar{\Sigma}\) Annihilation:

\[
\sigma_{SN} \equiv f_{-6}^{\text{annih}} 10^{-6} \sigma_{NN}
\]

- 2nd exponential in scattering-length distribution of n-like interactions, due to S

\[N_{\Xi, \bar{\Lambda}} = f_{-4}^{\text{prod}} f_{-6}^{\text{annih}} f_{\Xi, \bar{\Lambda}} N_{11} 10^{5}\]

May be optimistic, depending on \(g_{\text{eff, SBB}}\) for LHC.
LHC III.

- LHCb
- ALICE
- ...

Please contact me if interested…
Key points to take home

• **There may a tightly bound 6-quark state** $S=\text{uuddss}$
  - Unique, symmetric structure $\Rightarrow$ other hadrons don’t provide guidance
    - mass is not driven by chiral symmetry breaking (unlike baryons)
    - constituent quark model probably completely misleading
  - If $M_S < 2m_p + 2m_e$, $S$ is absolutely stable

• **If $S$ is stable, its an excellent Dark Matter candidate**
  - Relic abundance is natural. EXPLAINS Dark Matter to baryon ratio; can explain 7Li Discrepancy in BBN
  - Usual WIMP detection strategy isn’t applicable.

• **$S$ may be waiting to be discovered in existing $\gamma$-decays or LHC experiments…**
  mass can be accurately measured in $\gamma$-decay exclusive final states.

• **SDM will be challenging to detect, but not impossible.** Astrophysical and cosmological effects may allow it to be constrained, excluded or confirmed.
Backup Slides
Relic Abundance of \textit{uds} Dark Matter

Stat Mech + quark masses, $T_{QCD} \approx 150$ MeV $\Rightarrow \Omega_{SDM} / \Omega_b = 4.5 \pm 1$

\textbf{CORRECT udsDM RELIC DENSITY!} $\Omega_{DM} / \Omega_b = 5.3 \pm 0.1$

After hadronization: S excess is out-of-equilibrium abundance preserved if S’s don’t disintegrate, e.g., via $K^+ S \rightarrow \Sigma + \Lambda$

requires $g_{\text{effSBB}} < 2 \times 10^{-6}$

With $r_S \approx 0.2$ fm, $g_{\text{effSBB}}$ effective coupling is $\approx 10^{-6} (r_S / 0.2)^{10}$
Quark-Gluon Plasma $\Rightarrow$ Hadrons $\approx$ 150 MeV

- **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, $p,\bar{p},...;$ $<q\bar{q}>$ & $<GG>$ condensates
  - Abundance relative to photons (for species in equilibrium):

- **Baryogenesis** $\Rightarrow$
\[
\eta_{\text{tot}} = \eta \left(1 + \frac{\Omega_{DM}}{y_b \Omega_b}\right) \approx 4.1 \times 10^{-9}
\]

- $u,d,s$ ratio from q masses
  - $m_u = 2.118(38)$ MeV
  - $m_d = 4.690(54)$ MeV
  - $m_s = 92.52(69)$ MeV

G. R. Farrar, LHC-LLP, Oct. 24, 2018
• Hypothesis: DM has u,d,s in equal numbers
  - sexaquark DM, strange quark nuggets (Witten, 1984)

\[
\frac{\Omega_{DM}}{\Omega_b} = \frac{y_b \kappa_s 3 f_s}{1 - \kappa_s 3 f_s}
\]

- \(y_b = \text{DM mass/m}_p\) (mass per unit baryon number)
- \(f_s = \text{fraction of quarks that are s}\)
- \(3 f_s\) is number uds per unit baryon # — ranges from 0.964 to 0.948 as \(T\) decreases from 160 MeV to 140 MeV.
- \(\kappa_s\) is efficiency of uds \(\rightarrow\) DM (Boltzmann, from hyperon and S masses)

\[
\kappa_s(m_S, T) = \frac{1}{1 + (r_{\Lambda, \Lambda} + r_{\Lambda, \Sigma} + 2 r_{\Sigma, \Sigma} + 2 r_{N, \Xi})} \\
r_{1,2} \equiv \exp[-(m_1 + m_2 - m_S)/T]
\]
$\Omega_{DM} / \Omega_b$ follows from statistical mechanics, quark masses, and temperature of QGP-hadronization transition.

$$\frac{\Omega_{DM}}{\Omega_b} = \frac{m_S/(2m_p)}{1 - \kappa_S 3f_S}$$

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

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

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

$$\Omega_{DM} / \Omega_b = 5.3 \pm 0.1$$

Prediction also applies to strange quark nuggets.

G. R. Farrar, LHC-LLP, Oct. 24, 2018
Stable S as Dark Matter

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 $\sim \mu b$, assuming the standard velocity distribution.

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

Closing the window on $\sim$GeV Dark Matter with moderate ($\sim \mu b$) interaction with nucleons

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Dark Matter with Hadronic Interactions

(GRF + Xingchen Xu, to appear shortly)

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

\( m_\phi = 1 \text{ GeV} \) (flavor-singlet \( \omega-\varphi \) combo), sourced by \( p \) or \( A \)

- \( v/c \) (DM) \( \sim 10^{-3} \)
  - \( 10^3 \text{ km/s} \) (galaxy clusters) down to 1 km/s (atm & \( z = 17 \))
  - must solve Schroedinger Eqn. \textbf{Born approximation generically fails badly}
  - cross section depends only on combos

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

\[ \begin{array}{c}
\text{FIG. 1: } \sigma m_\phi^2 \text{ as a function of } a = \frac{v}{2\alpha} \text{ and } b = \frac{2\alpha \mu}{m_\phi} . \\
\text{FIG. 3: Ratio of Born Approximation and Schroedinger Equation} \\
\text{FIG. 2: 3D plot of } \sigma m_\phi^2 \text{ in the } a, b \text{ plane; } b \text{ increases to the left and } a \text{ decreases toward the back.} \\
\text{FIG. 4: } \sigma m_\phi^2 \text{ versus } v \text{ in km/s, for 5 values of } b = \frac{2\alpha \mu}{m_\phi} .
\end{array} \]
Plenty of Room for SDM, for now…

(GrF + Xingchen Xu, to appear shortly)


\[
\alpha = \frac{\sigma}{\sigma_\text{Born}}
\]

Allowed regions of coupling from XQC (best Direct Detection)

FIG. 7: Allowed regions (blue) in the coupling-DM mass plane $\alpha$ (vertical axis) and $m_{DM}$ in GeV (horizontal axis) from XQC using...
BBN’s problem with primordial \(^7\text{Li}\)

- Big Bang Nucleosynthesis works brilliantly \textit{except} \(10\sigma\) problem
  - Predicted abundance of \(^7\text{Li} = (5.61 \pm 0.26) \times 10^{-10}\)
  - Observed abundance of \(^7\text{Li} = (1.58 \pm 0.31) \times 10^{-10}\)

- Discrepancy is now very serious:
  - Nuclear rates all well-measured
  - \(\eta = n_b/n_\gamma = (6.58 \pm 0.02) \times 10^{-10}\) from CMB
  - Astrophysics now secure (Spite plateau):
    - small scatter
    - \(^7\text{Li}\) constant over > 3 decades of low metallicity

- \textbf{S solves the puzzle} (GRF + Richard Galvez, in preparation)
  - No other (reasonable) solution known
S dark matter breaks up $^7$Li & $^7$Be if $\sigma(S^{-7}\text{Be})$ is on resonance

- $\sigma$($S^{-7}\text{Be}$) is on resonance
  - $E_{th} = \sigma$($S^{-7}\text{Be}$)
  - Seems to solve $^7\text{Li}$ puzzle
  - Doesn't affect He or d

KE threshold for breakup =
- $1.58, 2.46, 4.47, 5.75, 19.3 [2.2] \text{ MeV}$
- $^7\text{Be} \quad 7\text{Li} \quad ^3\text{He} \quad T \quad 4\text{He} \quad [d]$

The “action” is at T~100 keV so S only affects weakly bound nuclei

Evolution of abundances

Standard Be7 case is dashed line
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: \( \sigma < \sim 10 \text{ mb if v-indept} \) — no problem for S
  • Buen-Abad, Marques-Tavares, Schmaltz (2015):
    • momentum transfer helps reconcile \( H_0 \) & \( \sigma_8 \)

• 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.