Stable Sexaquark as Dark Matter

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CIPANP, May 29, 2018

Stable Sexaquark as Dark Matter

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

[Hints from Astrophysics]

Primordial Nucleosynthesis

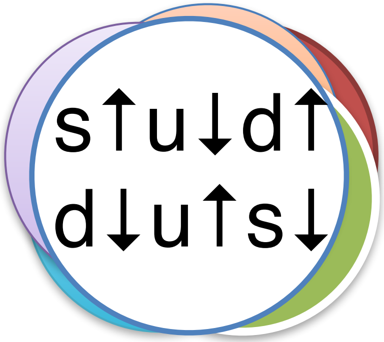
Dark-Matter to Ordinary-Matter ratio

Detecting S dark matter

Unique among multi-quark states:

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

antisymmetric (singlet) in:
color
flavor
spin
totally symmetric in space



s↑u↓d↑
d↓u↑s↓

S

(Most-Attractive Channel)^3 :

6-quark, Q=0, B=2
Spin-0, scalar
Flavor singlet
$m_S < 2$ 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 $m_S \sim 2\, m_p$?

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

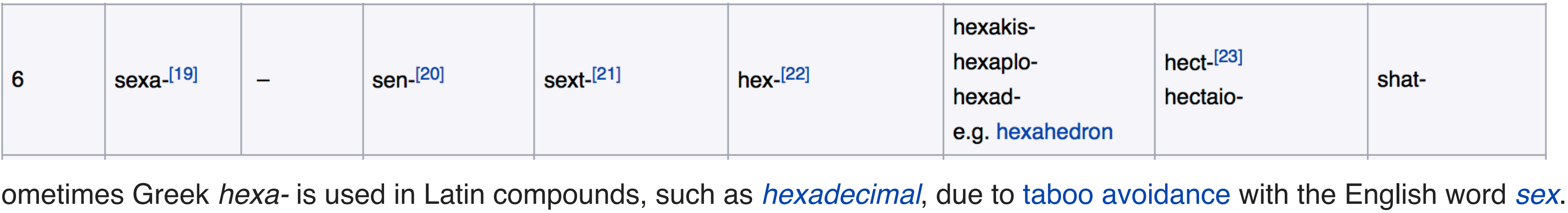
- $m_S < 2\,(m_p + m_e)$: S is absolutely stable
- $m_S > 2\,(m_p - 8\ \mathrm{MeV})$: nuclei are stable

Interesting DM candidate

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

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

Stable Sexaquark Hypothesis



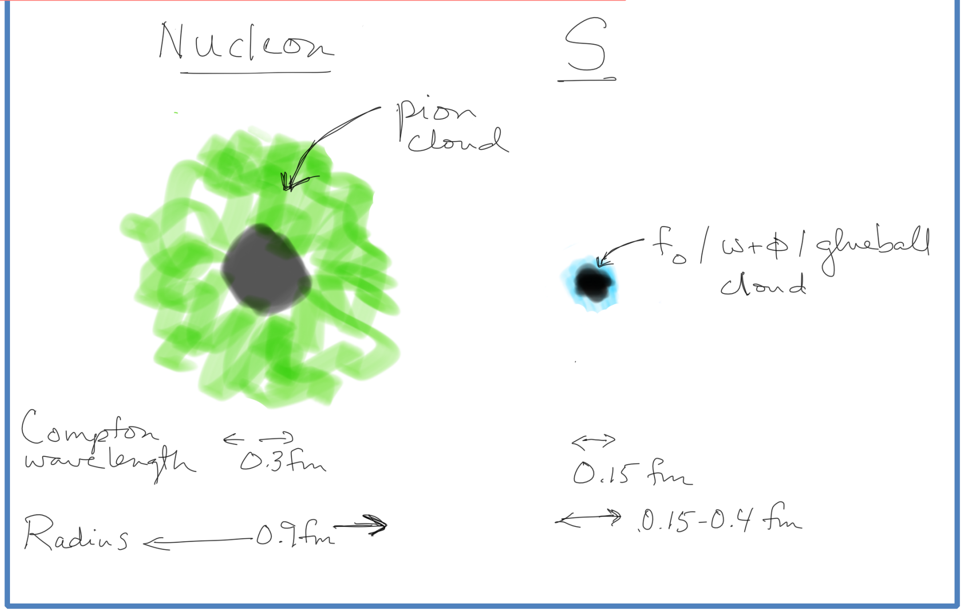
6	sexa-[19]	–	sen-[20]	sext-[21]	hex-[22]	hexakis- hexaplo- hexad- e.g. hexahedron	hect-[23] hectaio-	shat-

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

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

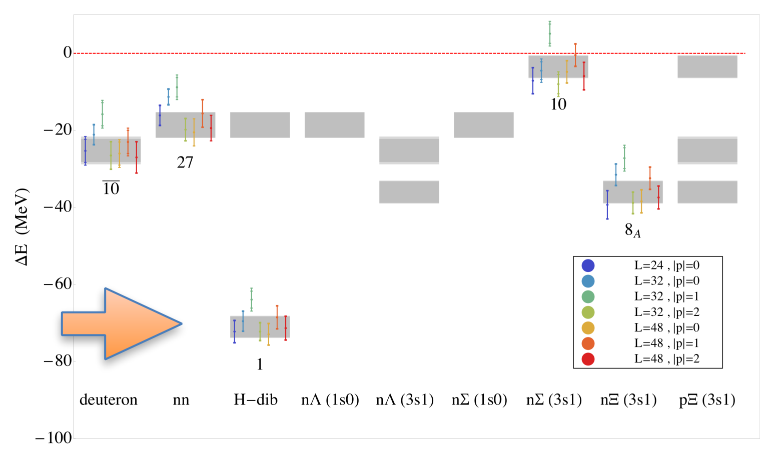
Spin-0, scalar

Flavor singlet

m ~ 1.7-2 GeV

Stable S?

- $\tau > \tau_{\text{Univ}}$
  - **$M_S < 2\ m_p + 2\ m_e$ = 1877.6 MeV ➜ absolutely stable**
  - **$M_S > 2\ m_p + 2$ BE** = 1860 MeV **➜ nuclei absolutely stable**
  - higher and lower mass may also work $\Gamma \sim G_F^4$ x (wave function overlap)^2
- **Lattice predicts binding (Beane+13)**
  - (m_q = 850 MeV so not realistic)
  - 80 MeV binding



- **Experiments exclude decaying S**

=> it must be STABLE ! ;-)

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 m_{DM} & $\sigma_{f.o.}$)

Ω_{DM} / Ω_{b}

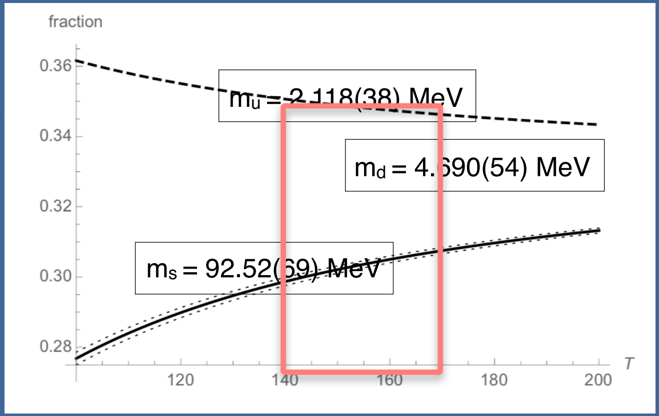
follows from **stat mech , quark masses** &
temperature of **QGP-hadronization** transition

$m_S/(2m_p)$

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

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

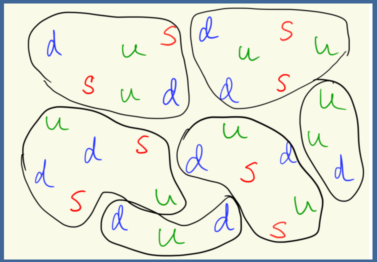
$$r_{1,2} \equiv \exp[-(m_1+m_2-m_S)/T]$$



m_u = 2.118(38) MeV

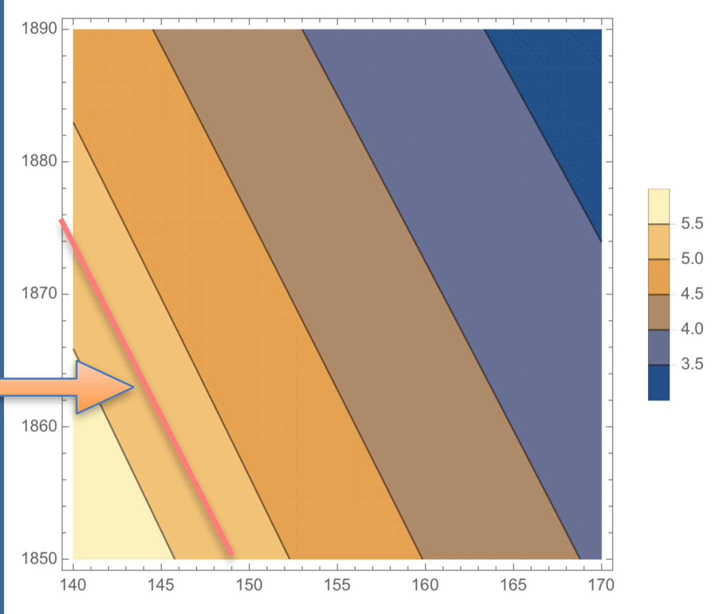
m_d = 4.690(54) MeV

m_s = 92.52(69) MeV



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

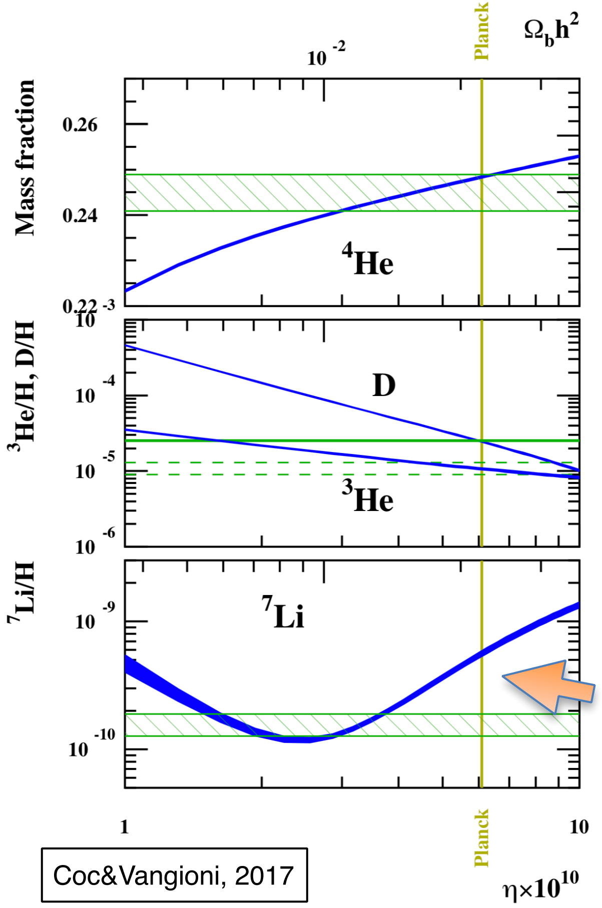
Ω_{DM} / Ω_{b} = 5.3 ± 0.1



Prediction also applies to strange quark nuggets...

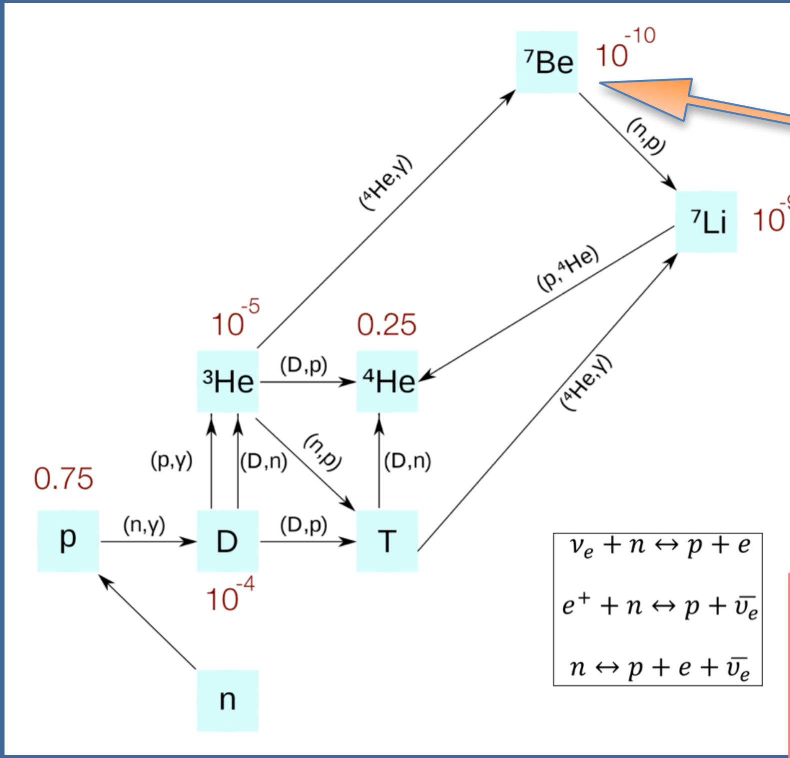
BBN's problem with primordial ^{7}Li

- Big Bang Nucleosynthesis works brilliantly ***except 10σ problem***
  - Predicted abundance of ^{7}Li = **(5.61 ± 0.26) 10^{-10}**
  - Observed abundance of = **(1.58 ± 0.31) 10^{-10}**
- Discrepancy is now very serious:
  - Nuclear rates all well-measured
  - **η** = n_b/n_γ = (6.58 ± 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

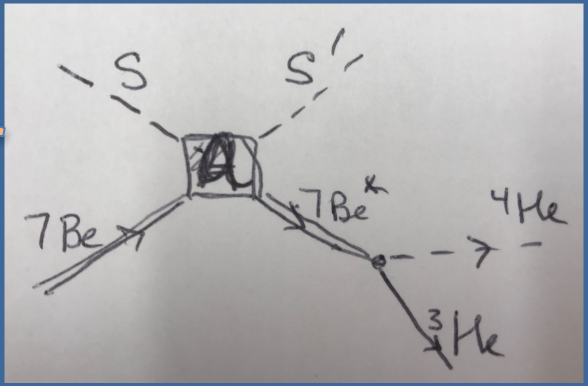


Coc&Vangioni, 2017

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

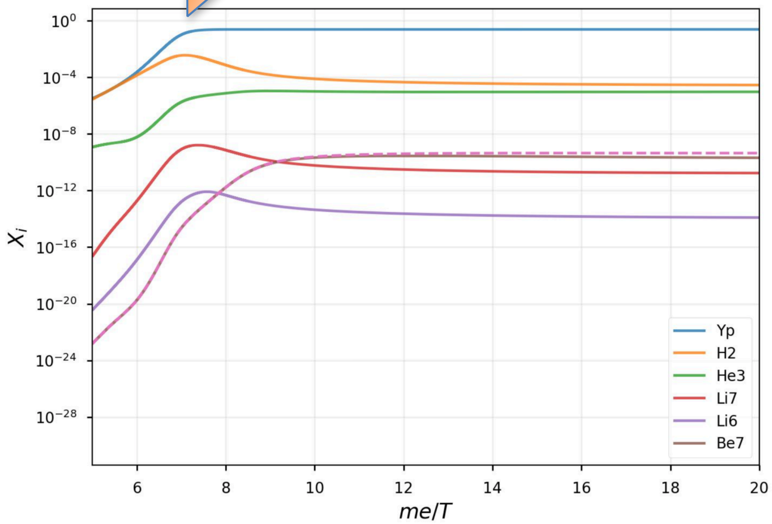


$$\nu_e + n \leftrightarrow p + e$$
$$e^+ + n \leftrightarrow p + \bar{\nu}_e$$
$$n \leftrightarrow p + e + \bar{\nu}_e$$



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

Evolution of abundances.



Standard Be7
case is dashed
line

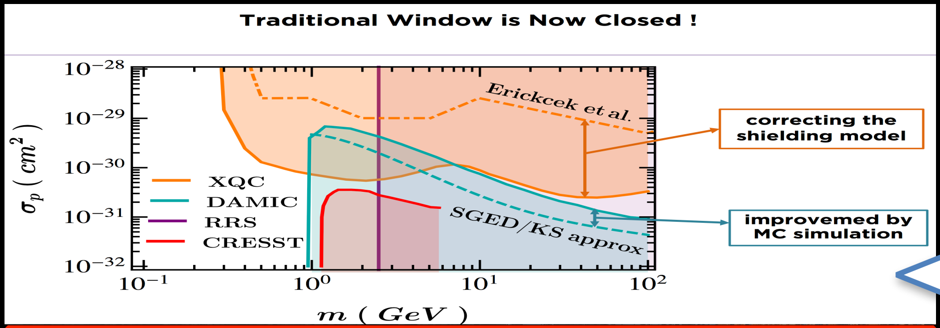
- Solves the puzzle
- **Doesn’t affect He or d**

KE threshold for breakup =

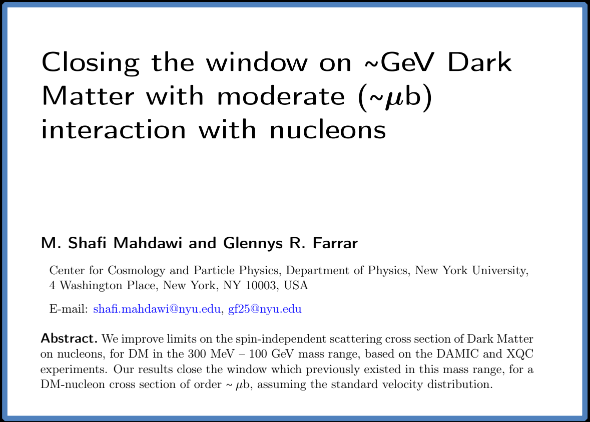
1.58, 2.46, 4.47, 5.75, 19.3 [2.2] MeV
7Be 7Li 3He T 4He [d]

10^{-26} – 10^{-25} cm^2

Stable S as Dark Matter



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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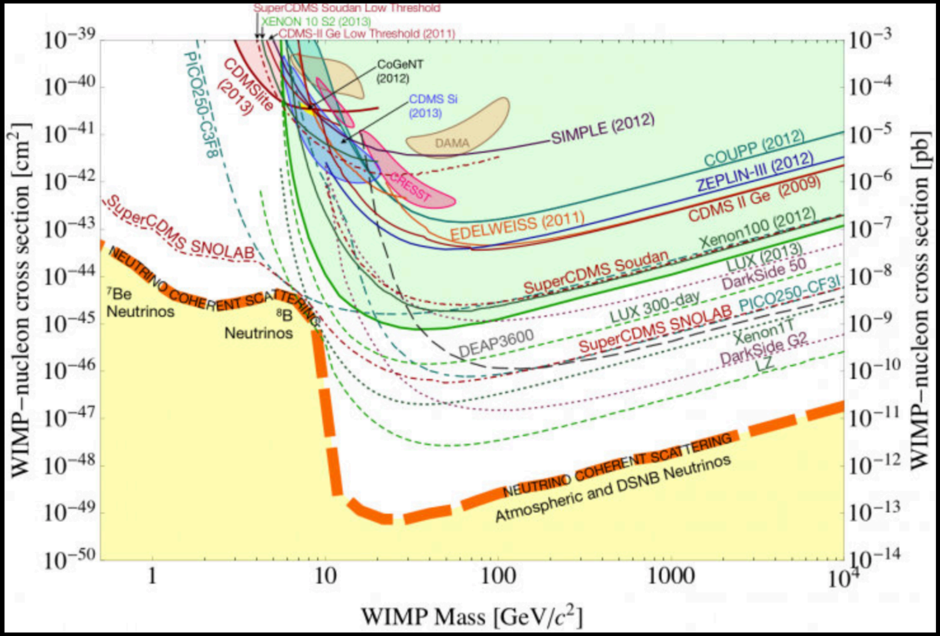
Abstract. We improve limits on the spin-independent scattering cross section of Dark Matter on nucleons, for DM in the 300 MeV – 100 GeV mass range, based on the DAMIC and XQC experiments. Our results close the window which previously existed in this mass range, for a DM-nucleon cross section of order ~ 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 $b = \frac{2\alpha\mu}{m_\phi}$

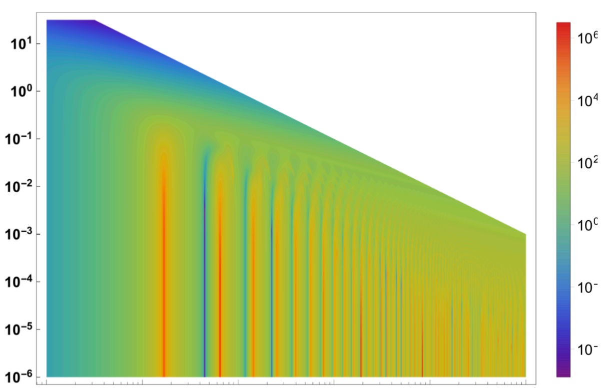


FIG. 1: $\sigma\, m_\phi^2$ as a function of $a = \frac{v}{2\alpha}$ and $b = \frac{2\alpha\mu}{m_\phi}$.

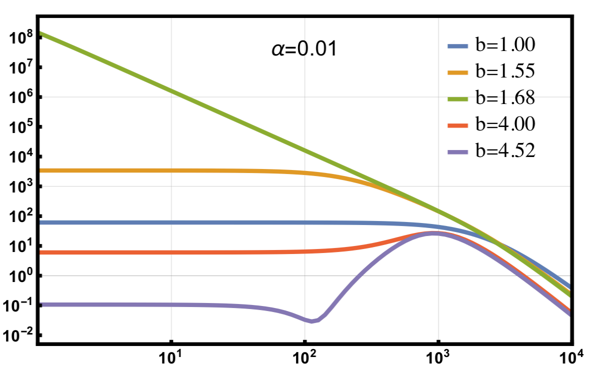


FIG. 4: $\sigma\, m_\phi^2$ versus v in km/s, for 5 values of $b = \frac{2\alpha\mu}{m_\phi}$.

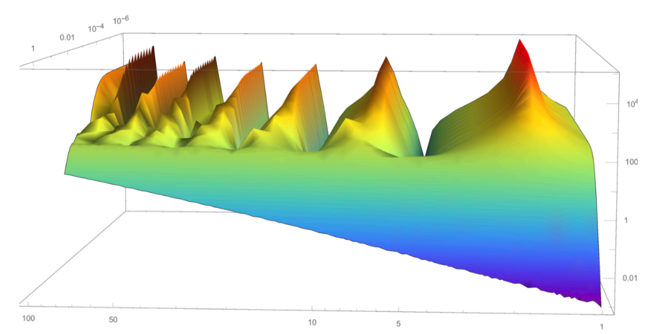


FIG. 2: 3D plot of $\sigma\, m_\phi^2$ in the a, b plane; b increases to the left and a decreases toward the back.

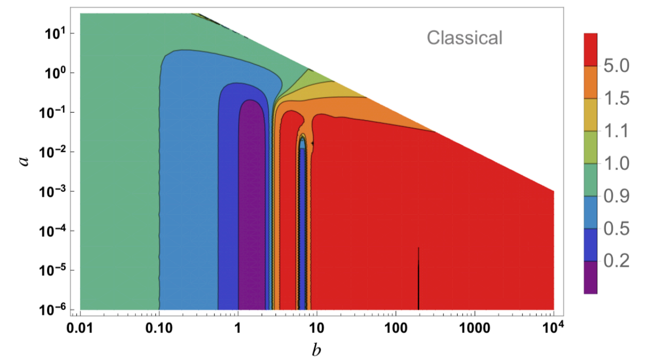
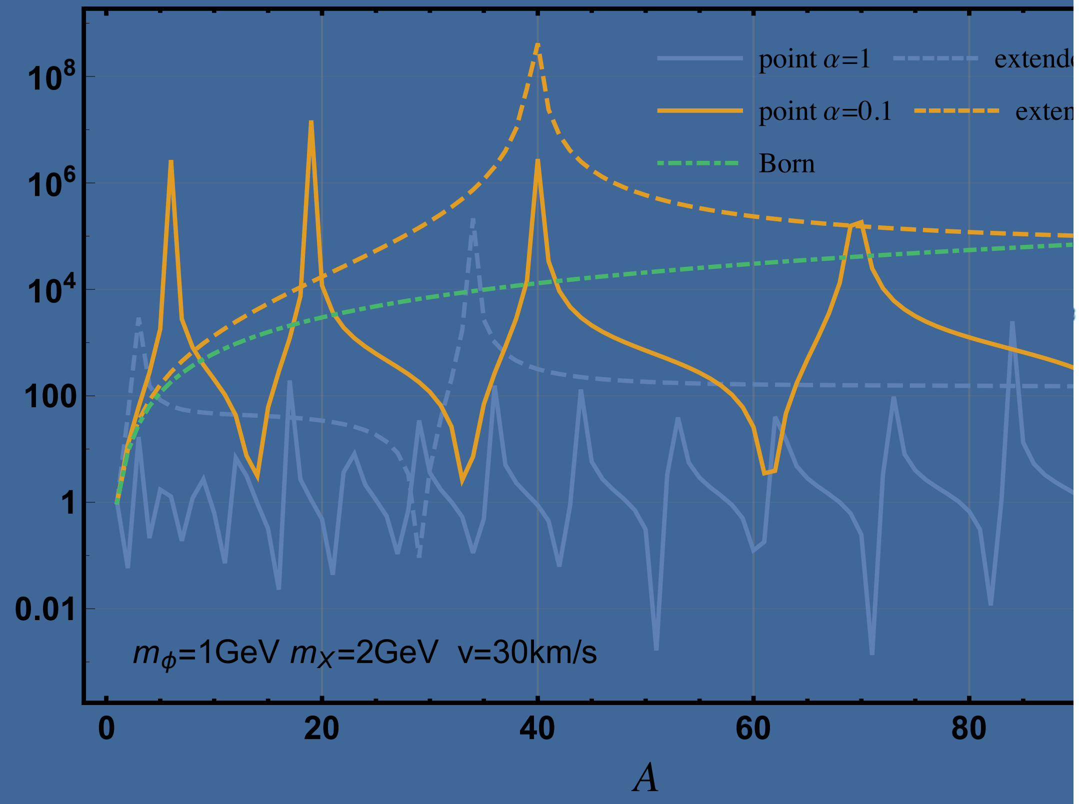


FIG. 3: Ratio of Born Approximation and Schroedinger Equation

Plenty of Room for HIDM, for now…

(GRF + Xingchen Xu, to appear shortly)

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



Allowed regions of coupling from XQC (best Direct Detection)

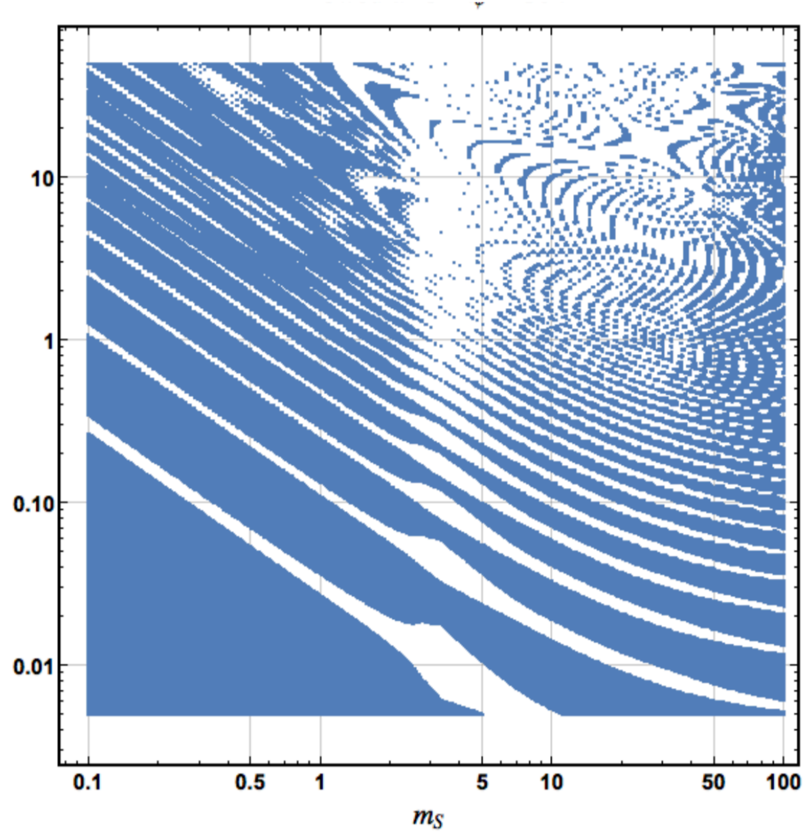
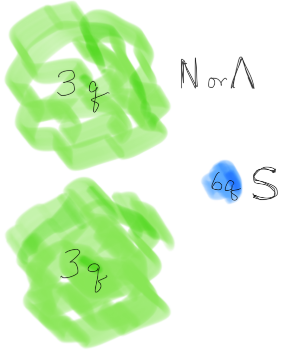


FIG. 7: Allowed regions (blue) in the coupling-DM mass plane α (vertical axis) and m_{DM} in GeV (horizontal axis) from XQC using

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 fast production in S=-2 hypernuclei (but small overlap with baryons)



- **Wavefunction overlap with baryons is very small.** Extremely rare fluctuation required for S ⇔ ΛΛ; S⇔NN is G_F^4 smaller =>
  - nuclei can be stable ($\tau > 10^{29}$ yr) even for $m_S > 2\, m_p$
  - hard to produce in fixed target experiments

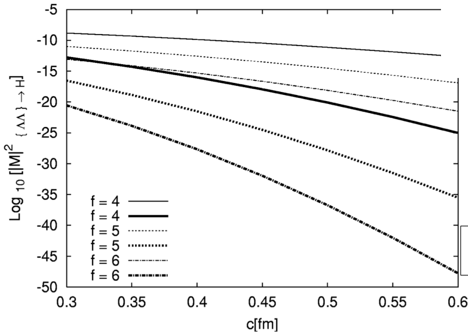


FIG. 1. Log_{10} of $|\mathcal{M}|^2_{\Lambda\Lambda\to H}$ versus hard core radius in femtometers, for ratio $f = R_N/R_H$ and two values of the Isgur-Karl oscillator parameter: $\alpha_B = 0.406$ GeV (thick lines) and $\alpha_B = 0.221$ GeV (thin lines).

GRF+G.Zaharijas 2004

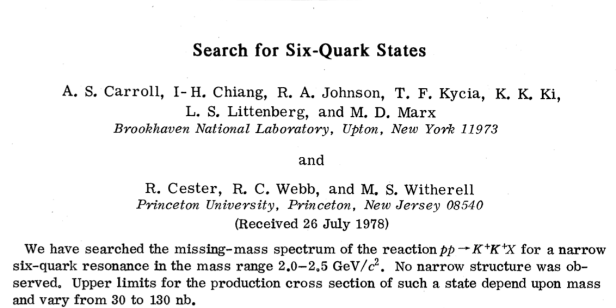
- **S is similar to** (much more copious) **neutrons**

- **Promising accelerator detection strategies**
  - **Apparent lack of baryon number and strangeness conservation:**
    - $\Delta B = \pm 2$ with $\Delta S = \mp 2$
  - **Reconstruct missing mass, e.g.:**
    - $\Upsilon \to \Lambda\, \Lambda\, \bar{S}$ (+ pions) $M_S^2 = (p_\Upsilon - p_{\Lambda 1} - p_{\Lambda 2} - \sum p_{\pi_i})^2$

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:
  - 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 **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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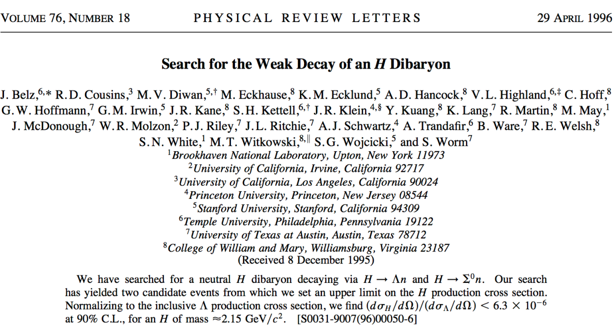
and

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 $pp \rightarrow K^+K^+X$ 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,[6,†] 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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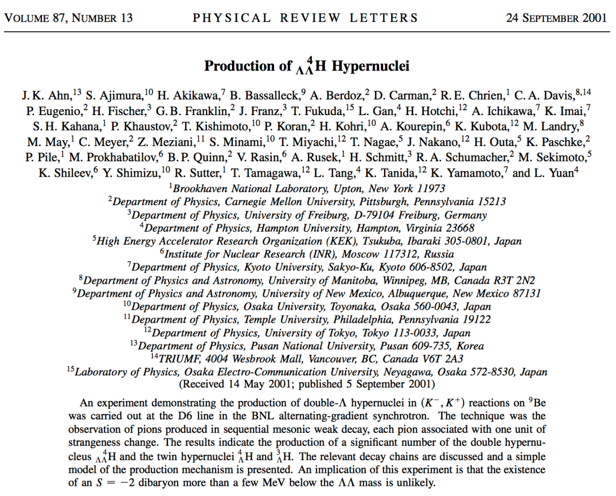
(Received 8 December 1995)

We have searched for a neutral H dibaryon decaying via $H \rightarrow \Lambda n$ and $H \rightarrow \Sigma^0 n$. 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.

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 [illegible] GeV in pp -> K K X
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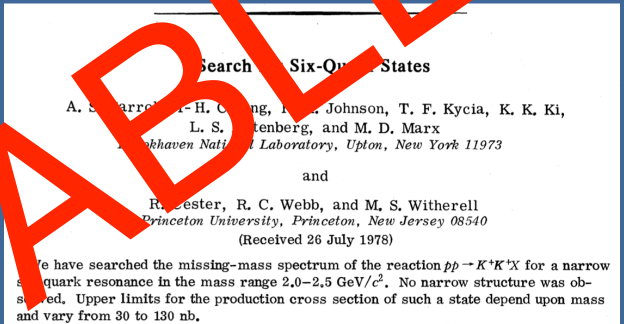

Search [illegible] Six-Qu[illegible] States

A. [illegible]arro[illegible]-H. C[illegible]ng, [illegible]. Johnson, T. F. Kycia, K. K. Ki,
L. S. [illegible]tenberg, and M. D. Marx
[illegible]okhaven Nati[illegible]l Laboratory, Upton, New York 11973

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R. [illegible]ester, R. C. Webb, and M. S. Witherell
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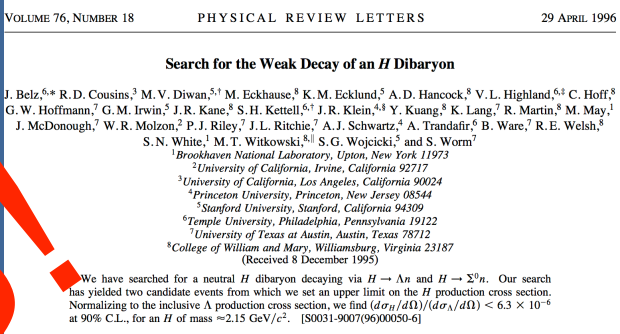

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Search for the Weak Decay of an *H* Dibaryon

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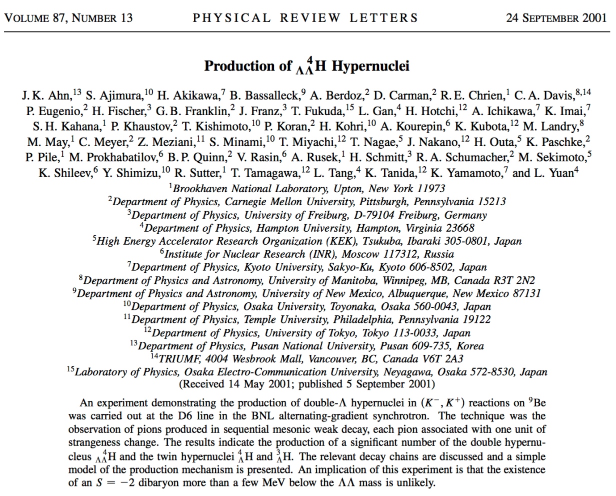
We have searched for a neutral H dibaryon decaying via $H \rightarrow \Lambda n$ and $H \rightarrow \Sigma^0 n$. Our search has yielded two candidate events from which we set an upper limit on the H production cross section. Normalizing to the inclusive Λ production cross section, we find $(d\sigma_H/d\Omega)/(d\sigma_\Lambda/d\Omega)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



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

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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 ${}_{\Lambda\Lambda}^{4}$H and the twin hypernuclei ${}_{\Lambda}^{4}$H and ${}_{\Lambda}^{3}$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 $\Lambda\Lambda$ mass is unlikely.

NOT APPLICABLE
to S!

Cosmology & structure formation

- DM-baryon interaction: momentum transfer => *slight drag on DM during structure formation*
  - Dvorkin, Blum, Kamionkowski (2014):
    - **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_0 & σ_8**
  - Boring or an opportunity? To be determined…
- S-S self interactions + S-baryon interactions:
  - may have similar benefits as Self Interacting DM
    - core-cusp, “too-big-to-fail” & missing sub-halos problems.

Galaxies & Clusters

DM-gas scattering provides a source of heating, needed for

- Milky Way's extended hot gas halo — 2 x10^6 K
- Quenching star formation
- Avoiding "cooling flow catastrophe" in X-ray clusters

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 7Li Discrepancy in BBN and Dark Matter to baryon ratio**
  - Usual WIMP detection strategy isn't applicable.
  - May reconcile tension in H_0 & σ_8 and explain astrophysics puzzles ("quenching", core-cusp, DM rotation curves…)
- ***S may be waiting to be discovered in existing Υ-decays or LHC experiments… mass can be accurately measured in Υ-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

Classic Approach: would be great, but *very* low rate due to low overlap

$$\begin{array}{lcccc}
 & K^- & p \; \rightarrow & \bar{\Lambda} & S \\
B: & & +1 & -1 & +2 \\
S: & s & & \bar{s} & ss
\end{array}$$

- $\bar{\Lambda}$ is a gold-plated signature : $\bar{\Lambda} \rightarrow \pi^+ \bar{p}$
  - Easy to ID & reconstruct 4-momentum
  - $c\tau = 8$ cm   all $\bar{\Lambda}$ are ID'd
- S: undetected, but 4 momentum determined
  - $p_S = p_K + p_p - p_{\bar{\Lambda}}$
  - NA61: est.~ 20 MeV accuracy on "missing-mass" of S
  - For $p_{beam} < 5.35$ GeV/c , no conventional source of $\bar{\Lambda}$'s
- NA61: 9 GeV/c K- beam

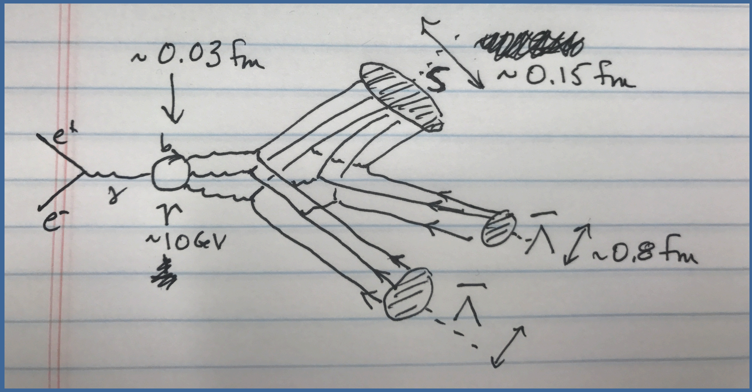
Sexaquark Discovery Strategy

- Apparent lack of B and S conservation:
  - **$\Delta B = \pm 2 \quad + \quad \Delta S = \mp 2$**

- Reconstruct missing mass, e.g.:
  - **$\Upsilon \to \Lambda\,\Lambda\,\bar{S}$** (+ pions) $M_S^2 = (p_Y - p_{\Lambda 1} - p_{\Lambda 2} - \sum p_{\pi_i})^2$
  - LHC: $\bar{S} + N \to \bar{\Lambda}\ K^+$ $M_S^2 = (p_{\bar{\Lambda}} + p_K - p_N)^2$
- Snolab nuclei: $pn \to S\, e^+ \nu$ G_F^4 $\tau > 10^{+29}$ yr

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

(+ 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**
- ***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 ΔB = ± 2, ΔS = ∓ 2 very hard

Background does not have narrow peak in missing mass!

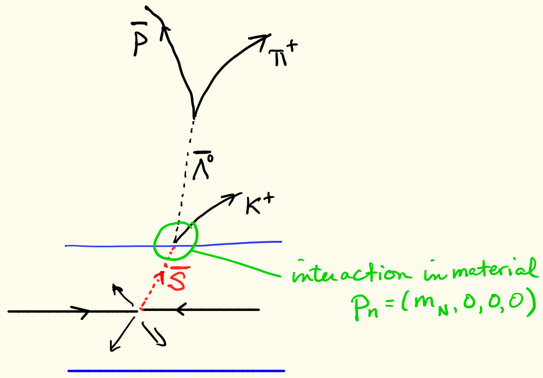
LHC

- Hadronic collisions: low production rate due to small wfn overlap
- Find a needle in a haystack (10^{11} recorded events; potential for trigger >>> more
- Statistical examination of correlation between

  $\Delta B = \pm 2$, $\Delta S = \mp 2$
- **$\bar{S}$ annihilation in tracker, tag by**

  $\bar{\Xi}^{+,0} \to \bar{\Lambda}\, \pi^{+,0}$ ($c\tau = 5\gamma$ cm) $\bar{\Lambda} \to \bar{p}\, \pi^{+}$

  or $\bar{\Lambda}\, K^{+}$



$$\underset{\cdots\bar{s}\bar{s}}{\bar{S}} + p \longrightarrow \underset{\bar{s}}{\bar{\Lambda}}\; \underset{\bar{s}u}{K^+}$$

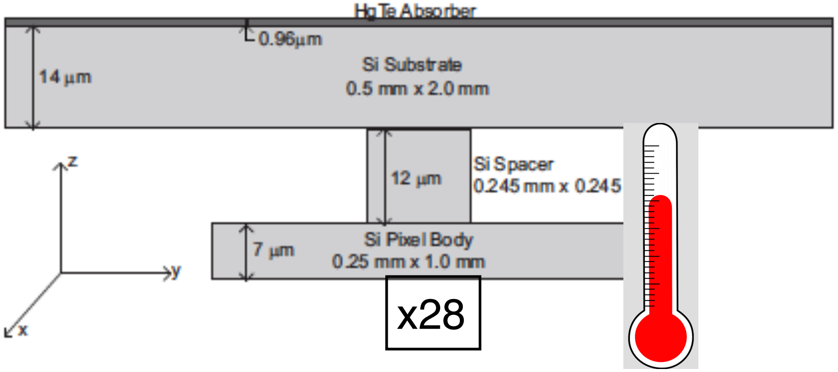
$$\bar{S} \quad p, n \longrightarrow \underset{.\bar{s}\bar{s}}{\bar{\Xi}^{+0}}\; \pi^{0,+}$$

$$P_t(\bar{S}) \sim 1\,\text{GeV}$$

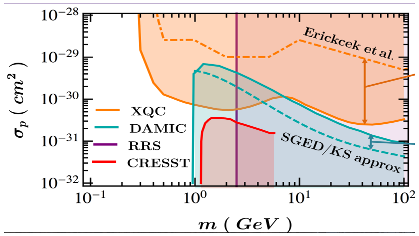
$$\boxed{m_S^2 = p_{\bar{S}}^2 = \left(p_{K^+} + p_{\bar{\Lambda}} - p_n\right)^2}$$

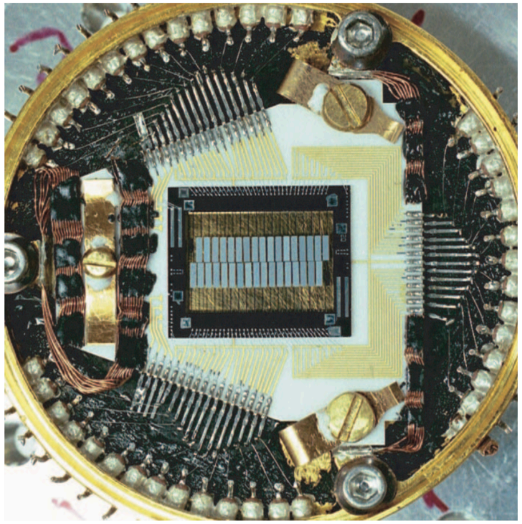
- 2nd exponential in scattering-length distribution of n-like interactions, due to S

X-Ray Quantum Calorimeter (XQC)



- On sounding rocket, 200 km above earth
- Best limit for high x-secn (McCammon+02,Wandelt+02,GF+Zaharijas05, Erickcek+07, Mahdawi & GF 17)
  - sensitive to X-rays with E ≳ 29 eV
  - 100 sec flight, ~ 100 events
  - nuclear recoil => X-rays, which thermalize *(assumption)*





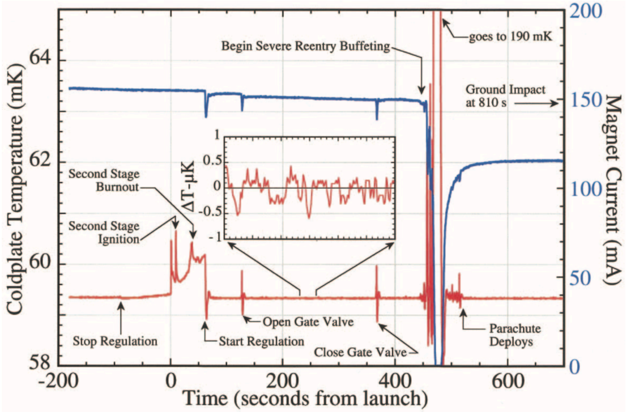


Fig. 7.—In-flight performance of the temperature control system, showing the coldplate temperature and magnet current. Temperature fluctuations during data taking are about 210 nK rms. The gate-valve motor is located on the vacuum jacket and caused the most serious thermal disturbance up to reentry. Accelerations during reentry exceeded 20 *g* with tumbling at ~1 Hz, introducing heat to the cold stage faster than it could be removed. Temperature regulation is recovered once tumbling stops, allowing calibration data to be obtained.

Calibrate with X-rays

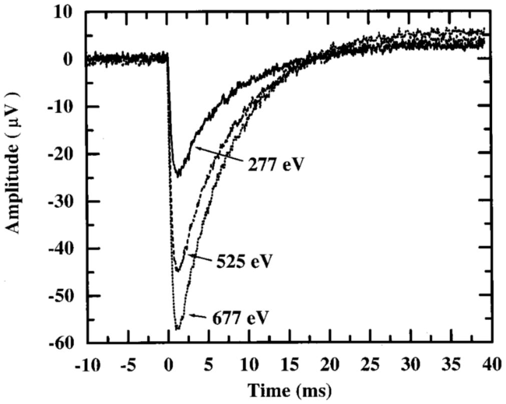


Fig. 8.—Unfiltered X-ray pulses from the gate-valve calibration source.

Closer look at XQC sensitivity

Silicon nucleus recoil: $KE_{max} \sim 500$ eV => $v_{max} \sim 20$ km/s << v_e =>

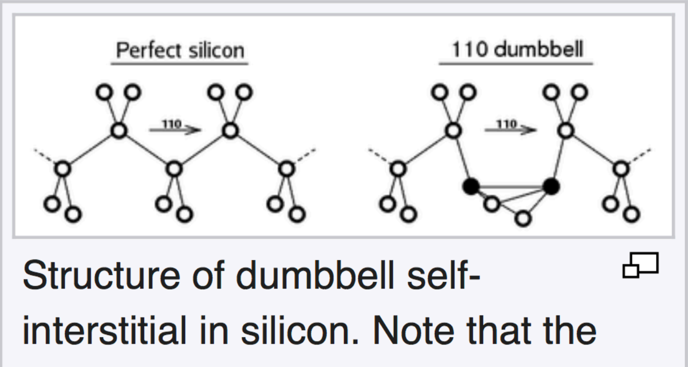
- atomic interaction is adiabatic =>
- negligible ionization.

Si atom moving in semiconductor crystal:

- rearranges covalent bonds
- produces interstitial defects
- 500eV atom produces Frenkel pairs (V+I)
  - $E_{Fp\_min} = 5$ eV
  - $E_{migration} \sim 0.1$ eV
- Cascade energy loss producing
  - N ~ (KE_{rec} / 5 eV) Frenkel pairs,

<~2% of KE_{rec} goes to thermalization

=> $KE_{rec,min} > 1.5$ keV => $KE_{DM,min} > 6$ keV => $v_{DM,min} > 300$ km/s



Structure of dumbbell self-interstitial in silicon. Note that the

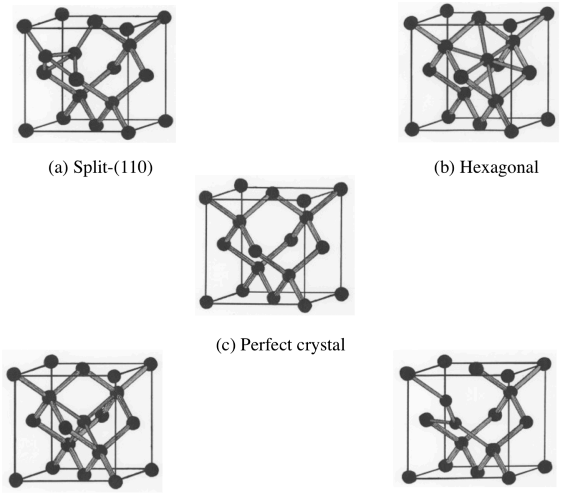


Figure 1. Illustrations of the split-⟨110⟩, hexagonal, and tetrahedral self-interstitial defects, together with the perfect crystal and the saddle point of Pandey's concerted exchange.