Refined mass window for a stable sexaquark

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With Glennys Farrar, 190X.XXXXX to appear

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Introduction

What is sexaquark (S): *uuddss* color-spin-flavor singlet

$$|S\rangle = \frac{1}{24}(\epsilon_{\alpha\mu\rho}\epsilon_{\beta\nu\sigma}\epsilon_{im}\epsilon_{jk}\epsilon_{ln} - \epsilon_{\alpha\beta\rho}\epsilon_{\mu\nu\sigma}\epsilon_{im}\epsilon_{jl}\epsilon_{kn})u^{\dagger}_{\alpha,i}u^{\dagger}_{\beta,j}d^{\dagger}_{\mu,k}d^{\dagger}_{\nu,l}s^{\dagger}_{\rho,m}s^{\dagger}_{\sigma,n}|\Omega\rangle$$

(Farrar, Wintergerst, *in prep*)

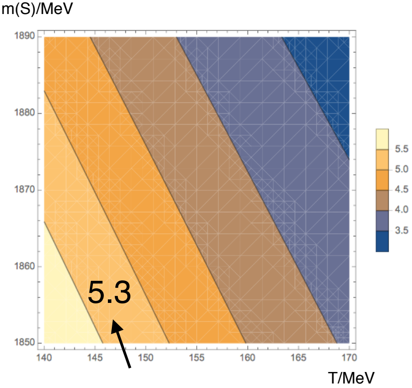
- Quantum numbers: $Q = 0$, $B = 2$, S$= -2$, P$= 1$
- Compact in size $\sim$ 0.1 - 0.3 fm,

$$r_S = \lambda_S + 0.5\lambda_{\omega-\phi}$$

c.f. proton $\sim$ 0.9 fm with pion clouds.

(Farrar 17)

DM candidate in SM: abundance $\sim$ 5 times of baryons from QCD plasma.



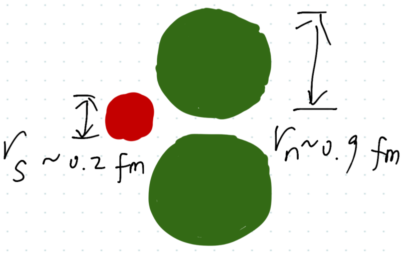
Breakup of S by mesons, need vertex $g(S\Lambda\Lambda) \lesssim 10^{-6}$ to maintain $\Omega_{\rm DM}/\Omega_b \sim 5$. (Farrar 18)

Spatial overlap

Coupling constant $g(S\Lambda\Lambda) = \frac{\mathcal{O}_{\rm sp}}{\sqrt{40}}$. Spatial wavefunction overlap

$$\mathcal{O}_{\rm sp} = \langle \psi_{sp}(\Lambda_1)\psi_{sp}(\Lambda_2)|\psi_{sp}(S)\rangle \sim \left(\frac{r_S}{r_\Lambda}\right)^{18}.$$

(Farrar, Zaharijas, 03)



Take $r_S = 0.2$ fm, $r_\Lambda = 0.9$ fm,

$$\mathcal{O}_{\rm sp} \sim 10^{-12}.$$

DM abundance requirement $\mathcal{O}_{\rm sp} \lesssim 10^{-6}$ easily satisfied.

Mass window

- Unstable for $m_S > 2(m_p + m_e) = 1877.6$ MeV

$$S \to ppee\bar{\nu}\bar{\nu},\ npe\bar{\nu},\ nn.$$

- Absolutely stable for $m_S < 1877.6$ MeV by B conservation. But nuclei could decay if S is too light.
- Narrow mass window for absolutely stable S and nuclei:

$$1877.6 - \mathrm{B.E.} < m_S < 1877.6\,\mathrm{MeV},$$

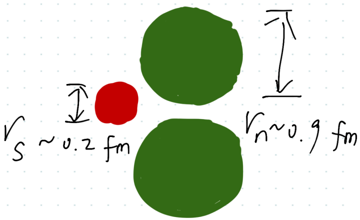
  e.g. B.E. ~ 16 MeV in oxygen, ~ 2 MeV in deuteron.
- This work: for $m_S \sim$ 1382-2055 MeV, how unstable are S and nuclei.

Untable S: $S \to nn$

Model $S \to nn$ by an effective Yukawa interaction

$$\mathcal{L} = gS\bar{n}n^C + \mathrm{h.c.}$$

Coupling constant $g \propto \mathcal{O}_{\mathrm{sp}} = \langle \psi_{sp}(n_1)\psi_{sp}(n_2)|\psi_{sp}(S)\rangle$. Take $\mathcal{O}_{\mathrm{sp}}$ as a free parameter.



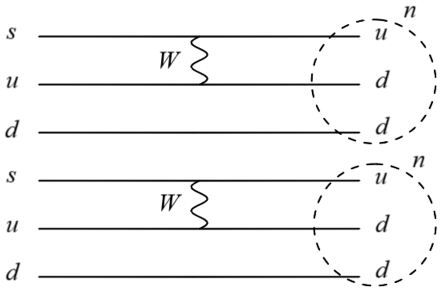
Estimates for $r_S \sim 0.2$ fm, $r_n \sim 0.9$ fm,

$$\mathcal{O}_{\mathrm{sp}} \sim 10^{-12}.$$

But not enough yet: the weak interaction.

$S \to nn$: EFT

ΔS$=\pm$2, doubly-weak interaction of quarks: $g^2 \propto G_F^4 p^8 \sin^4\theta_c$



Choice of p: Physical mass $\sim$ MeV (ud) and $\sim$ 100 MeV (s); $\Lambda_{\mathrm{QCD}} \sim$ 100 MeV; Constituent mass $\sim$ 300 MeV; Heisenberg uncertainty $\sim$ GeV.

$S \to nn$: EFT

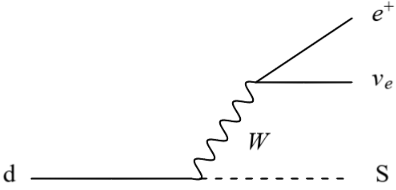
- Combine weak interaction and spatial overlap,

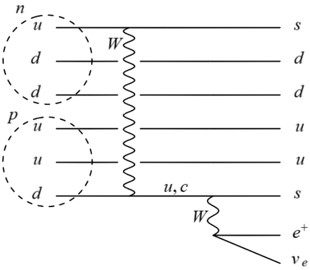
$$g^2 = \mathcal{O}_{\rm sp}^2 \times \left(\frac{p}{\rm MeV}\right)^8 \times 10^{-44}.$$

- Decay rate

$$\Gamma(S \to nn) = \frac{g^2 m_S}{8\pi}\left(1 - \frac{4m_n^2}{m_S^2}\right)^{3/2}$$

depends on m_S, $\mathcal{O}_{\rm sp}$ and p.





$$\mathcal{L} \supset gSd^\mu W_\mu + g_W W_\mu \bar{\psi}\gamma^\mu(1-\gamma^5)\psi$$

$$g^2 \sim g_W^2 G_F^2 p^6 \sin^4\theta_c \mathcal{O}_{\mathrm{sp}}^2$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} = \frac{g^2 g_W^2}{3m_W^4}\frac{1}{32\pi^3 m_d m_{\mathcal{S}}}\sqrt{E_e^2 - m_e^2}E_e(m_d - m_{\mathcal{S}} - E_e)^2$$

Experimental limits

- Sudbury Neutrino Observatory (SNO):

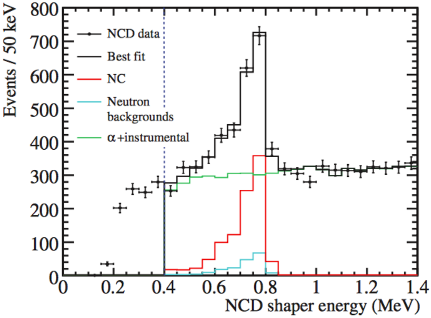
$$\nu + \mathrm{d} \to \boxed{n} + p + \nu$$

$$\nu_e + \mathrm{d} \to 2p + \boxed{e^-}$$

- S trapped in Earth crust $\sim 10^{14}/\mathrm{cm}^3$ (Neufeld, Farrar, McKee 2018). Neutrons from $S \to nn$ may be detected by SNO.
- In SNO heavy water tank, #d$\sim 10^{32}$. Positrons from $\mathrm{d} \to Se^+\nu_e$ produces identical signals as electrons.
- SNO neutron and electron counts place upper limits on $\Gamma_{S\to nn}$ and $\Gamma_{\mathrm{d}\to Se\nu}$.

SNO neutron and electron counts

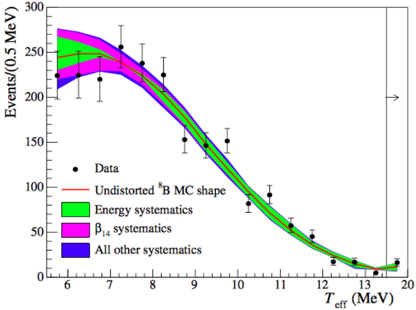
SNO neutron counts



(a) $\Gamma^{-1}_{S\to nn} > 10^{19}\,\mathrm{yr.}$

>> age of universe

SNO electron counts

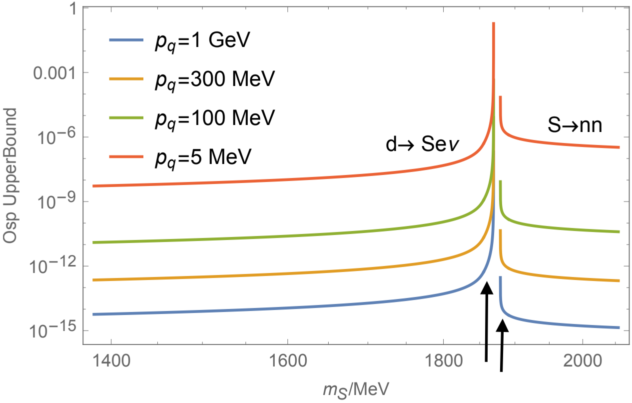


(b) $\Gamma^{-1}_{d\to Se\nu} > 10^{28}\,\mathrm{yr.}$

(SNO 1602.02469)

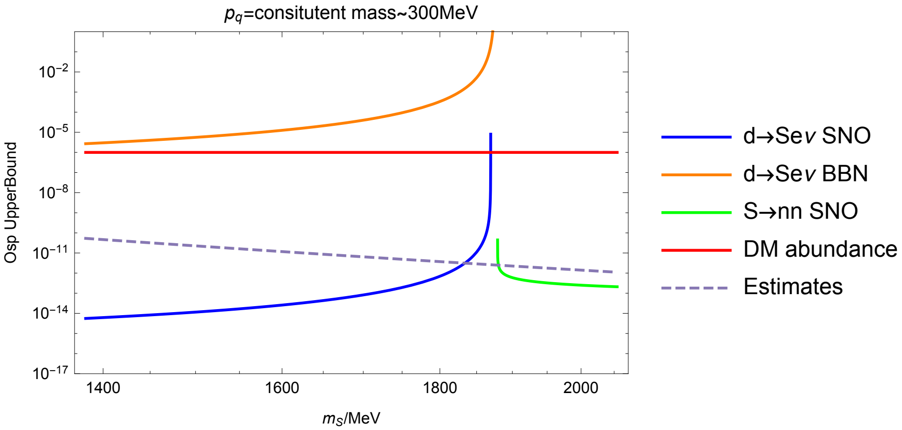
SNO limits

Upper limits on $\mathcal{O}_{\rm sp}$ by SNO neutron and electron counts



Combined limits on $\mathcal{O}_{\rm sp}$

Combined upper limits on $\mathcal{O}_{\rm sp}$ with $p = 300$ MeV



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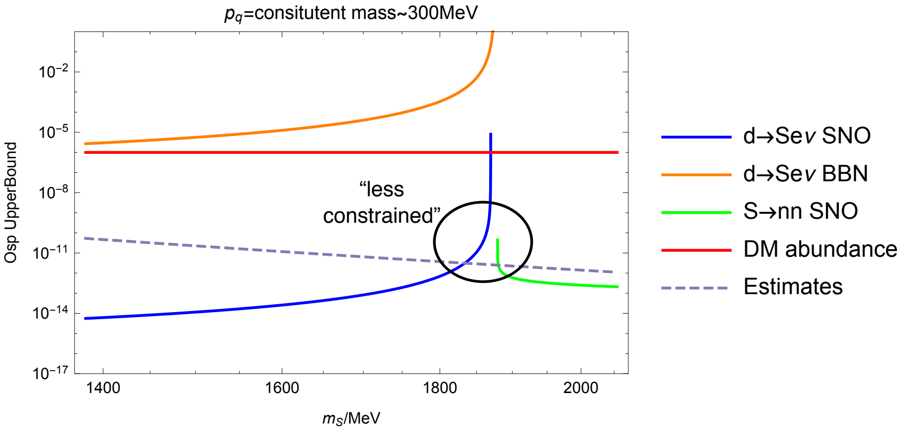
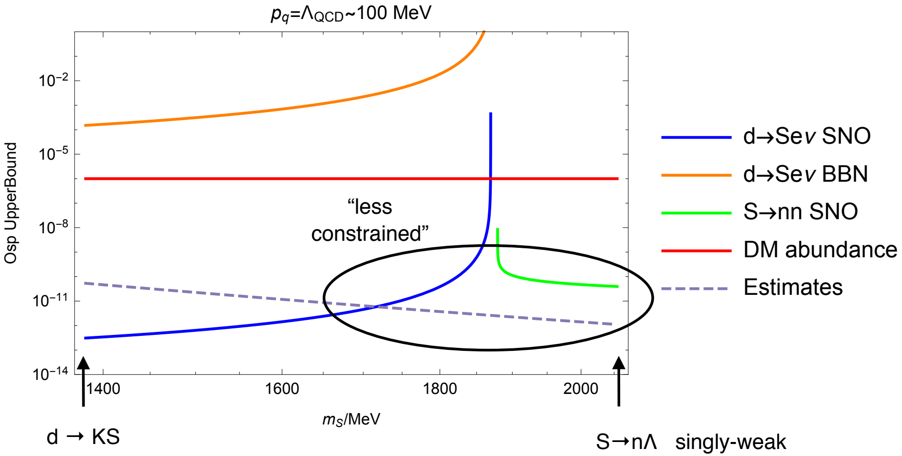


Combined limits on $\mathcal{O}_{\rm sp}$

Combined upper limits on $\mathcal{O}_{\rm sp}$ with $p = 100$ MeV



Range of m_S

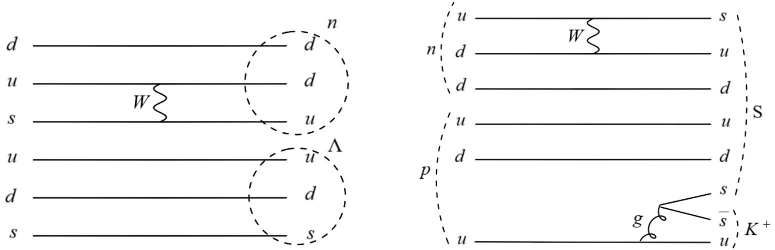
- $m_S > m_n + m_\Lambda = 2055$ MeV, singly-weak decay of S

$$S \to n\Lambda$$

- $m_S < m_d - m_K = 1382$ MeV, singly-weak decay of d with a gluon

$$\mathrm{d} \to K^+ S$$

- Beyond there, need much smaller $\mathcal{O}_{\rm sp}$ because of shorter lifetime.

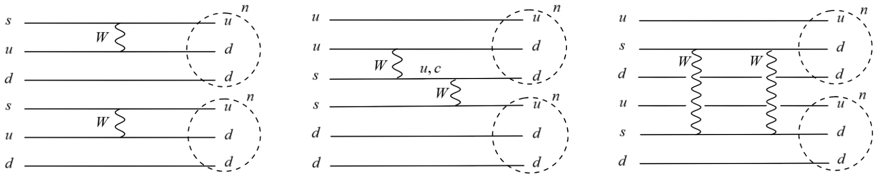


Conclusions

- For $m_S \sim$ 1382-2055 MeV, S and deuteron are not so unstable if $\mathcal{O}_{\rm sp}$ is sufficiently small.
- For m_S not too away from $2m_n$, $\mathcal{O}_{\rm sp}$ is less constrained (above the estimated curve).
- Future work: oxygen in SuperK might place stronger bounds for $m_S < 2m_p$?

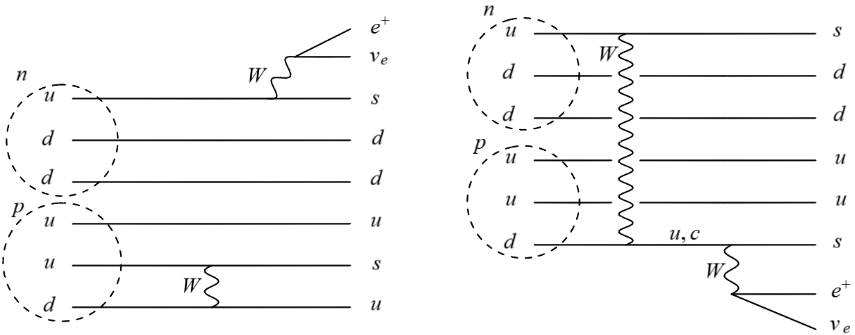
Thank you!

Back up slides



Sum over color-spin-flavor wavefunctions of S and n.

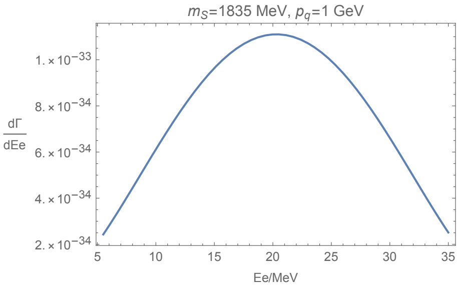
Back up slides

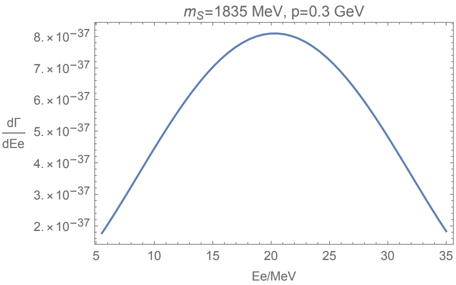


Sum over color-spin-flavor wavefunctions of d (n and p) and S.

Back up slides

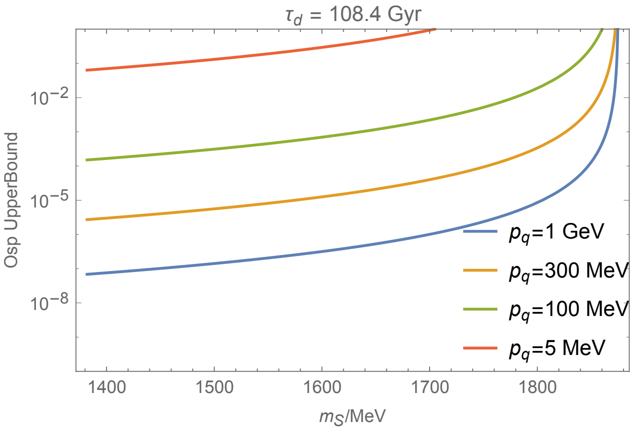
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} = \frac{g^2 g_W^2}{3m_W^4}\frac{1}{32\pi^3 m_d m_S}\sqrt{E_e^2 - m_e^2}E_e(m_d - m_S - E_e)^2$$





$\mathrm{d} \to Se^+\nu_e$: BBN limit

$\Gamma_{\mathrm{d}\to Se\nu}$ not too large to mess up the BBN deuteron abundance



Much weaker than SNO.