Stable Sexaquark as Dark Matter

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Stable Sexaquark, arXiv:1708.08951v2 [hep-ph]
uds-*DM*, arXiv:1805.03723v2 [hep-ph]

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

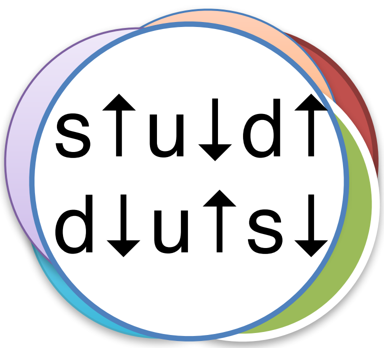
[Detecting S dark matter]

Discovering a stable sexaquark in the lab

Unique among multi-quark states:

Fermi statistics is compatible with a
totally symmetric spatial wave function AND

Color singlet
Flavor singlet
Spin singlet (scalar)



S

(Most-Attractive Channel)^3 :

6-quark, Q=0, B=2
$m_S < 2$ GeV???

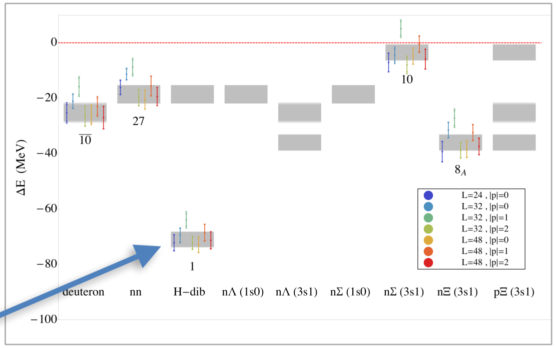
Same quark content as H-dibaryon* (Jaffe 1977), but different physics: **not a loosely bound di-Λ!**

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

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 = 1.2 - 2 GeV



Interesting DM candidate

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

— — — — — — — — — — — —

- triple-singlet (color,flavor,spin): MAC, lattice, models: all => $m_S < 2\ m_\Lambda$
- *extensive experimental searches* ***exclude*** *weak-lifetime & m > 2 GeV*

➜ bound state exists; mass < 2 GeV   ($\tau > \tau_{Univ}$ or stable)

Stable Sexaquark Hypothesis

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

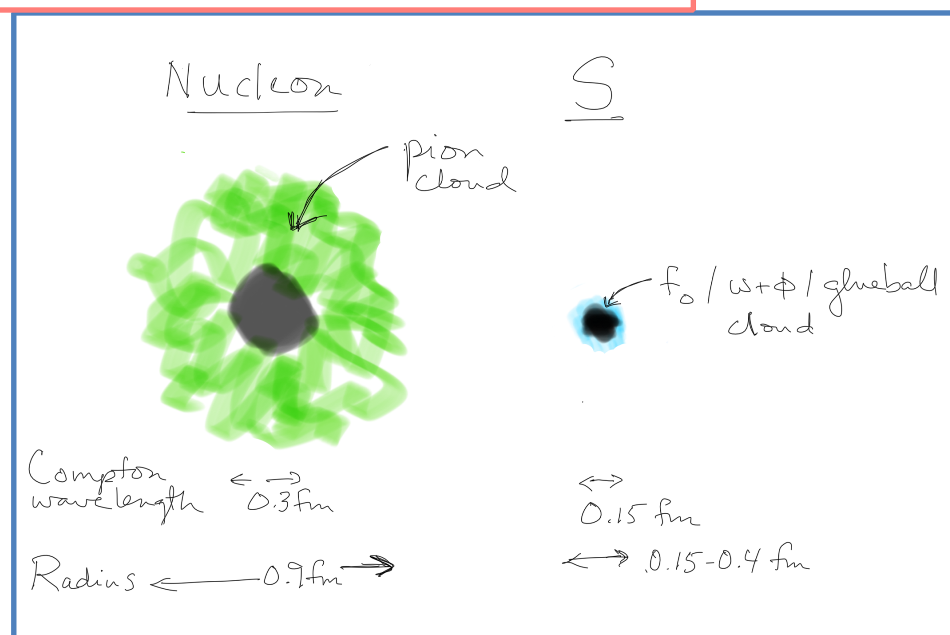
6	sexa-[19]	–	sen-[20]	sext-[21]	hex-[22]	hexakis- hexaplo- hexad- e.g. hexahedron	hect-[23] hectaio-	shat-

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

6-quark, Q=0, B=2
Spin-0, scalar
Flavor singlet
m ~ 1.7-2 GeV

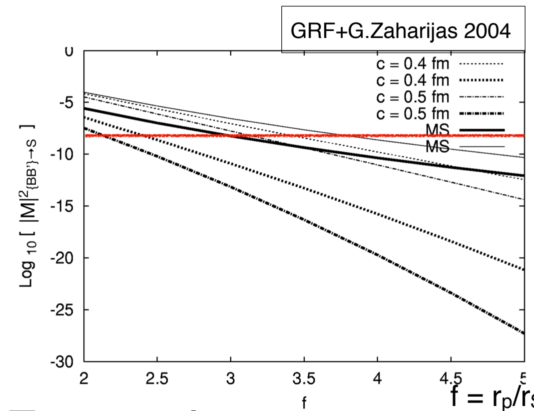


Conditions on QCD Dark Matter

- ✓ $\tau_{DM} > \tau_{Univ}$, 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)
  - Bonus: explains BBN ^{7}Li anomaly!

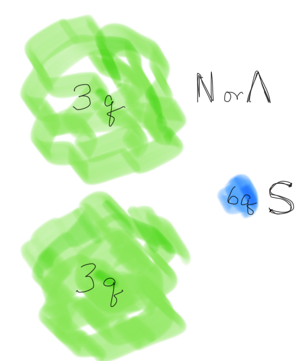
S has not been discovered at accelerators because it is elusive

- **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 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



*apart from BaBar

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 pp -> K K X

- Require H-dibaryon decay:
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  - Kim+ Belle 2013: no narrow resonance in ϒ ➔ Λ p K

- Limits from production in doubly-strange hypernuclei:
  - Ahn+ BNL 2001
  - Takahashi+ KEK 2001

Search for Six-Quark States

A. S. Carroll, I-H. Chiang, R. A. Johnson, T. F. Kycia, K. K. Ki, L. S. Littenberg, and M. D. Marx
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and

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(Received 26 July 1978)

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Experimental Searches

NOT APPLICABLE to S!

- Require M > 2 GeV:
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Sexaquark Discovery Strategies

- S itself: *neutral, generally "missing"*
- Apparent lack of Baryon# and Strangeness conservation:
  - missing $B = \pm 2$ + missing $S = \mp 2$
    - *inclusive: maximizes event rate, hermetic detector; ID!*
    - *Statistical correlation sufficient; do not have to ID everything.*
- Reconstruct missing mass, e.g.:
  - $\Upsilon \to \Lambda\, \Lambda\, \bar{S}$ (+ pions) $M_S^2 = (p_\Upsilon - p_{\Lambda 1} - p_{\Lambda 2} - \sum p_{\pi i})^2$
    - ***exclusive: big penalty in statistics, but gain from mass peak***
  - LHC: $\bar{S} + N \to \bar{\Lambda}\ K^+ \ldots$ $M_S^2 = (p_{\bar{\Lambda}} + p_{K^+\ldots} - p_N)^2$
    - *compromise: potentially a sweet spot (tbd)*

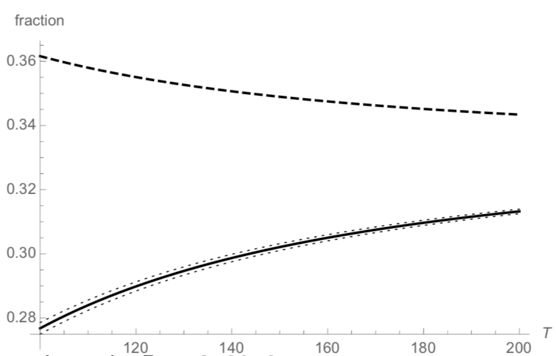
Quark-Gluon Plasma ➜ Hadrons @~150 MeV

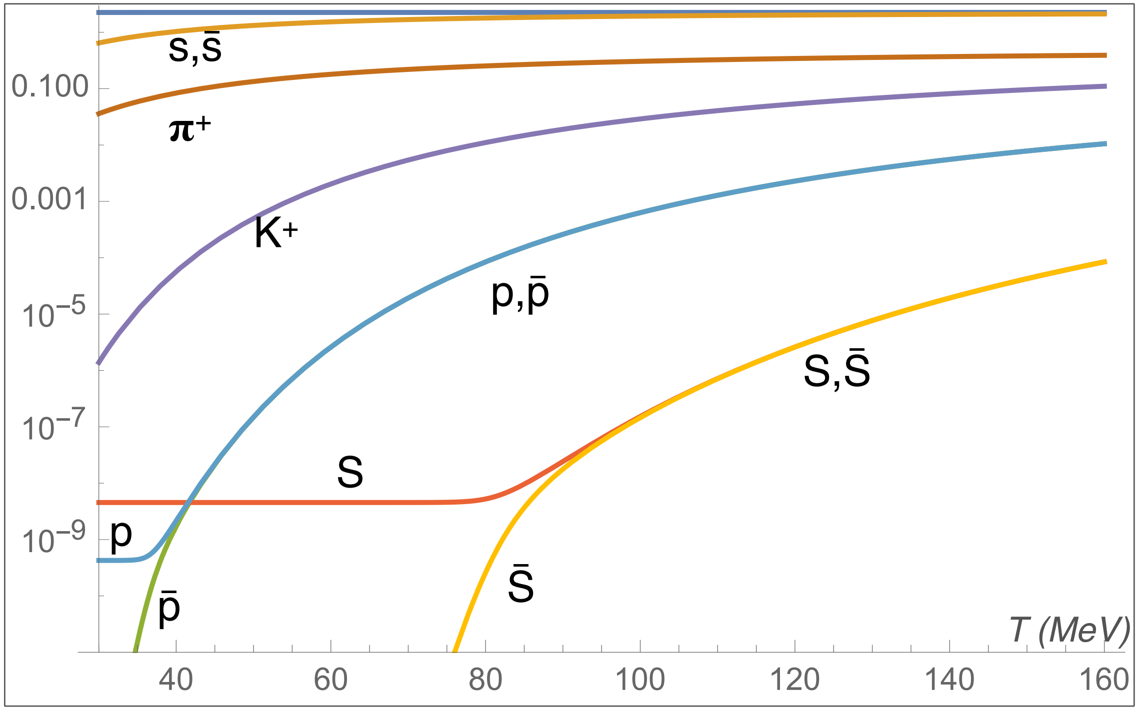
- Lattice QCD: crossover transition 160-140 MeV
  - T > 160 MeV: u,ū,d,d̄,s,s̄,gluons; NO vacuum condensates
  - T < 140 MeV: pions, kaons, p,p̄, …; <qq̄> & <GG> condensates
  - Abundance relative to photons (for species in equilibrium):
- Baryogenesis ⇒

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

- 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

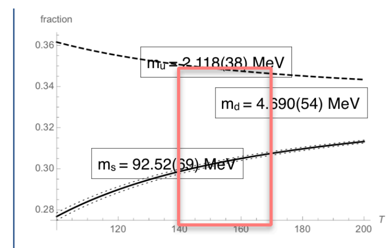


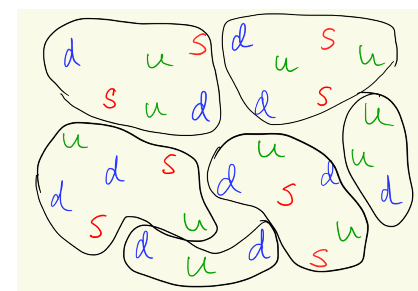


DM to (left-over) baryon ratio

- 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 (mass per unit baryon number)*
- *f_s = 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.*
- *κ_s is efficiency of uds ➜ DM (Boltzmann, from hyperon and S masses)*

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

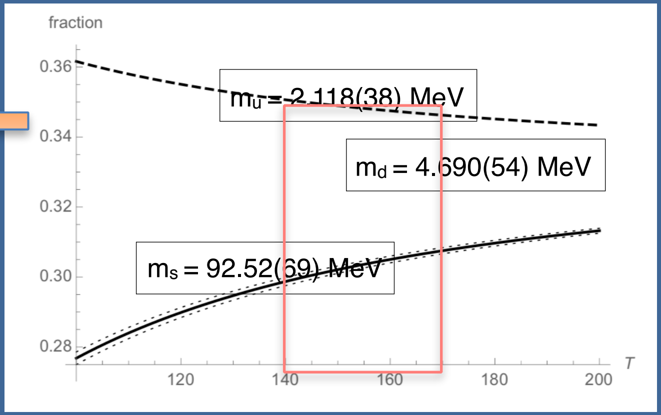
Prediction: $\Omega_{DM} / \Omega_b = 4.5 \pm 1$

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

(Ω_{DM} / Ω_b observed = 5.3 ± 0.1)

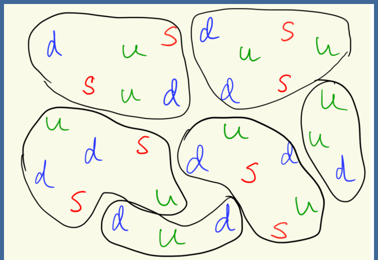
$m_S/(2m_p)$

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

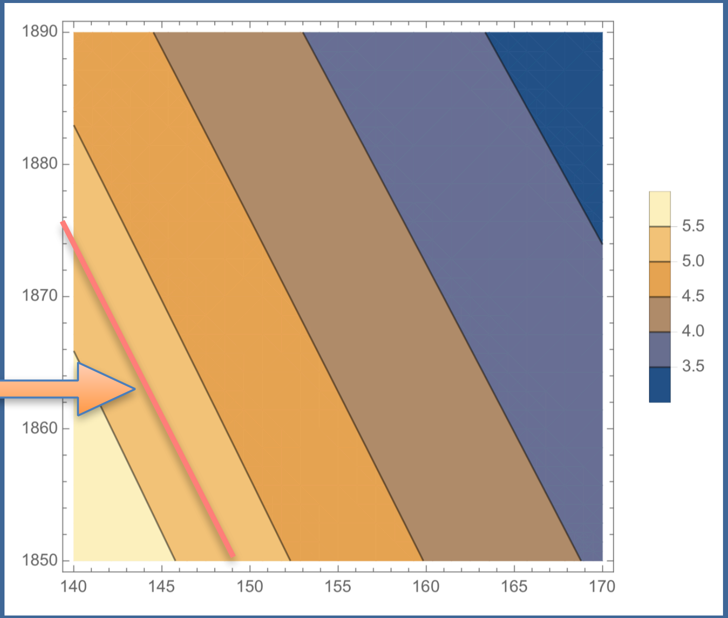


$$\kappa_s(m_S, T) = \frac{1}{1 + (r_{\Lambda,\Lambda} + r_{\Lambda,\Sigma} + 2r_{\Sigma,\Sigma} + 2r_{N,\Xi})}$$

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



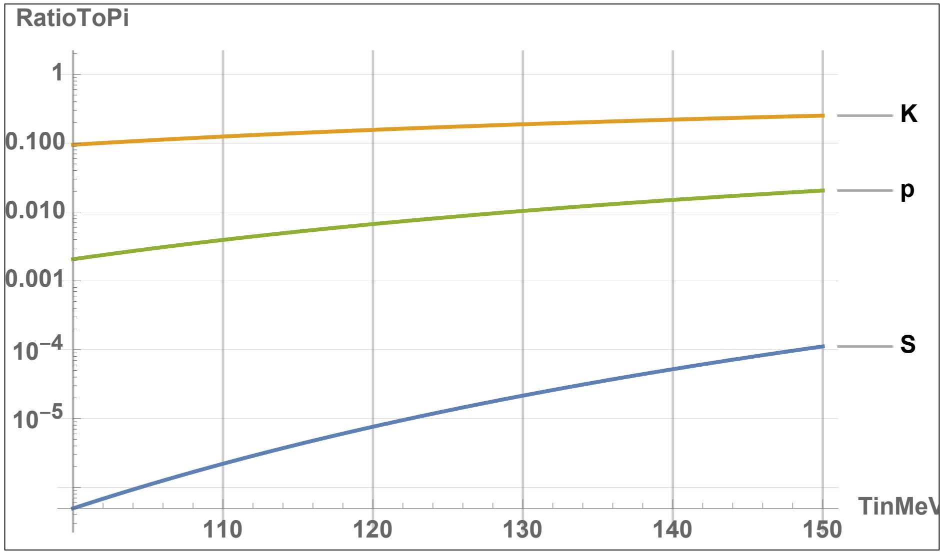
Prediction is both correct AND accurate to ~20% for entire range (uncertainties cancel)



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

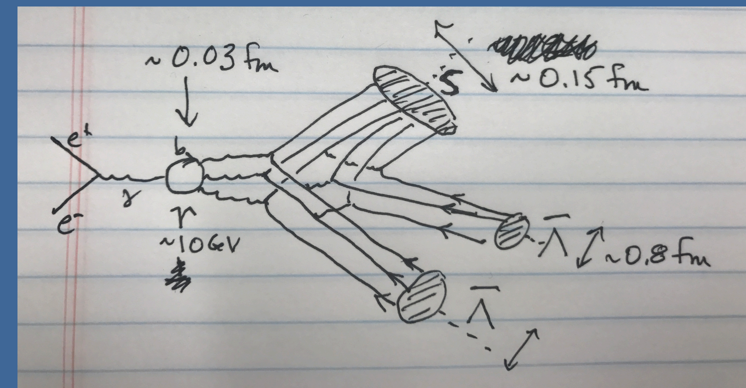
Prediction also applies to strange quark nuggets...

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 ➜
  - $N_{S+\bar{S}} \approx 10^{-4} N_\pi$ ➜ $E_{Smiss} \approx 10^{-4} (M_S/E_\pi) E_{\pi tot}$ … **1 ppm missing E** ☹
- Important exercise: can a statistical correlation between missing
  $B = \pm 2$ & missing $S = \mp 2$ be established? (question of ID systematics)

$\Upsilon \to \Lambda\, \Lambda\, \bar{S}$ & $\bar{\Lambda}\, \bar{\Lambda}\, S$ (+ pions)



- Υ **is *localized* source of ggg**

    ⇒ *production of S is (relatively) enhanced*

- Many x 10^8 events collected (CLEO, BaBar, Belle)
    - detectors pretty hermetic, have good mass resolution, O(10 MeV)
    - Λ decays quickly to $p\pi^-$ so easy to ID. $c\tau$ = 8 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 Λ'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!

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

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.

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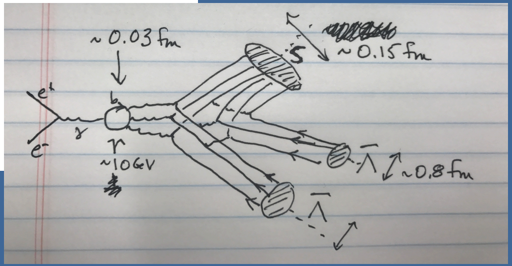


- BaBar: ***exclusive*** BF[$\Upsilon(2S,3S) \to \Lambda\, \Lambda\, \bar{S} + \bar{\Lambda}\, \bar{\Lambda}\, S$] < *1.4 x 10^{-7}*
  - 2 x 10^8 events; main backgrounds $\Upsilon(2S,3S) \to \Lambda\, \Lambda\, \bar{\Lambda}\, \bar{\Lambda} + X$ & noise in E-cal
- Predicted ***inclusive*** BF [$\Upsilon(ggg)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

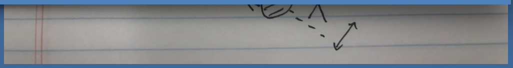
  Exclusive Penalty:
  - start with biggest exclusive 3-body channel: BF[$\Upsilon(2S,3S) \to \phi\, K\, K$] = 2 x 10^{-6}
  - penalty of $S+\bar{S}$ relative to ϕ : 6 x 10^{-5}
- Predict Exclusive BF [$\Upsilon(ggg) \to \Lambda\, \Lambda\, \bar{S} + \bar{\Lambda}\, \bar{\Lambda}\, S$] ~ *10^{-11}*

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

High Energy Physics – Experiment

Search for a Stable Six-Quark State at BABAR

BaBar exclusive limit is a factor 10^4 from being constraining — need inclusive or semi-inclusive



- 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
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LHC beam lifetime

- DM capture by Earth => DM atmosphere

Neufeld, GRF, McKee, ApJ2018

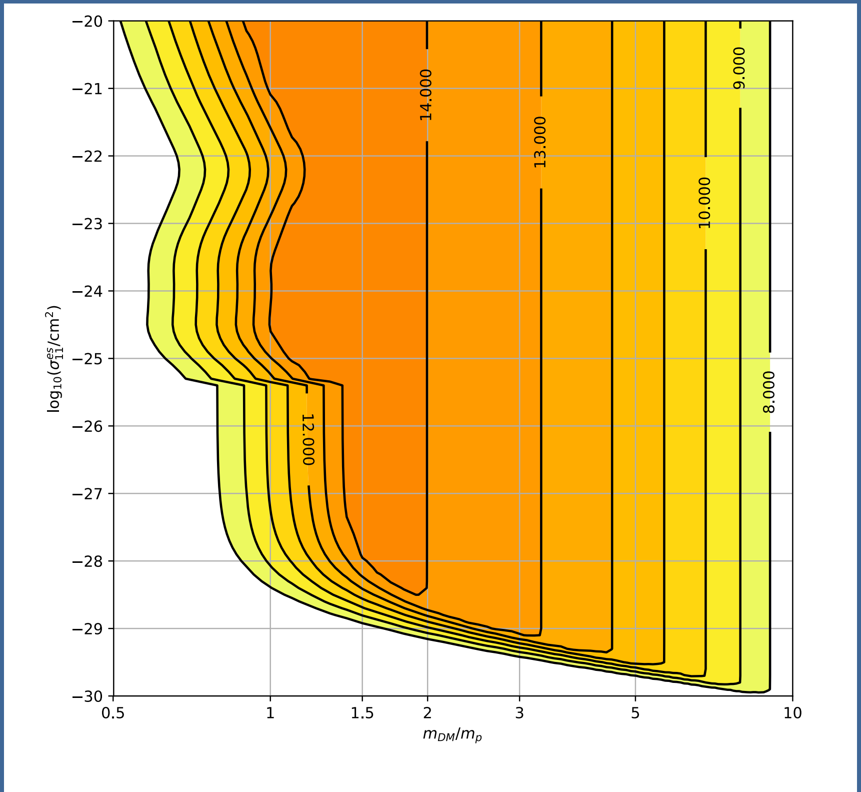
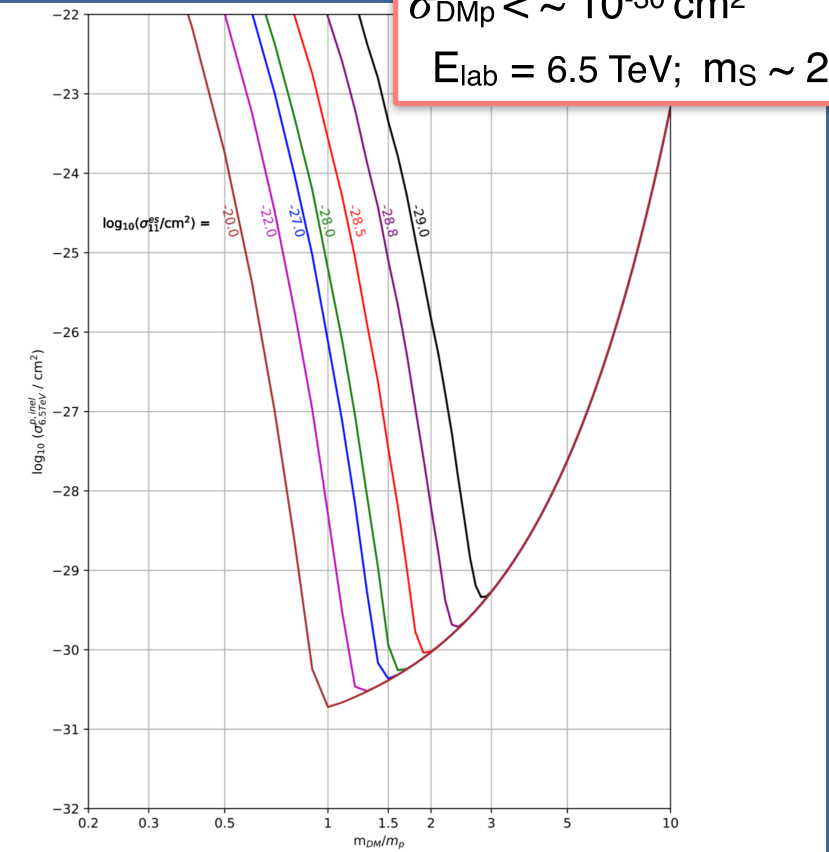


Fig. 6.— Number density of HIDM at the Earth's surface, $n_{DM}(R_\oplus)$, in the $m_{DM} - \sigma_{11}^{es}$ plane. Contours are labeled by $\log_{10}(n_{DM}/cm^{-3})$.



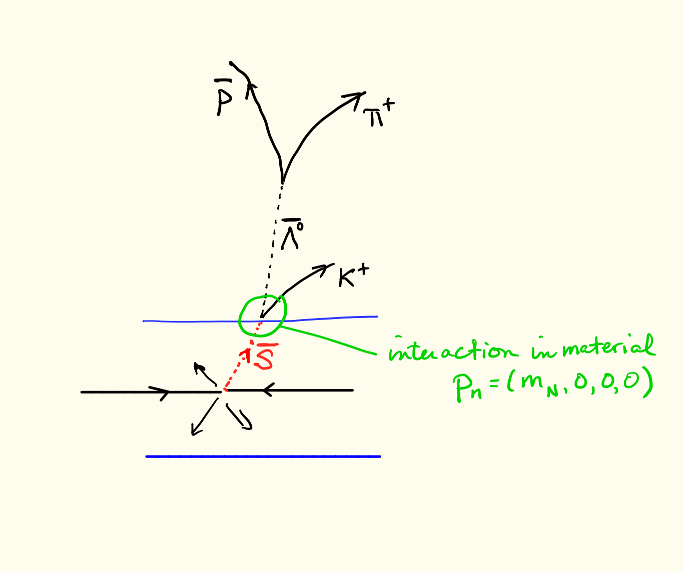
$\sigma_{DMp} <\sim 10^{-30}$ cm^2

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

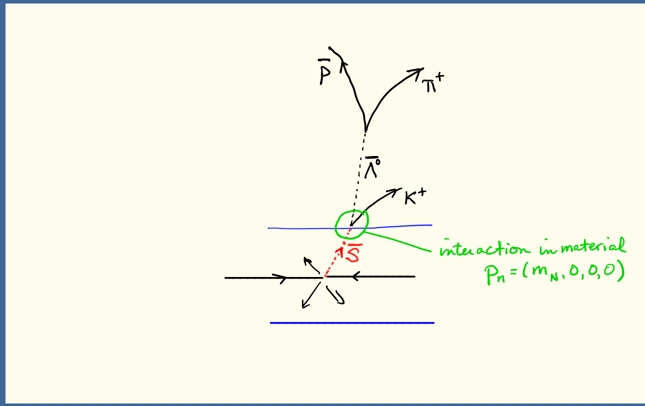
Fig. 7.— Upper limits on $\sigma_{6.5\,TeV}^{p,inel}$ implied by an LHC beam lifetime of 100 hr. Results are shown for five values of σ_{11}^{es} for which the LSS lies in the crust ($10^{-29.0}$, $10^{-28.8}$, $10^{-28.5}$, 10^{-28}, and 10^{-27} cm^2), and two values for which the LSS lies in the atmosphere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

LHC I.

- Low production rate *(uuddss in small vol; SU(18) singlet)*
- 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!)



LHC II.



- Low production rate *(uuddss in small vol=>)*
  - $g_{eff,SBB} \approx 10^{-6} (r_S / 0.2)^{10}$
  - *~ 100 particles in central tracker/event x N_{11} 10^{11}*
  - *~ 10 events (worst case, hopefully, since overlap may be enhanced at larger momentum)*
- Statistical examination of correlation **ΔB = ± 2, ΔS = ∓ 2** ???
- Heavy ion collisions produce more particles — feasible to reconstruct ???
- *Find a distinctive needle in a haystack* (~10^{11} recorded events)?
  - ★ **$\bar{S}$ annihilation in tracker, tag by $\bar{\Lambda}$ K⁺ pointing to tracker** or $\bar{\Xi}^{+,0} \to \bar{\Lambda}\, \pi^{+,0}$, $\bar{\Lambda} \to \bar{p}\, \pi^+$

Rate estimate: (GRF arXiv:1708.08951)

$\bar{S}$ Production:

- 30 charged particles with pseudo-rapidity $|\eta| < 2.4$; N events = N_{11} 10^{11}
- $f^{\rm prod}_{-4} 10^{-4}$ is the $\bar{S}$ production rate relative to all charged particles
- ➜ $N_{\bar{S}} \approx 3\, f_{-4}\, N_{11}\, 10^8$

$\bar{S}$ Annihilation: $\sigma_{\bar{S}N} \equiv f^{\rm annih}_{-6} 10^{-6} \sigma_{NN}$

O(1)

$$N_{\bar{\Xi},\bar{\Lambda}} = f^{\rm prod}_{-4}\, f^{\rm annih}_{-6}\, f_{\bar{\Xi},\bar{\Lambda}}\, N_{11}\, 10^5.$$

May be optimistic, depending on $g_{eff,SBB}$ for LHC.

$f_{\bar{\Xi},\bar{\Lambda}}$: fraction of final states containing $\bar{\Xi}, \bar{\Lambda}$

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

Heavy Ion Collisions

- Sum up observed B and observed S, event by event.
- Any excess anti-correlation?
  - net B ~ net -S

Please contact me if interested…

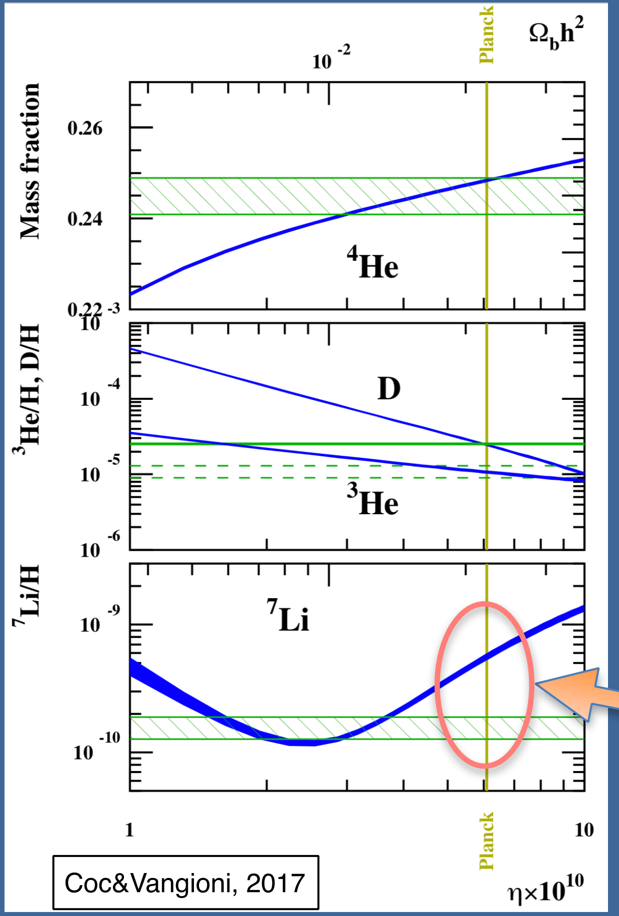
Sexaquark Discovery Strategy

- 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.:
  - **$\Upsilon \to \Lambda\,\Lambda\,\bar{S}$** (+ 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 peak*
  - LHC: $\bar{S} + N \to \bar{\Lambda}\ K^+ \ldots$ $M_S^2 = (p_{\bar{\Lambda}} + p_{K^+\ldots} - p_N)^2$
    - *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: $d \to S\, e^+ \nu$ $\sin\theta_C^4$ x GIM suppression x G_F^4 , $\tau > 10^{+29}$ yr ($m_S <$ ~1875 MeV)

BBN's problem with primordial ^{7}Li

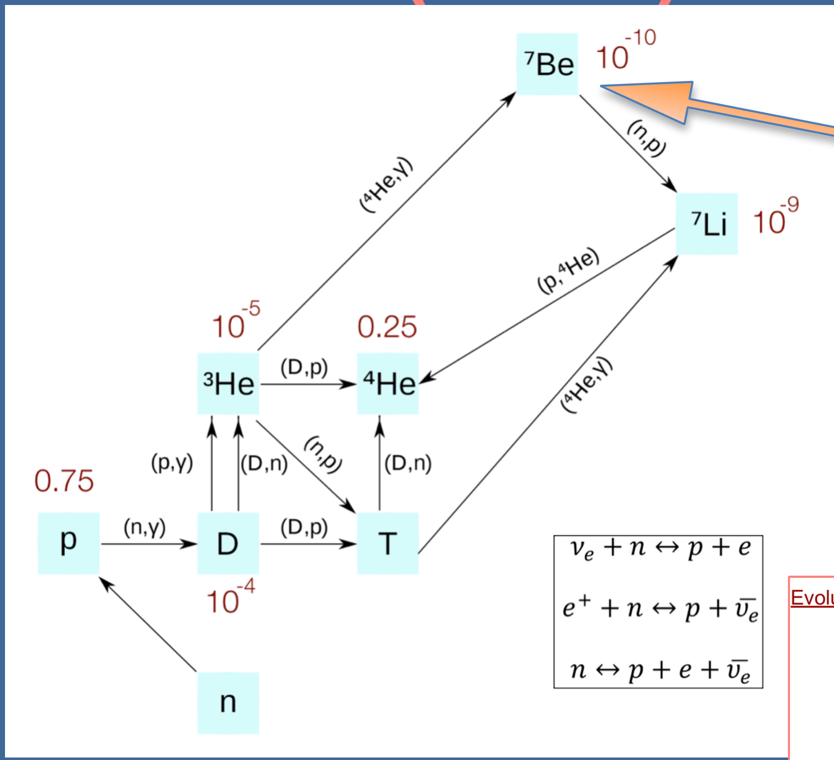
- Big Bang Nucleosynthesis works brilliantly ***except 10σ problem***
  - Predicted abundance of ^{7}Li = **$(5.61 \pm 0.26)\ 10^{-10}$**
  - Observed abundance of = **$(1.58 \pm 0.31)\ 10^{-10}$**

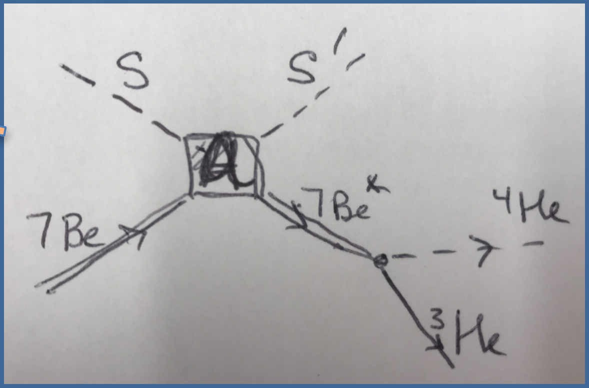


- Discrepancy is now very serious:
  - Nuclear rates all well-measured
  - $\eta = n_b/n_\gamma = (6.58 \pm 0.02)\ 10^{-10}$ from CMB
  - Astrophysics now secure (Spite plateau):
    - small scatter
    - ^{7}Li constant over > 3 decades of low metallicity

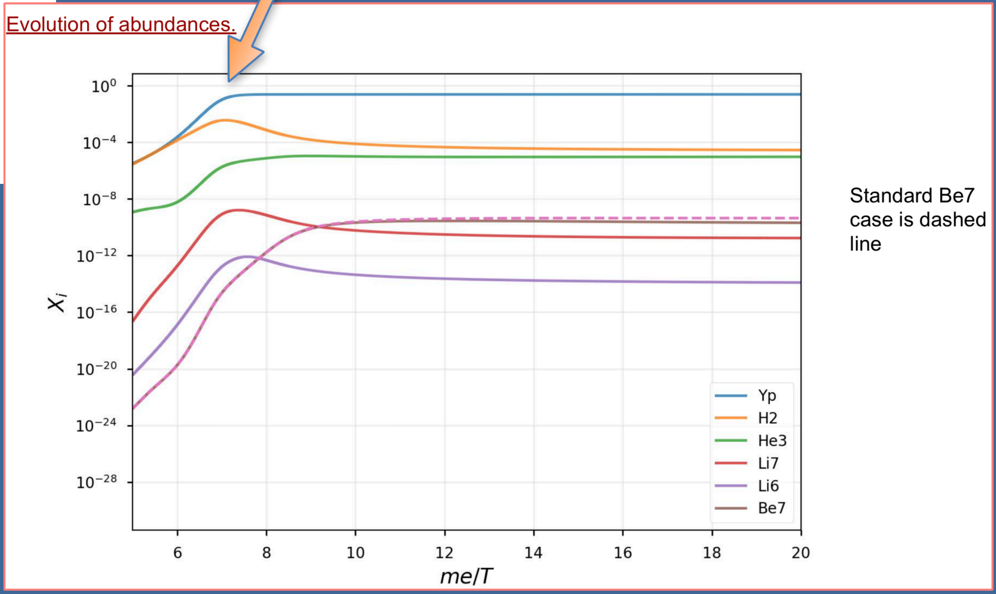
- **S solves the puzzle** **(GRF + Richard Galvez, in preparation)**
  - No other (reasonable) solution known

S dark matter breaks up ^{7}Li & ^{7}Be if σ(S-^{7}Be) is on resonance





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

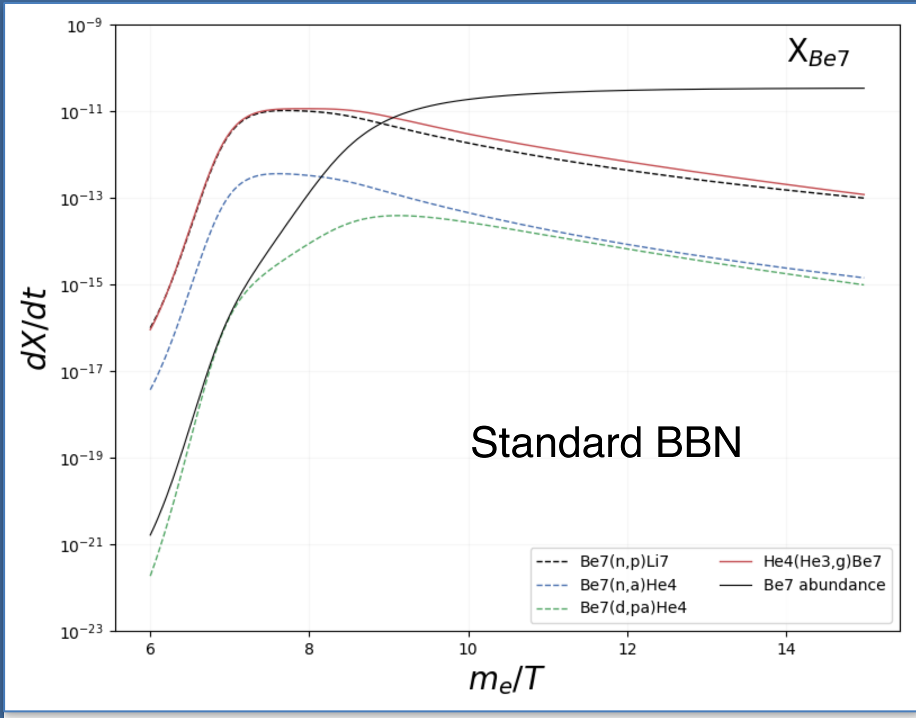


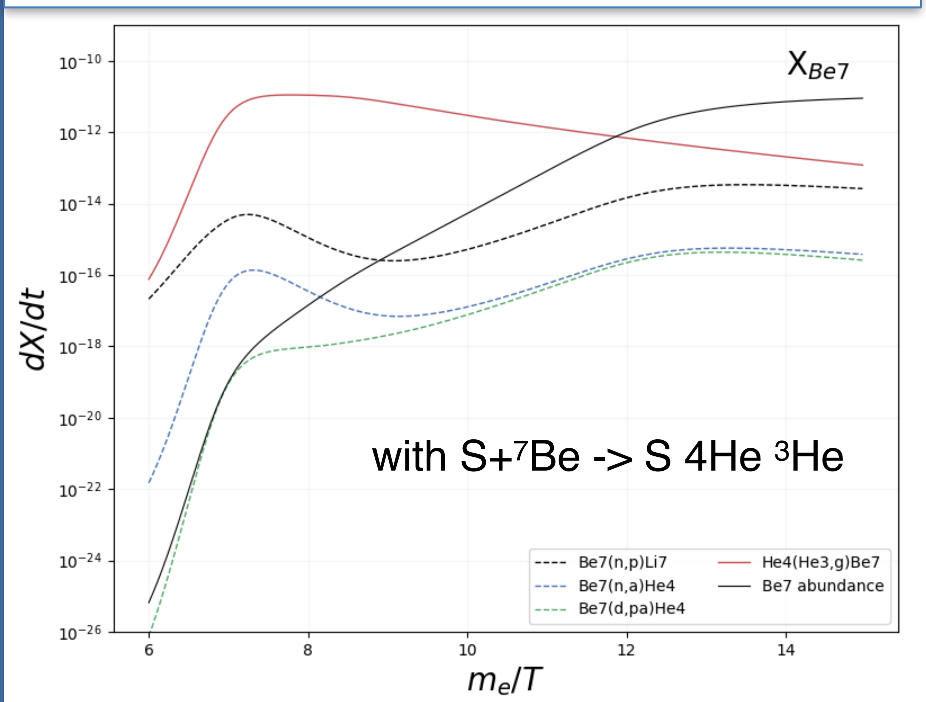
Standard Be7 case is dashed line

- Seems to solve ^{7}Li puzzle
- Doesn't affect He or d

KE threshold for breakup =

1.58, 2.46, 4.47, 5.75, 19.3 [2.2] MeV
7Be 7Li 3He T 4He [d]

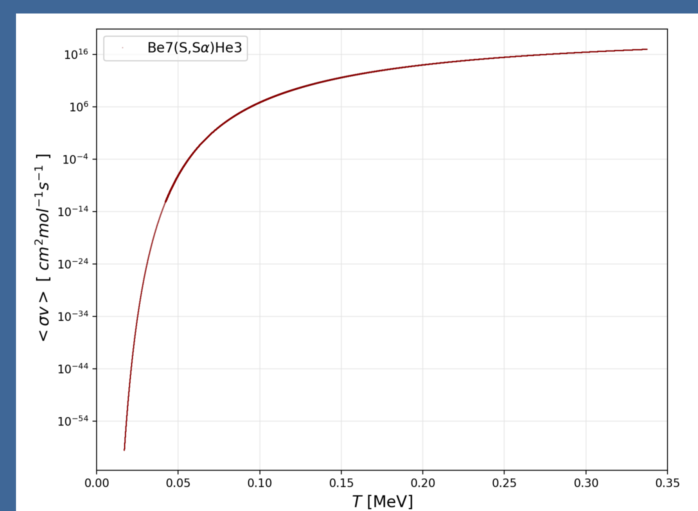




S dark matter breaks up ^{7}Li & ^{7}Be

- ^{7}Be->^{7}Li after atoms form.
- No other BBN predictions modified (all other BE are larger)
- GRF, R. Galvez, X. Xu in prep

Predicted abundance of ^{7}Li = **(5.61 ± 0.26) 10^{-10}**
is reduced to
Observed abundance of = **(1.58 ± 0.31) 10^{-10}**



Key points to take home

- ***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)
    - constituent quark model probably completely misleading
  - ***If $M_S < 2\,m_p + 2\,m_e$, 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 ϒ-decays or LHC experiments… mass can be accurately measured in exclusive reactions***
- ***SDM will be challenging to detect, but not impossible. Astrophysical and cosmological effects may allow it to be constrained, excluded or confirmed.***

Backup Slides

Parenthesis:

Relic Abundance of *uds* Dark Matter

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

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

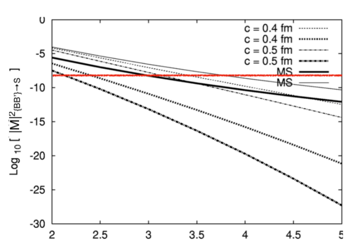
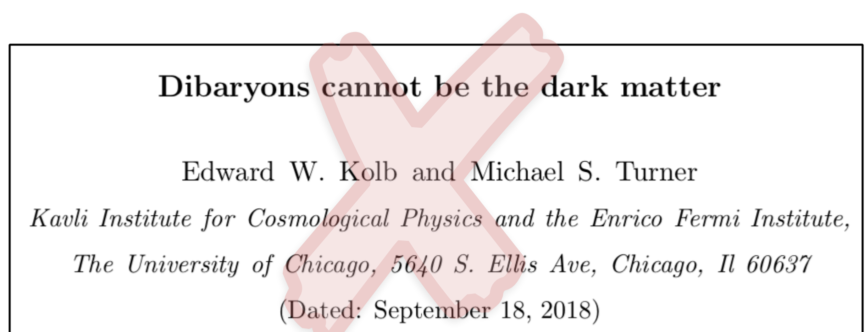


FIG. 6. Wavefunction overlap $\tilde{g}^2$ between S and two baryons



Dibaryons cannot be the dark matter

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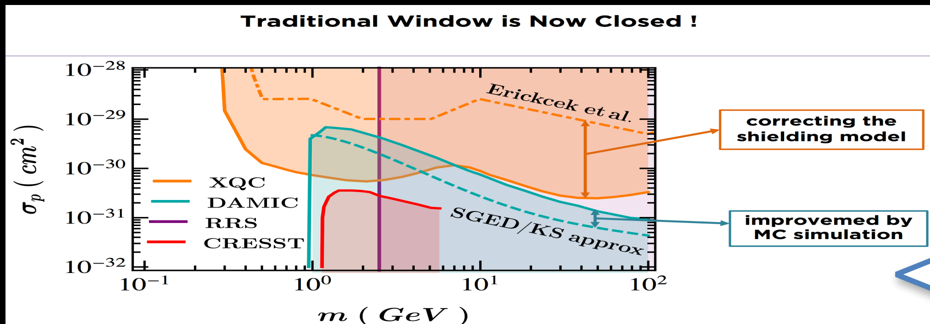
(Dated: September 18, 2018)

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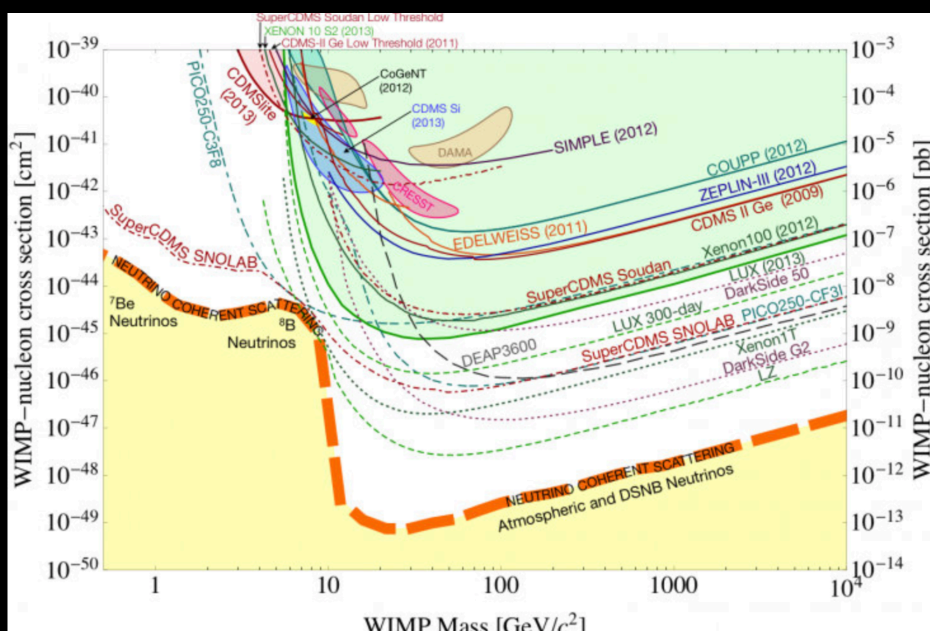
Abstract. We improve limits on the spin-independent scattering cross section of Dark Matter on nucleons, for DM in the 300 MeV – 100 GeV mass range, based on the DAMIC and XQC experiments. Our results close the window which previously existed in this mass range, for a DM-nucleon cross section of order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

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



Dark Matter with Hadronic Interactions

(GRF + Xingchen Xu, 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) down to 1 km/s (atm & z = 17)
  - must solve Schroedinger Eqn. **Born approximation generically fails badly**
  - cross section depends only on combos $a = \frac{v}{2\alpha}$ and $b = \frac{2\alpha\mu}{m_\phi}$

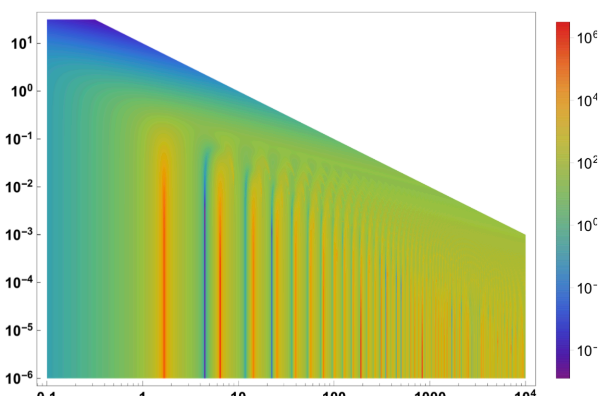


FIG. 1: $\sigma\, m_\phi^2$ as a function of $a = \frac{v}{2\alpha}$ and $b = \frac{2\alpha\mu}{m_\phi}$.

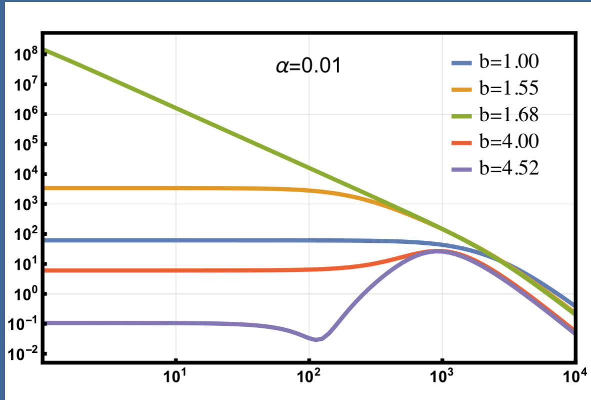


FIG. 4: $\sigma\, m_\phi^2$ versus v in km/s, for 5 values of $b = \frac{2\alpha\mu}{m_\phi}$.

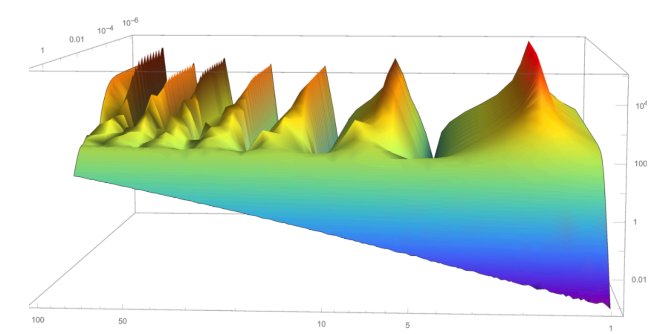


FIG. 2: 3D plot of $\sigma\, m_\phi^2$ in the a, b plane; b increases to the left and a decreases toward the back.

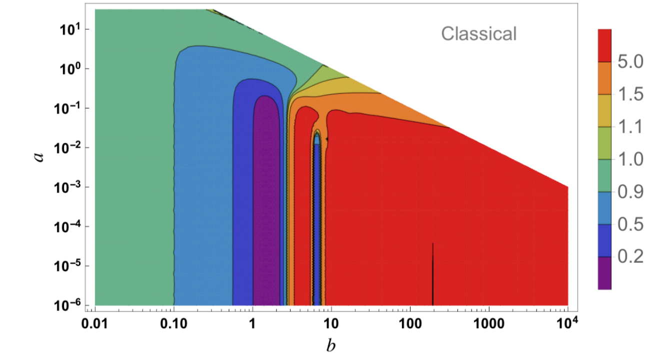
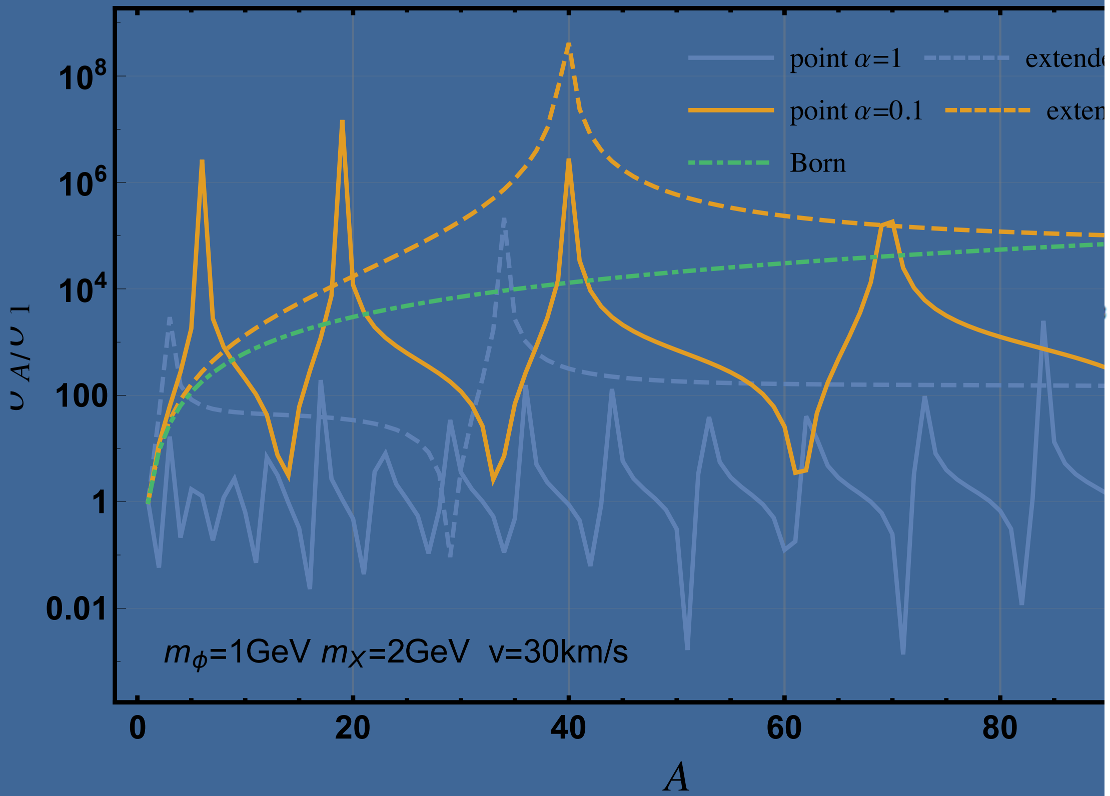


FIG. 3: Ratio of Born Approximation and Schroedinger Equation

Plenty of Room for SDM, for now…

(GRF + Xingchen Xu, to appear shortly)

Caution: A-dependence sensitive to nuclear form factor. Born approximation often misleading, by orders of magnitude.



Allowed regions of coupling from XQC (best Direct Detection)

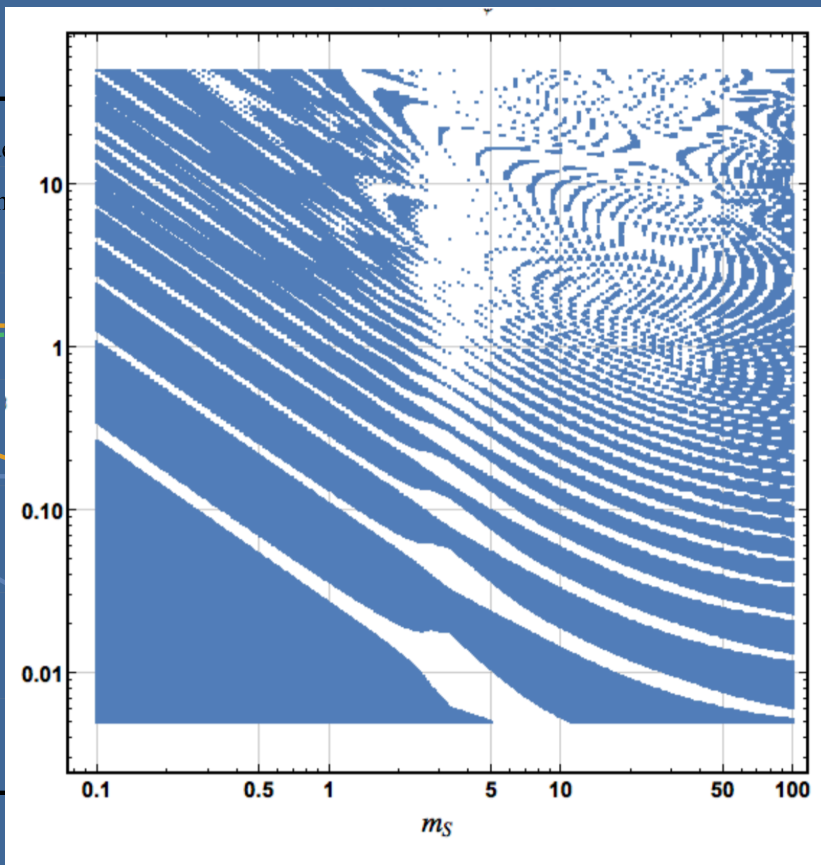


FIG. 7: Allowed regions (blue) in the coupling-DM mass plane α (vertical axis) and m_{DM} in GeV (horizontal axis) from XQC using

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.