Stable Sexaquark as Dark Matter

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Stable Sexaquark as Dark Matter

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

[Hints from Astrophysics]

Primordial Nucleosynthesis

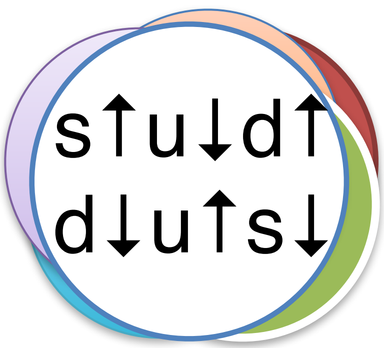
Dark-Matter to Ordinary-Matter ratio

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

(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

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 $m_S \approx m_{glueball} + 180$ MeV = (1.5-1.7)+ 0.18 GeV $\lesssim 2\ m_p$
- 3x di-quark mass = 1.2 - 2-ish GeV

- $m_S < 2\ (m_p + m_e)$: S is absolutely stable
- $m_S > 2\ (m_p - 8$ 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   ($\tau > \tau_{Univ}$ 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:

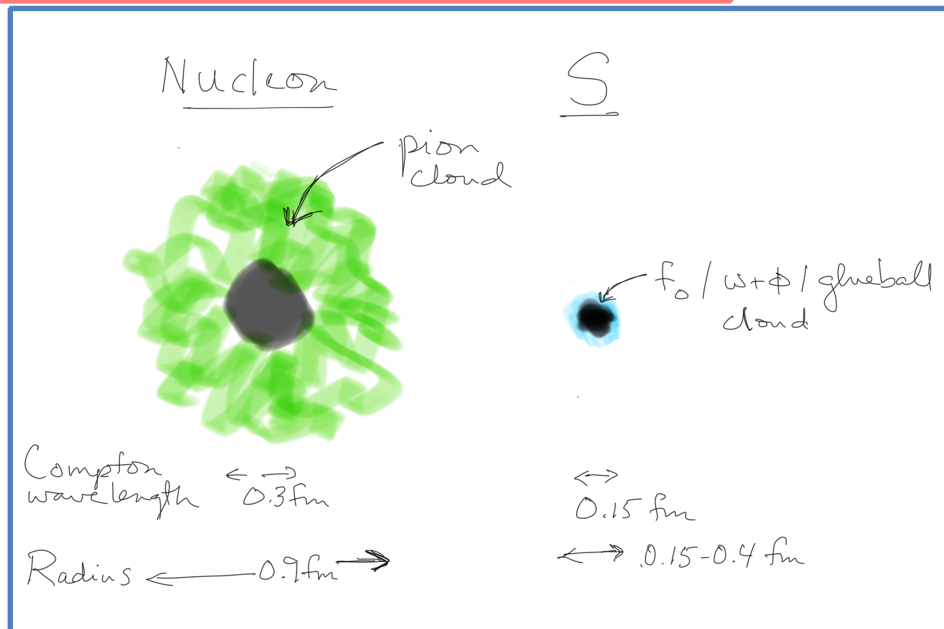
S does not couple to pions. ∴ much smaller than usual hadrons (proton, pion,…)

6-quark, Q=0, B=2

Spin-0, scalar

Flavor singlet

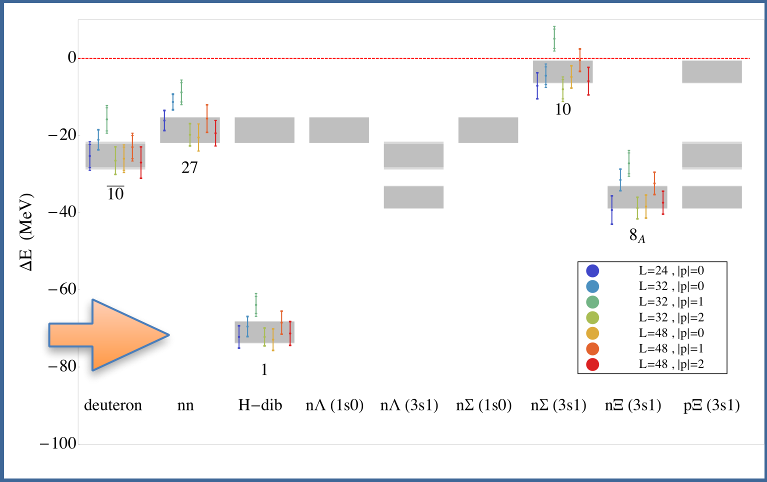
m ~ 1.7-2 GeV



Stable S?

- $\tau > \tau_{Univ}$ if:
  - **$M_S < 2\ m_p + 2\ m_e$ = 1877.6 MeV ➜ absolutely stable**
  - if $M_S < m_p + m_e + m_\Lambda$, $\Gamma \sim G_F^4$ 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)

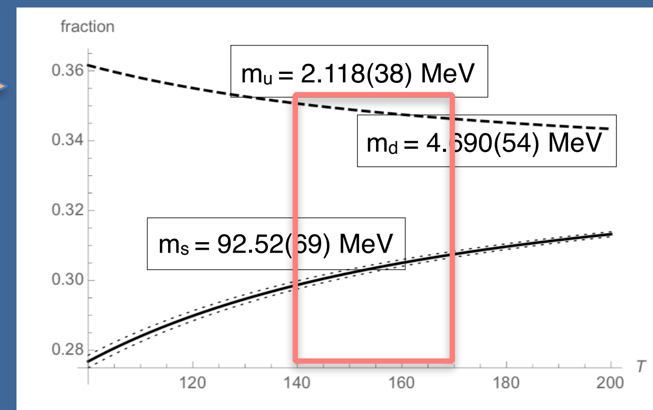
✓ Correct relic density (for natural m_{DM} & $\boldsymbol{\sigma}_{f.o.}$)

Ω_{DM} / Ω_b

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

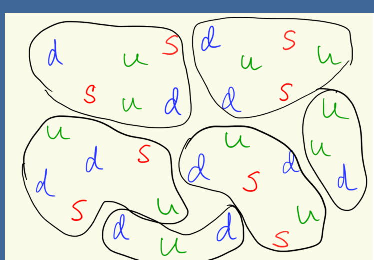
$m_S/(2m_p)$

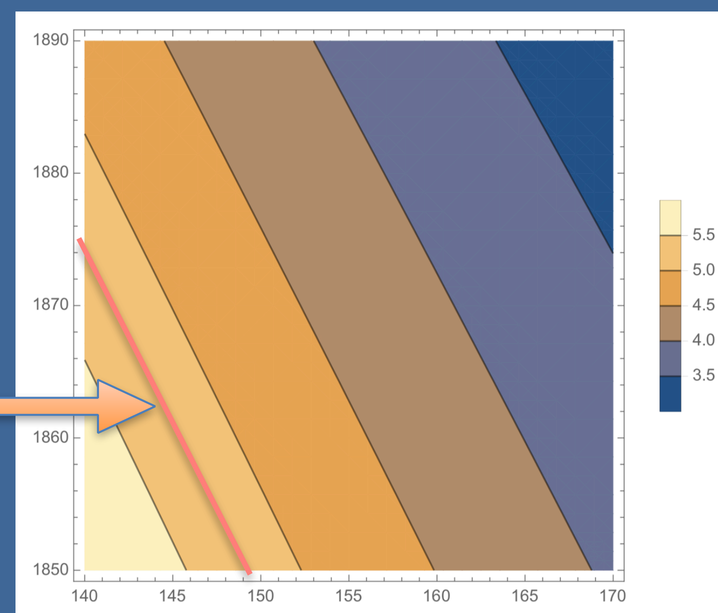
$$\frac{\Omega_{DM}}{\Omega_b} = \frac{y_b\,\kappa_s\,3f_s}{1-\kappa_s\,3f_s}$$



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

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





Ω_{DM} / Ω_b = 5.3 ± 0.1

Prediction also applies to strange quark nuggets…

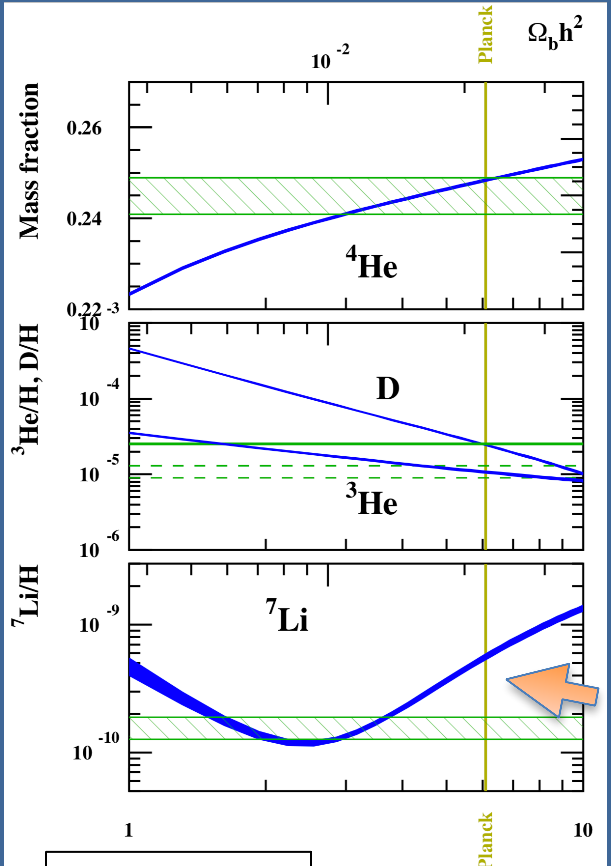
Problem with primordial ^{7}Li

(GRF + Richard Galvez, in preparation)

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

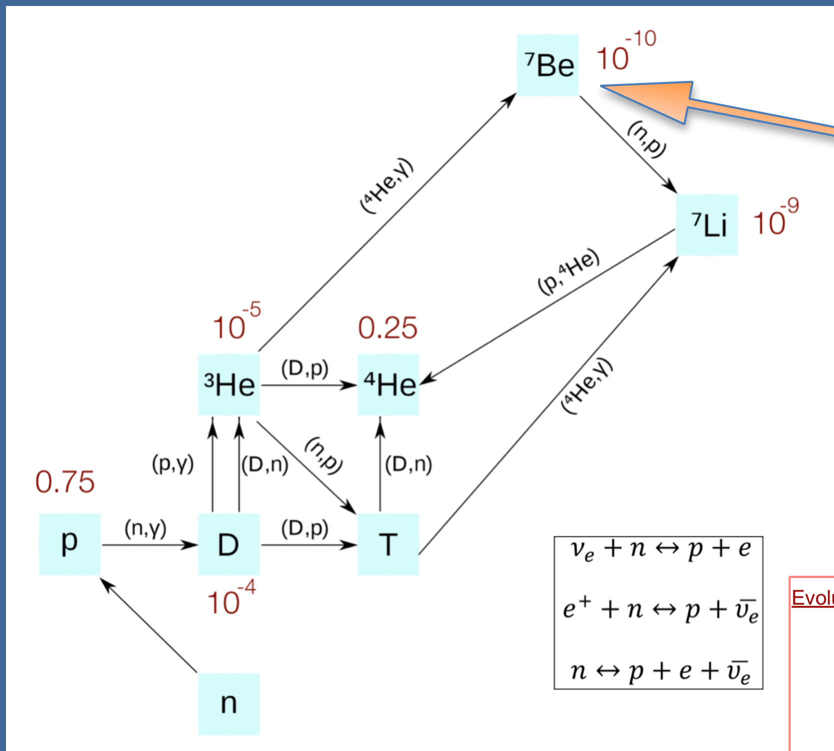
- Discrepancy is now very serious:
  - Nuclear rates all well-measured
  - $\eta = n_b/n_\gamma$ = (6.58 ± 0.02) 10^{-10} from CMB
  - Astrophysics now secure (Spite plateau):
    - small scatter
    - flat > 3 decades of low metallicity

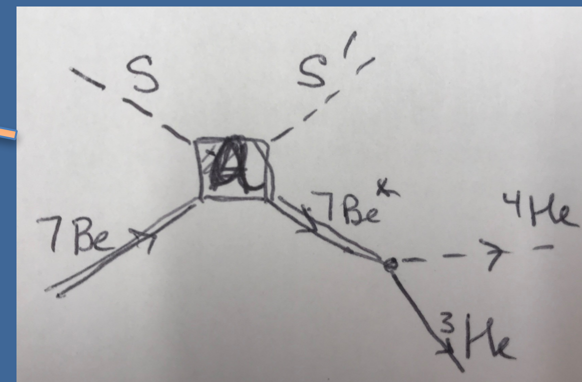
- **S solves the puzzle**
  - No other (reasonable) solution known

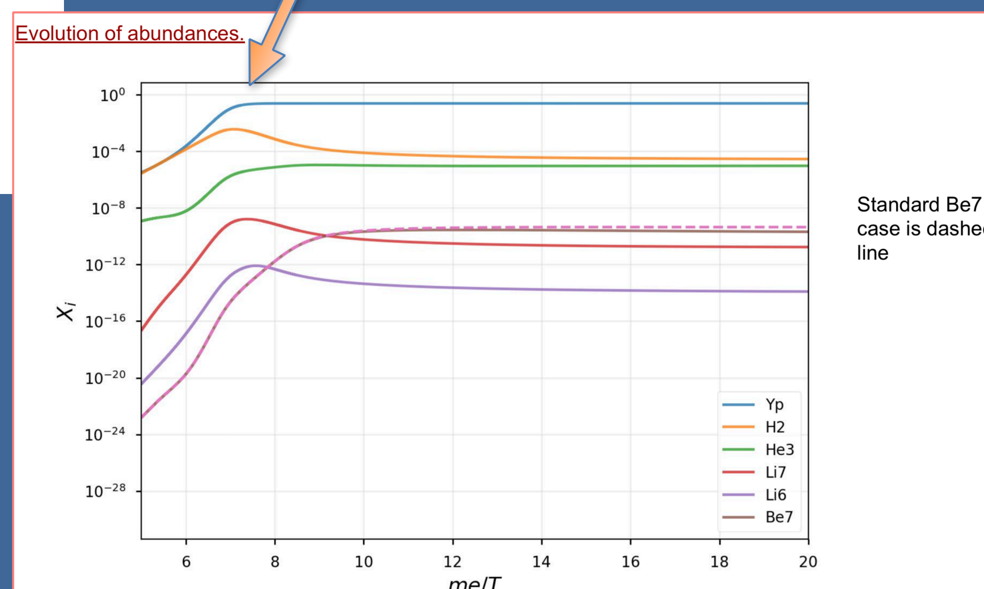


Coc&Vangioni, 2017

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







- **Solves the puzzle**
- **Doesn't affect He or d**
  - E threshold for breakup =

1.58, 2.46, 4.47, 5.75, 19.3 [2.2] MeV

7Be 7Li 3He T 4He [d]

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 may fail badly**
  - cross section depends only on combos $a = \frac{v}{2\alpha}$ and $b = \frac{2\alpha\mu}{m_\phi}$

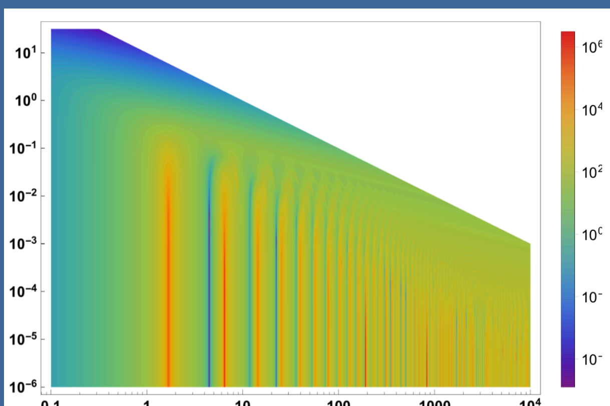


FIG. 1: $\sigma\, m_\phi^2$ as a function of $a = \frac{v}{2\alpha}$ and $b = \frac{2\alpha\mu}{m_\phi}$.

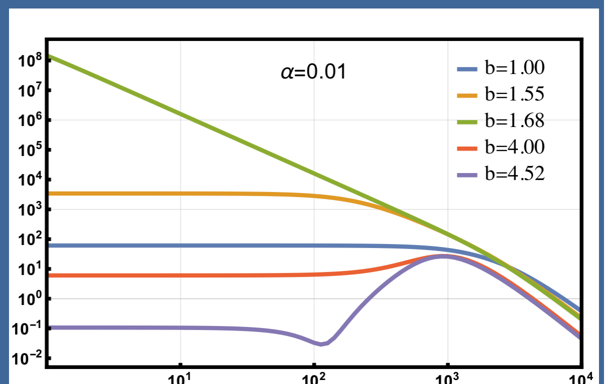


FIG. 4: $\sigma\, m_\phi^2$ versus v in km/s, for 5 values of $b = \frac{2\alpha\mu}{m_\phi}$.

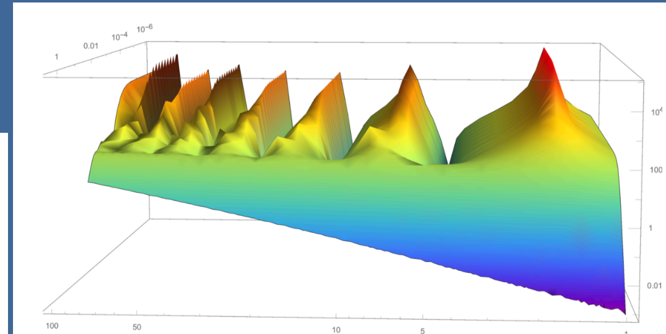


FIG. 2: 3D plot of $\sigma\, m_\phi^2$ in the a, b plane; b increases to the left and a decreases toward the back.

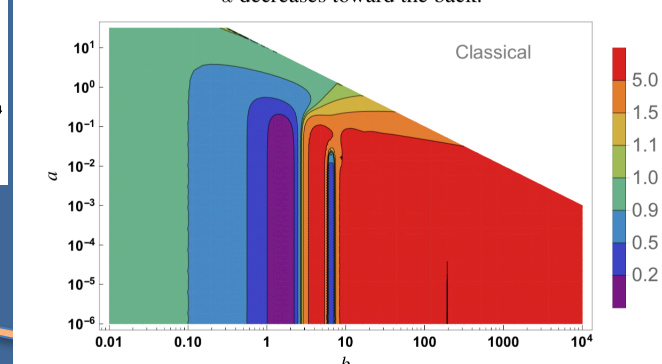
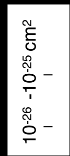
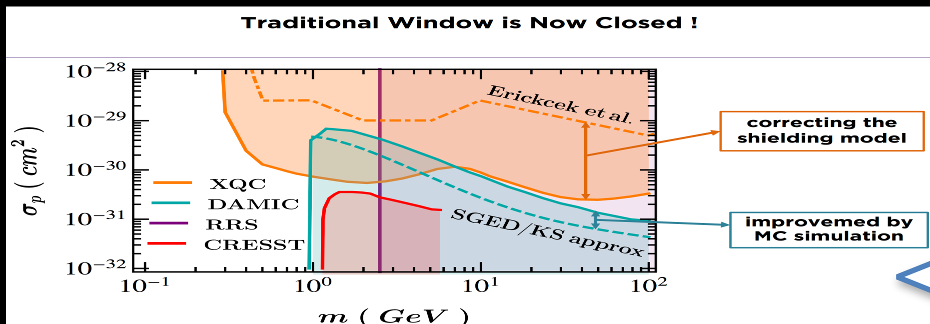


FIG. 3: Ratio of Born Approximation and Schroedinger Equation

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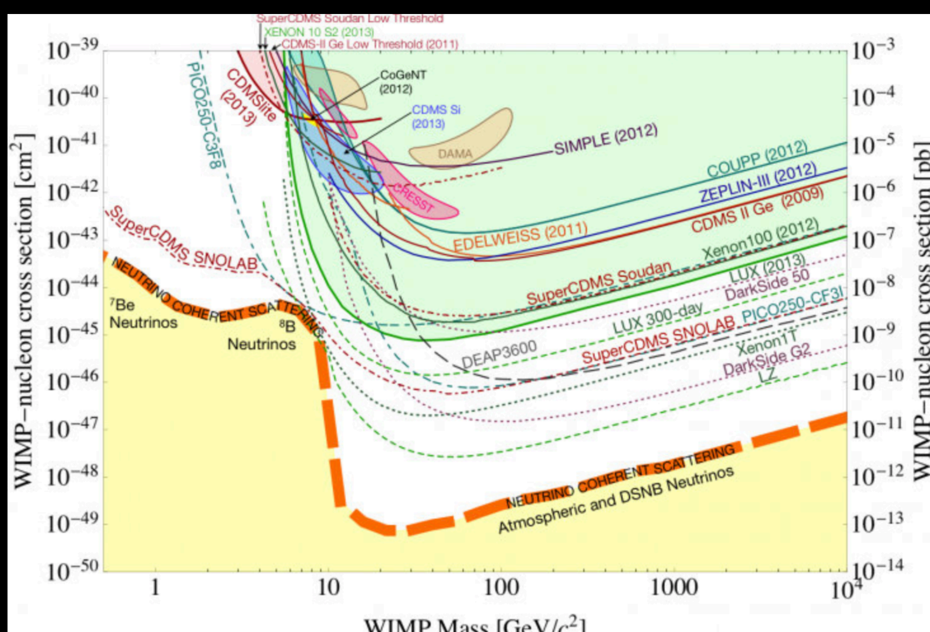
Abstract. We improve limits on the spin-independent scattering cross section of Dark Matter on nucleons, for DM in the 300 MeV – 100 GeV mass range, based on the DAMIC and XQC experiments. Our results close the window which previously existed in this mass range, for a DM-nucleon cross section of order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

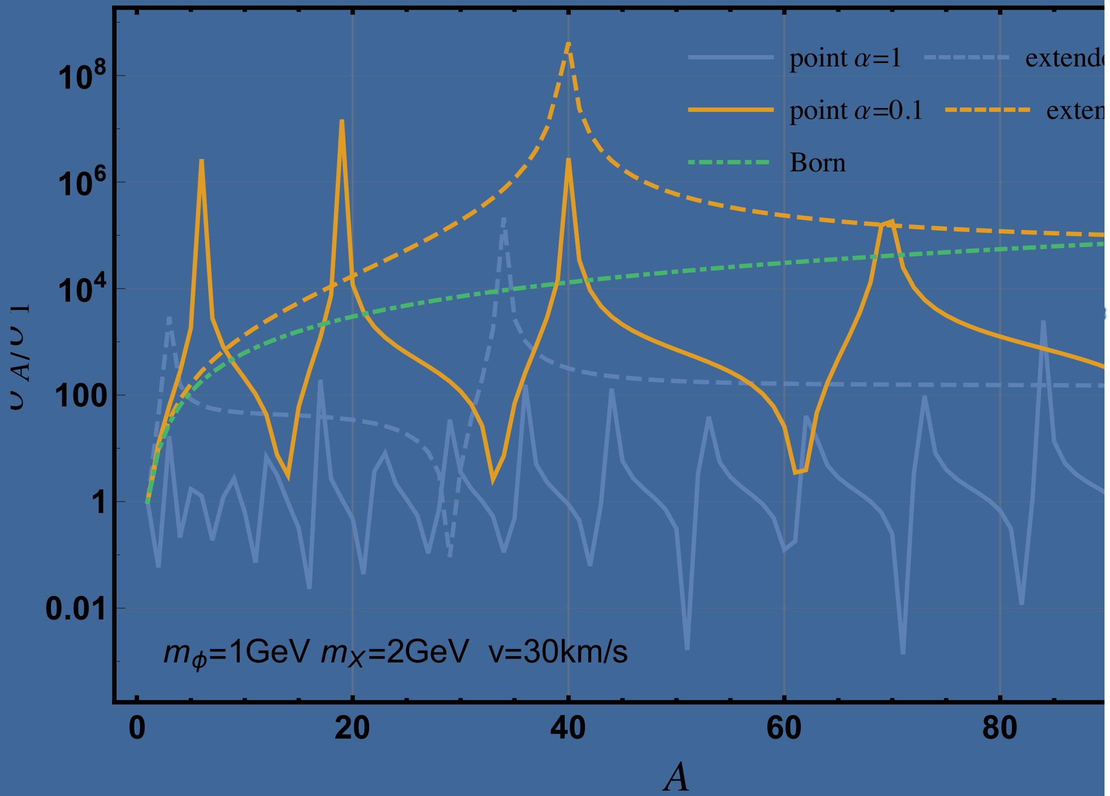
Shielded (e.g. underground) detectors are not sensitive



Plenty of Room for HIDM

(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 best Direct Detection

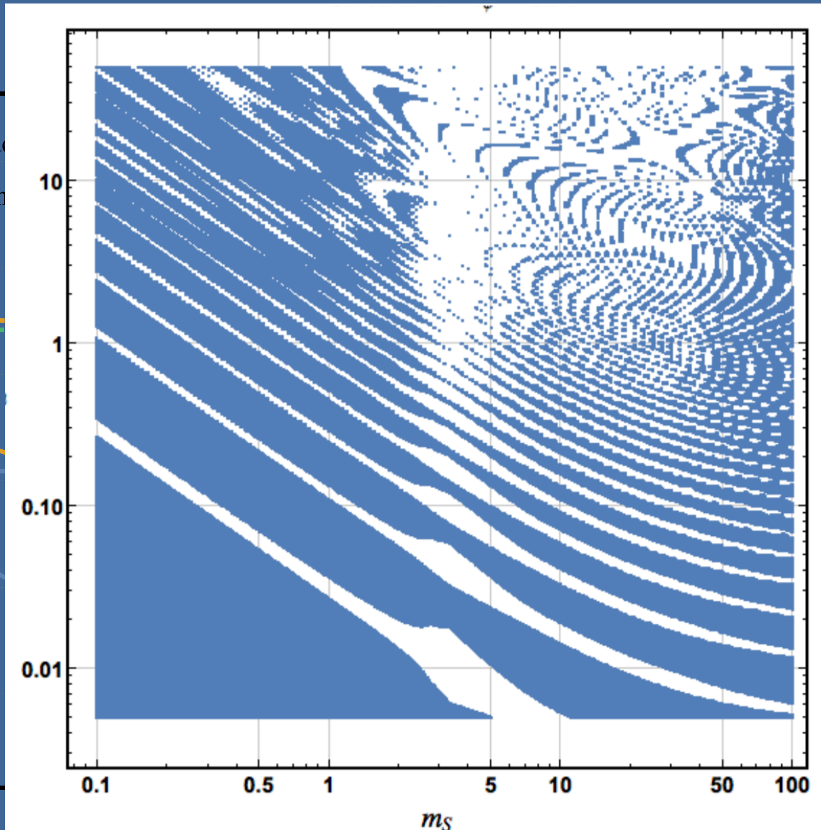
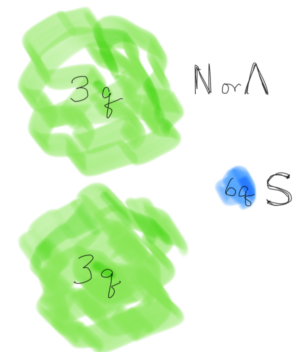


FIG. 7: Allowed regions (blue) in the coupling-DM mass plane α (vertical axis) and m_{DM} in GeV (horizontal axis) from XQC using

S has not been discovered because it is <u>elusive</u>

- **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

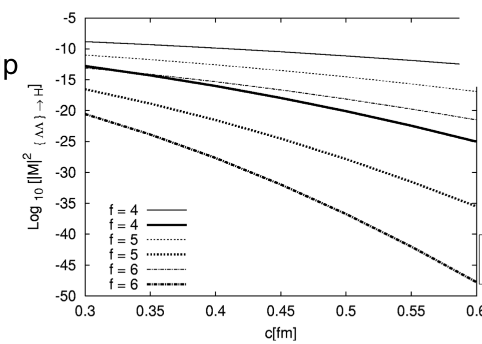


FIG. 1. Log_{10} of $|\mathcal{M}|^2_{\Lambda\Lambda\to H}$ versus hard core radius in femtometers, for ratio $f = R_N/R_H$ and two values of the Isgur-Karl oscillator parameter: $\alpha_B = 0.406$ GeV (thick lines) and $\alpha_B = 0.221$ GeV (thin lines).

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
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  - 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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(Received 26 July 1978)

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

VOLUME 76, NUMBER 18 PHYSICAL REVIEW LETTERS 29 APRIL 1996

Search for the Weak Decay of an *H* Dibaryon

J. Belz,[6,*] R.D. Cousins,[3] M.V. Diwan,[5,†] M. Eckhause,[8] K.M. Ecklund,[5] A.D. Hancock,[8] V.L. Highland,[6,‡] C. Hoff,[8] G.W. Hoffmann,[7] G.M. Irwin,[5] J.R. Kane,[8] S.H. Kettell,[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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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 $_{\Lambda\Lambda}^{4}$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 $_{\Lambda\Lambda}^{4}$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 ΛΛ mass is unlikely.

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

$$K^- \, p \rightarrow \bar{\Lambda} \;\; S$$

	K^-	p		$\bar{\Lambda}$	S
B:		+1		-1	+2
S:	s			$\bar{s}$	ss

- $\bar{\Lambda}$ 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

Experimental Searches

- Require M > 2 GeV:
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NOT APPLICABLE to S!

Search [illegible] Six-Qu[illegible] States

A. S[illegible]arro[illegible] I-H. C[illegible]ng, [illegible]. Johnson, T. F. Kycia, K. K. Ki,
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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 ΛΛ mass is unlikely.

Discovery Strategy

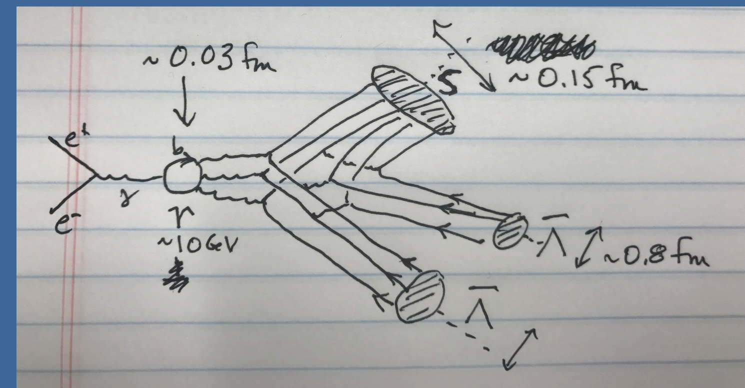
- Apparent lack of B and S conservation:
  - **$\Delta B = \pm 2 \quad + \quad \Delta S = \mp 2$**

- Reconstruct missing mass, e.g.:
  - **$\Upsilon \to \Lambda\, \Lambda\, \bar{S}$** (+ pions) $\quad M_S^2 = (p_Y - p_{\Lambda 1} - p_{\Lambda 2} - \sum p_{\pi_i})^2$
  - LHC: $\bar{S} + N \to \bar{\Lambda}\; K^+ \qquad M_S^2 = (p_{\bar{\Lambda}} + p_K - p_N)^2$

- Snolab nuclei: $pn \to S\, e^+ \nu \qquad G_F^4 \qquad \tau > 10^{+29}$ yr

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

(+ 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**
- ***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!

LHC

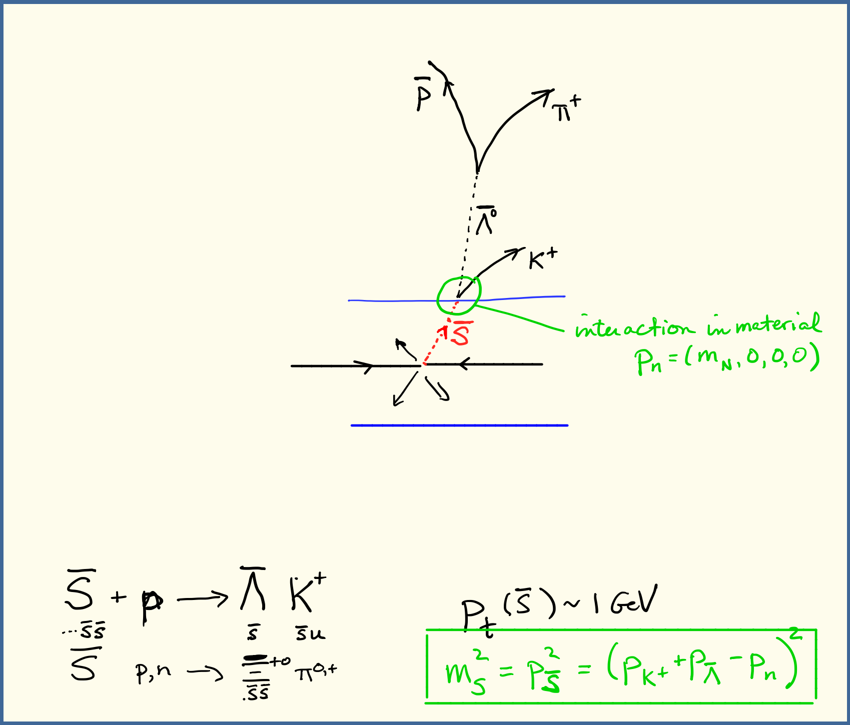
- Hadronic collisions: low production rate due to small wfn overlap
- Find a needle in a haystack (10^{11} recorded events; potential for trigger >>> more
- Statistical examination of correlation between

  $\Delta B = \pm 2$, $\Delta S = \mp 2$

- **$\bar{S}$ annihilation in tracker, tag by**

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

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



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

Cosmology & structure formation

- DM-baryon interaction: momentum transfer =>
  slight drag on DM during structure formation
  - Dvorkin, Blum, Kamionkowski (2014):
    - **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:
  - 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 — 2×10^6 K
- Quenching star formation
- Avoiding "cooling flow catastrophe" in X-ray clusters

Key points to take home

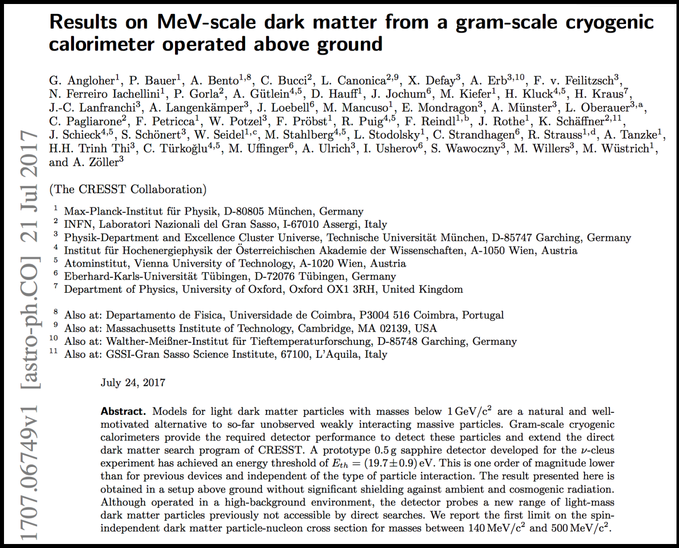
- ***There may a tightly bound 6-quark state* S= uuddss**
  - **Unique, symmetric structure ⇒ other hadrons don't provide guidance**
    - mass is not driven by chiral symmetry breaking (unlike baryons)
    - constituent quark model probably completely misleading
  - ***If $M_S < 2\, m_p + 2\, m_e$, 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.
  - Baryon asymmetric Universe is expected
  - 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

Strategies to detect DM

if DM is comprised of S's

- With v_{rel} = 30 km/s , KE_{DM} ~ 10 eV
  - $\langle E_{deposit} \rangle / KE_{DM}$ = 0.12 for Si target
    - = 0.02 for Hg target
    - = 0.44 for H or He target
  - **Energy-loss length of S in Earth crust:** $\lambda = 2\ cm / \sigma_{10mb}$
  - **Present detectors shielded or too high threshold (new CRESST expt has E_{th} = 19 eV, but 30 cm shielding ⇒ not sensitive)**



Results on MeV-scale dark matter from a gram-scale cryogenic calorimeter operated above ground

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Abstract. Models for light dark matter particles with masses below 1 GeV/c^2 are a natural and well-motivated alternative to so-far unobserved weakly interacting massive particles. Gram-scale cryogenic calorimeters provide the required detector performance to detect these particles and extend the direct dark matter search program of CRESST. A prototype 0.5 g sapphire detector developed for the ν-cleus experiment has achieved an energy threshold of $E_{th} = (19.7 \pm 0.9)$ eV. This is one order of magnitude lower than for previous devices and independent of the type of particle interaction. The result presented here is obtained in a setup above ground without significant shielding against ambient and cosmogenic radiation. Although operated in a high-background environment, the detector probes a new range of light-mass dark matter particles previously not accessible by direct searches. We report the first limit on the spin-independent dark matter particle-nucleon cross section for masses between 140 MeV/c^2 and 500 MeV/c^2.

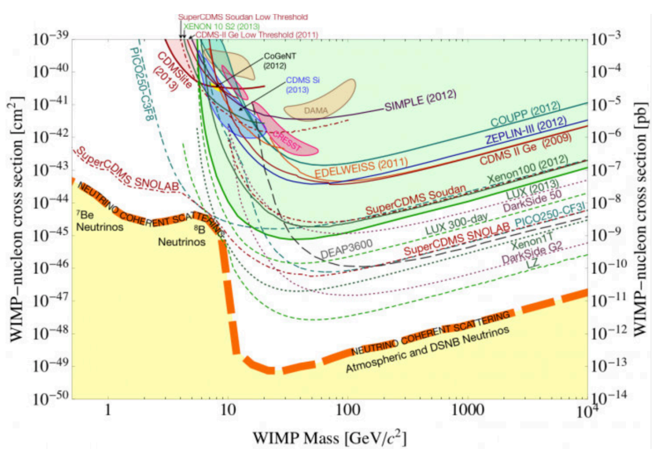
- Heating rate liquid He: ~ nW/mol ~ CR muon energy deposit rate.
  - can't *shield* muons & other CRs: veto? but what about neutrons?

Directly Detecting the S

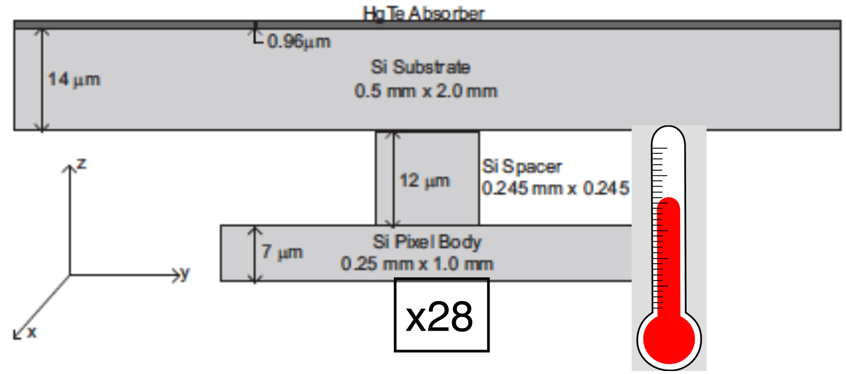
- ***Light, slow-moving, strongly interacting* DM is not visible in current detectors:**
  - **KE $_{DM}$ = 500 eV** ($\mathbf{m_{DM}}$ / 2 m_p) $\mathbf{v^2}$ / (220 km/s)^2
  - **<E$_{deposit}$>/KE $_{DM}$ = 0.12** for Si target

    = 0.02 for Hg target

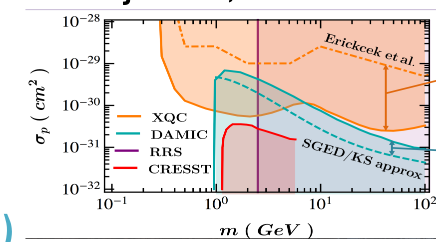
    = 0.44 for H or He target
  - **Energy-loss length in Earth crust:** $\boldsymbol{\lambda = 2\ cm / \sigma_{10mb}}$
  - **CRESST, Xenon1T, LUX, DAMIC are not sensitive**

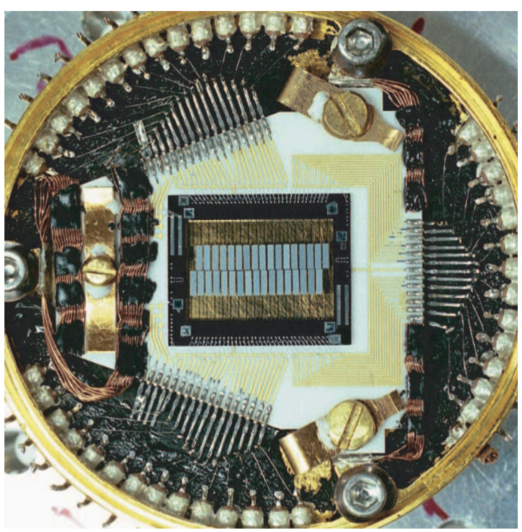


X-Ray Quantum Calorimeter (XQC)



- 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)*





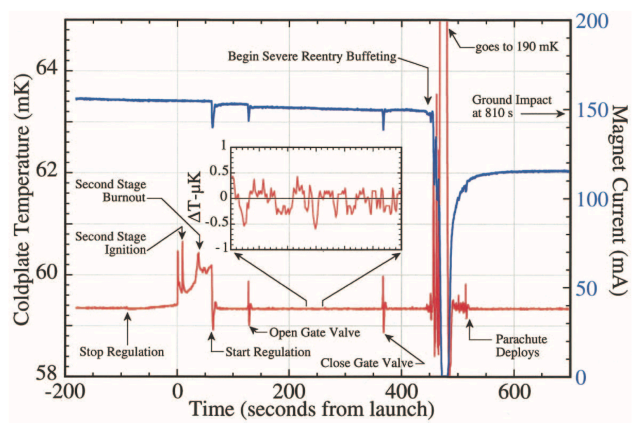


Fig. 7.—In-flight performance of the temperature control system, showing the coldplate temperature and magnet current. Temperature fluctuations during data taking are about 210 nK rms. The gate-valve motor is located on the vacuum jacket and caused the most serious thermal disturbance up to reentry. 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

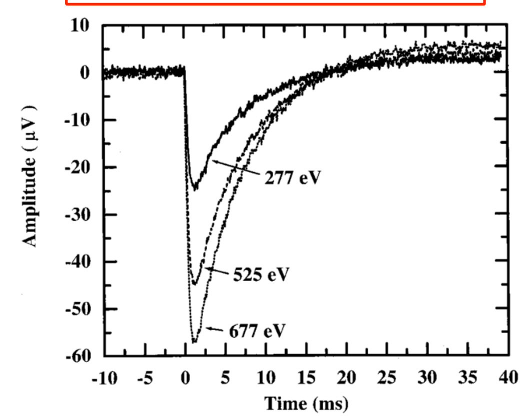
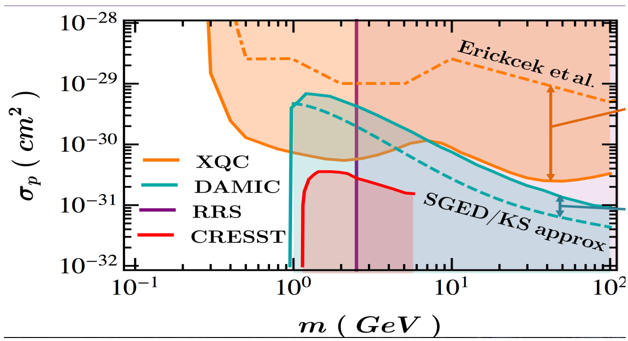


Fig. 8.—Unfiltered X-ray pulses from the gate-valve calibration source.

Challenge to Direct Detection of S

- **Taking XQC sensitivity at face value:**

  XQC above atmosphere is best. E_{thresh} = 30 eV
  (McCammon+02, Wandelt+02, GF+Zaharijas05, Erickcek+07, Mahdawi+GRF 2017)

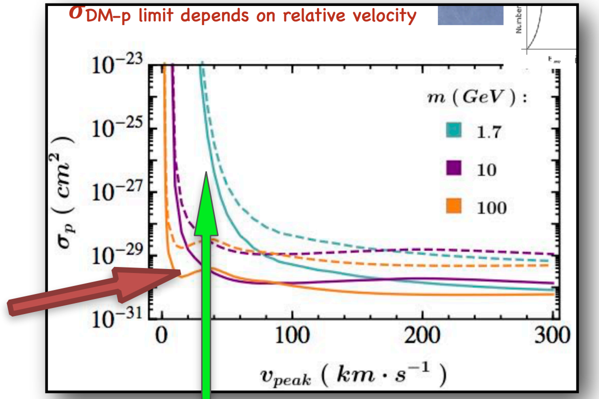
  - Mahdawi+GRF 2017: $\sigma_{DM} < 10^{-29}$ cm^2 *for standard velocity dispersion* — ***SDM has σ_{DM} ~ 10-100 mb***

  - ***$v_{min,XQC}$ = 100 km/s (2 m_p / m_{DM})$^{1/2}$***

- ***BUT:***

  - ***velocity distribution?***
    - ***(gas co-rotates, red vel ~ 10 km/s)***

  - ***does E_{rec} really thermalize?***



Co-rotation reduces SDM signal

Closer look at XQC sensitivity

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

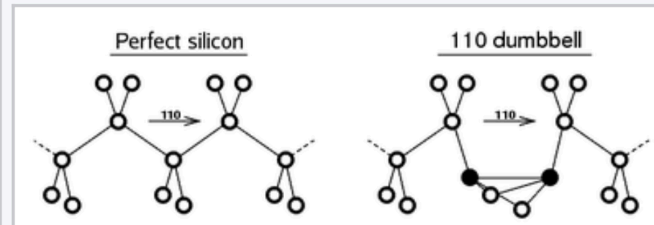
- atomic interaction is adiabatic =>
- negligible ionization.

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

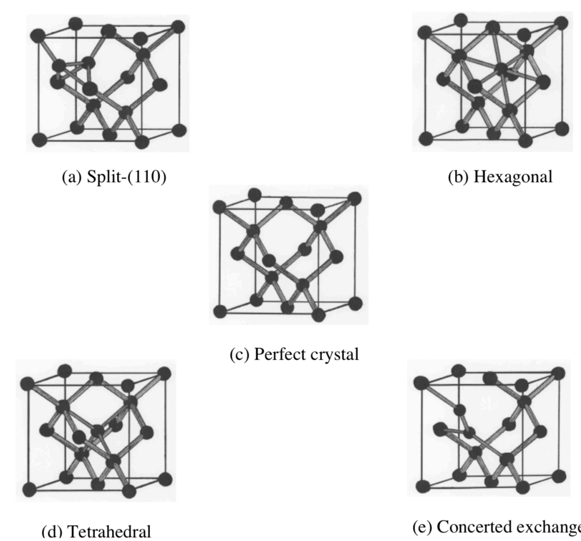


Figure 1. Illustrations of the split-⟨110⟩, hexagonal, and tetrahedral self-interstitial defects, together with the perfect crystal and the saddle point of Pandey's concerted exchange.