

# ELECTROMAGNETIC INTERACTION AND FREEZE-OUT ABUNDANCE OF SEXAQUARKS

PASCOS 2023

MARIANNE MOORE

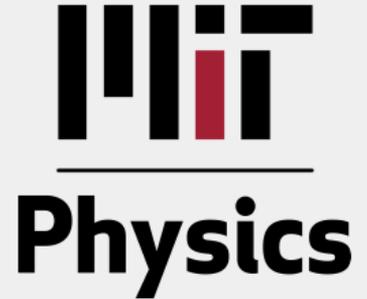
MIT

WITH TRACY R. SLATYER

JUNE 27, 2023

*Fonds de recherche  
Nature et  
technologies*

Québec 



# Outline

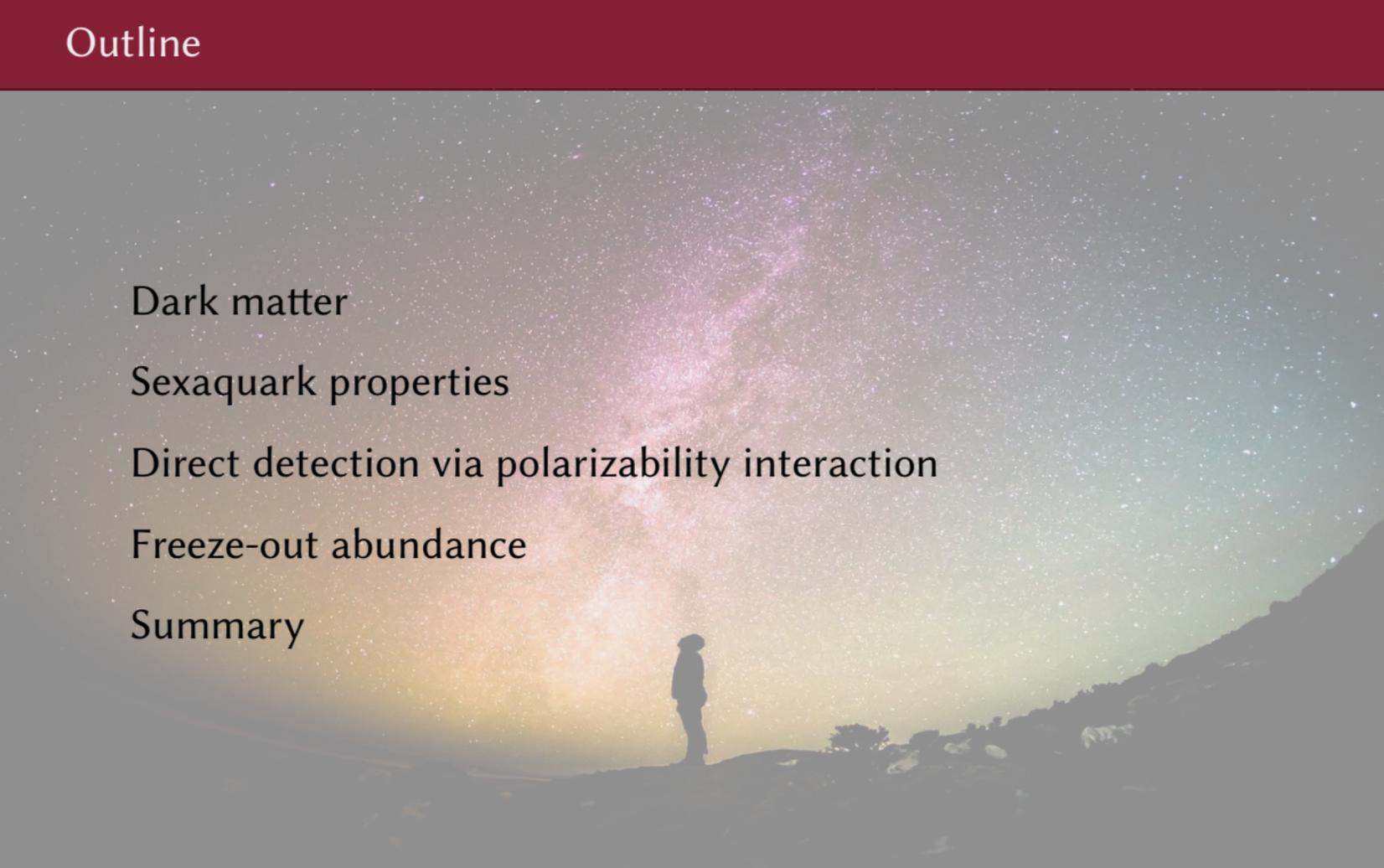
Dark matter

Sexaquark properties

Direct detection via polarizability interaction

Freeze-out abundance

Summary



# What is Dark Matter?

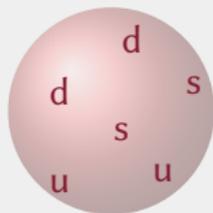
- (i) Dark (interacts little with photons)
- (ii) Non-relativistic
- (iii) Stable on cosmological timescales
- (iv) Interacts little with Standard Model particles



NASA, ESA, and Johan Richard

# The sexaquark may be a stable bound state

6-quark bound state



## Mass and properties

nucleus stability  $m_S \gtrsim 1860 \text{ MeV}$

sexaquark stability  $m_S \lesssim 1890 \text{ MeV}$

$S = 0$  (no net spin)

$Q = 0$  (no net charge)

previous studies on the sexaquark:

PRD **98**, 063005 (2018), JCAP **10**, 007 (2018),

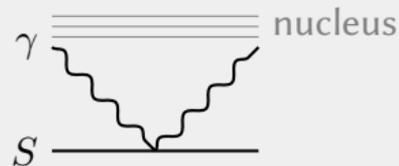
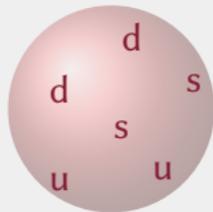
PRD **99**, 035013 (2019), PRD **99**, 063519 (2019),

PRD **105**, 103005 (2022), 1708.08951, 1805.03723,

2007.10378, 2112.00707, 2201.01334, 2306.03123

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## Scattering interactions

(i)  $S\gamma \rightarrow S\gamma$ : polarizability

(ii)  $S \text{ nucleus} \rightarrow S \text{ nucleus}$ :  $\pi\pi, \omega/\phi$ ,  
polarizability

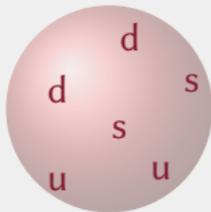
## Annihilation interactions

(i)  $S\bar{S} \rightarrow \text{SM particles}$

(ii)  $S\pi \rightarrow \text{baryons}$ : strong

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# The sexaquark has a large polarizability

Use lattice QCD to obtain an estimate of the polarizability  
(thanks to Will Detmold for preliminary data):

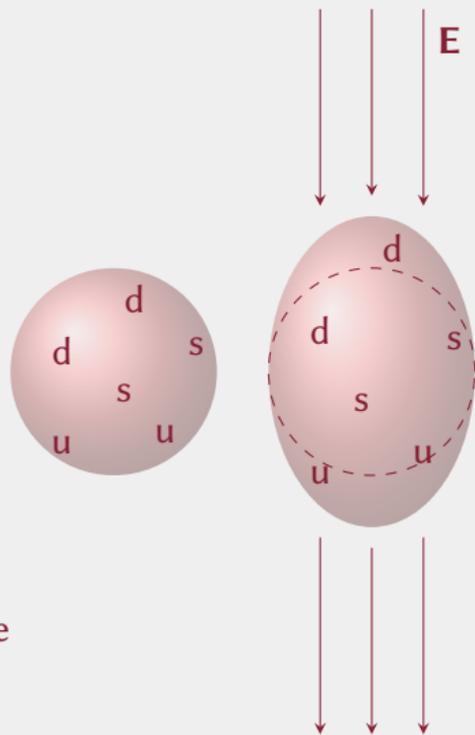
$$\alpha_S = 11.0(2.0) \times 10^{-4} \text{ fm}^3$$

It is similar to the measured polarizability of nucleons:

$$\alpha_p = 11.2(0.4) \times 10^{-4} \text{ fm}^3$$

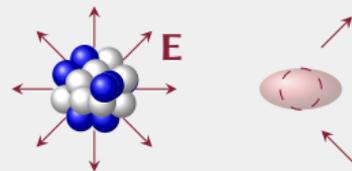
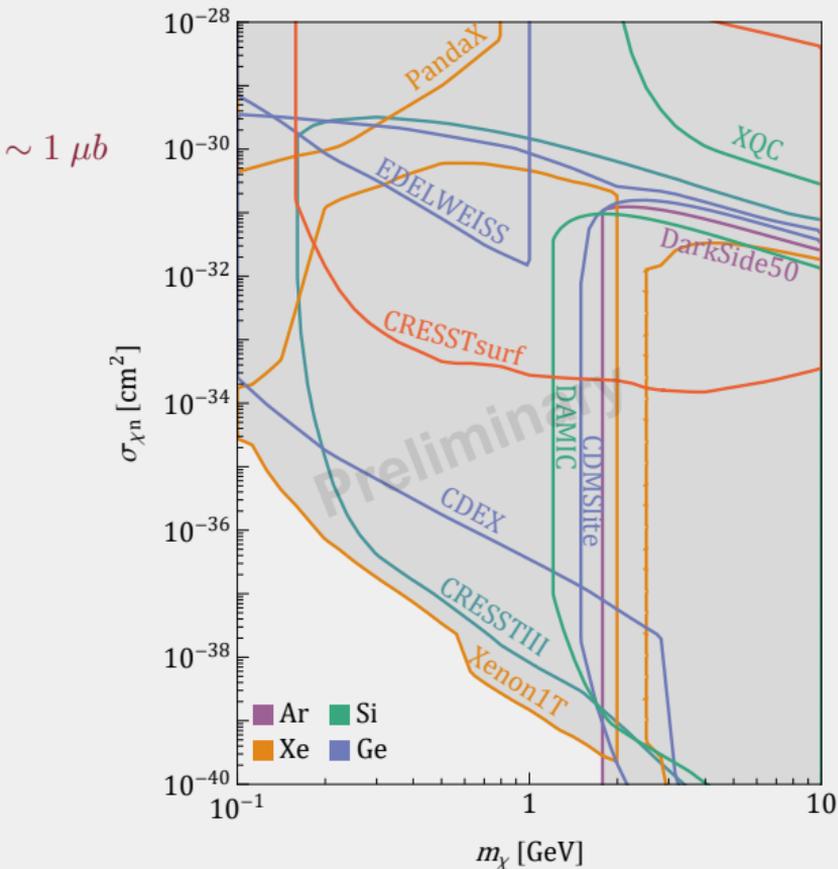
$$\alpha_n = 11.8(1.1) \times 10^{-4} \text{ fm}^3$$

The electric polarizability leads to a larger cross section than the magnetic polarizability.



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# Sexaquarks as 100% of dark matter is ruled out

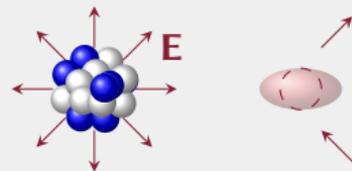
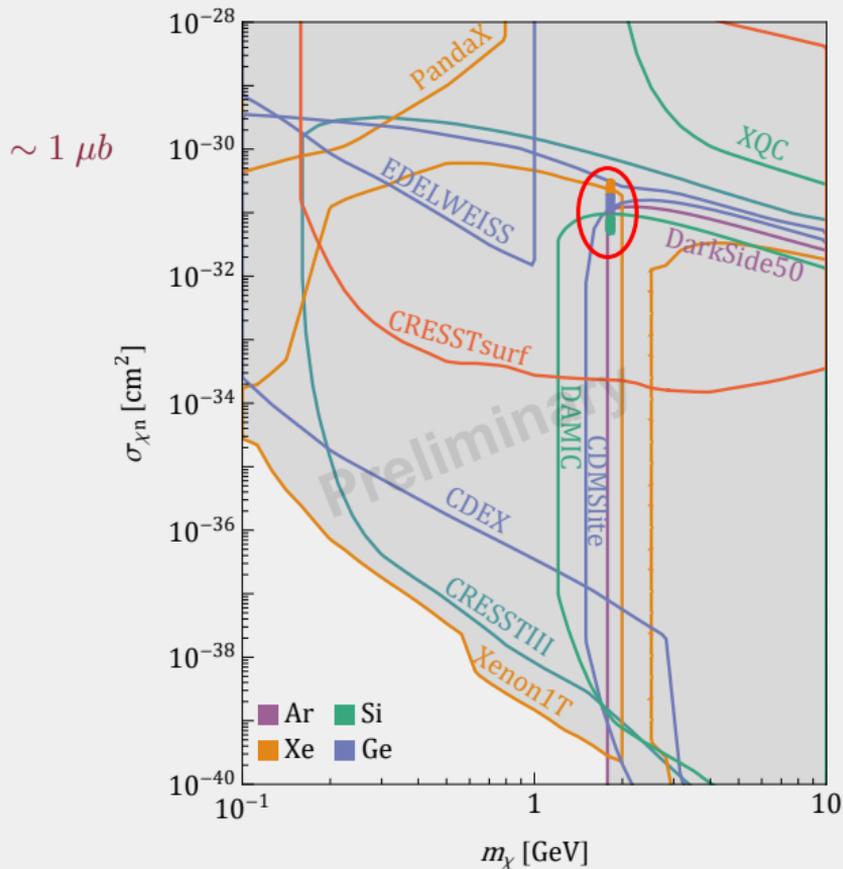


Nucleon cross section due to the  $\mathbf{E}$ -field of a nucleus:

$$\sigma_{Sn} = \frac{144\pi}{25} \underbrace{\mu_{Sn}^2}_{\text{reduced mass}} \overset{\text{polarizability}}{\alpha_S^2} \alpha^2 \underbrace{\frac{Z^4}{r_0^2 A^2}}_{\text{nucleus properties}}$$

PLB 480, 181 (2000)

# Sexaquarks as 100% of dark matter is ruled out



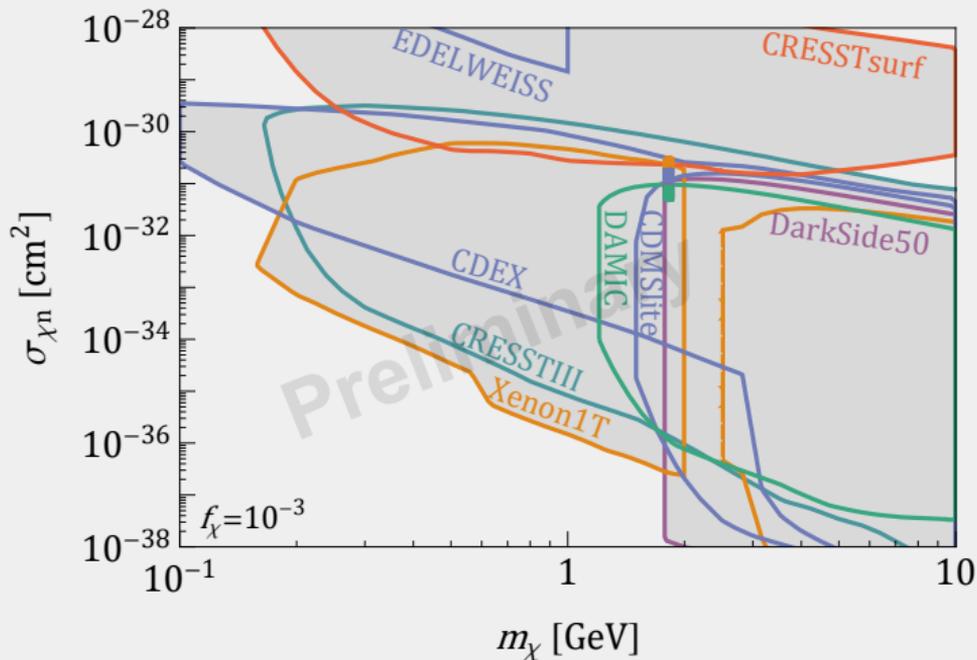
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# Sexaquarks as a sub-component of dark matter may be viable

Lower bounds move upward  $\propto f_\chi^{-1}$

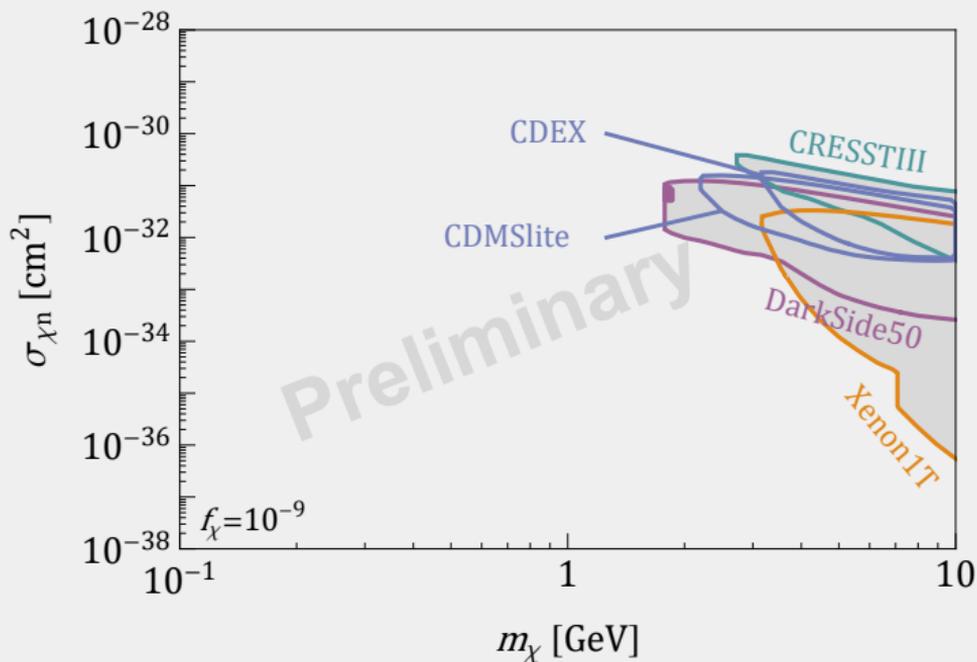


$$f_\chi = \frac{\Omega_\chi}{\Omega_{DM}}$$

McKeen, Moore et al., PRD **106**, 035011 (2022)

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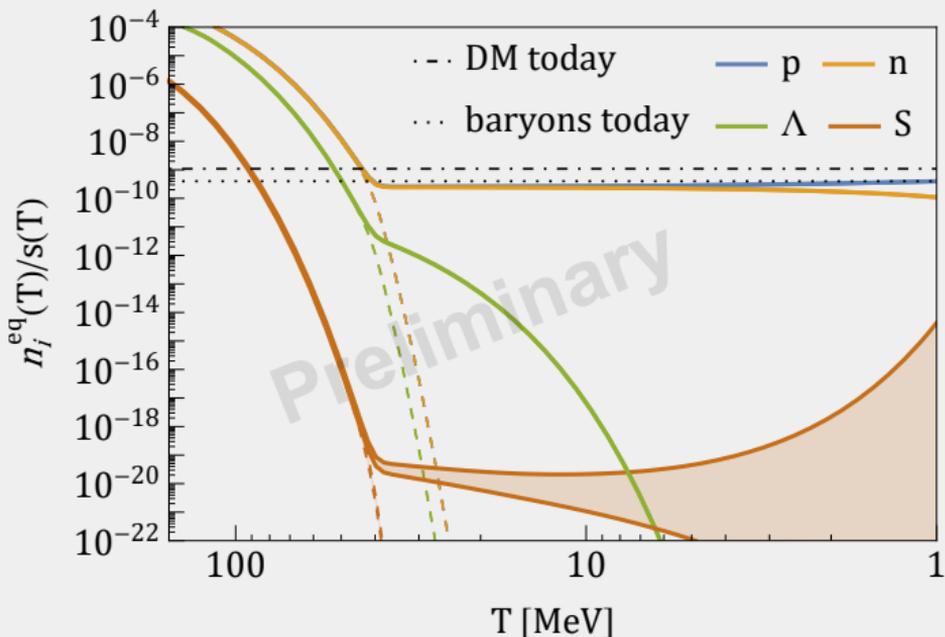


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McKeen, Moore et al., PRD **106**, 035011 (2022)

# Suppressed sexaquark equilibrium abundance compared to baryons

$$\sum_b \left[ n_b^{\text{eq}} - n_{\bar{b}}^{\text{eq}} \right] + 2 \left[ n_S^{\text{eq}} - n_{\bar{S}}^{\text{eq}} \right] = s(T) Y_{BS}$$



Baryon asymmetry:

$$Y_{BS} = Y_B + 2Y_S = Y_B + 2Y_B \frac{m_p \Omega_{\text{DM}}}{m_S \Omega_B}$$

$$n_i^{\text{eq}}(T) = g_i \left( \frac{m_i T}{2\pi} \right)^{3/2} e^{-(m_i - \mu_i)/T}$$

Sexaquarks must depart from equilibrium at early times to account for all of dark matter.

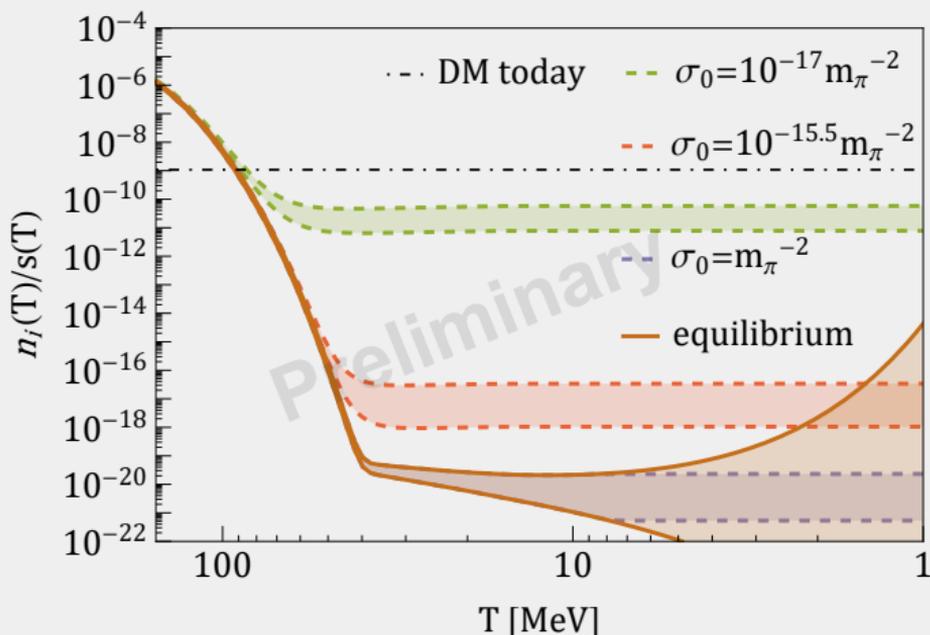
# Sexaquark freeze-out yields a small abundance

$$S\pi\pi \rightarrow \Lambda\Lambda$$

$$S\pi \rightarrow \{\Sigma\Sigma, \Lambda\Sigma, N\Xi\}$$

Boltzmann equation

$$\frac{dn_S}{dt} + 3Hn_S = - \sum_{bb'} \sigma_0 n_b^{\text{eq}} n_{b'}^{\text{eq}} [n_S/n_S^{\text{eq}} - 1]$$



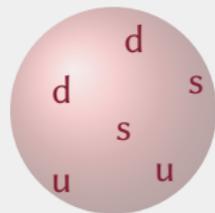
$\sigma_0$  controls the interaction strength.

An interaction strength within  $\sim 15$  orders of magnitude of typical strong interactions gives a negligible abundance.

in agreement with PRD **99**, 063519 (2019)

## Sexaquarks:

- $uuddss$  is a potentially stable bound state if its mass is  $\sim 1.8$  GeV
- The polarizability cross section is large and excludes sexaquarks as 100% of dark matter
- Sexaquarks as a very small subcomponent of dark matter is not yet constrained
- The sexaquark relic abundance is predicted to be  $f_\chi \sim 10^{-11}$  unless the breakup cross section  $S\pi \rightarrow$  baryons is very small



## Scattering interactions

- (i)  $S\gamma \rightarrow S\gamma$ : polarizability
- (ii)  $S$  nucleus  $\rightarrow S$  nucleus:  $\pi\pi, \omega/\phi$ , polarizability

## Annihilation interactions

- (i)  $S\bar{S} \rightarrow$  SM particles
- (ii)  $S\pi \rightarrow$  baryons: strong

# APPENDIX

# Details of the lattice QCD calculation

The calculation is done with the following parameters:

<i>lattice spacing:</i>	$\sim 0.12$	$\sim 0.12$	fm
<i>lattice volume:</i>	$32^3 \times 96$	$32^3 \times 48$	sites
<i>pion mass:</i>	$\sim 450$	$\sim 806$	MeV

Background electromagnetic fields shift the particle energy as

$$E_B = m \pm \mu|\mathbf{B}| + 4\pi\beta|\mathbf{B}|^2 + \dots$$

$$E_E = m + 4\pi\alpha|\mathbf{E}|^2 + \dots$$

We evaluate 4-point correlation functions of the form

$$\langle 0|\chi(x_1)J^\mu(y_1)J^\nu(y_2)\bar{\chi}(x_2)|0\rangle$$

# Details of the lattice QCD analysis

Data sets have 1006 and 776 configurations for 806 MeV and 450 MeV pion, respectively. This is small, and the configurations are not independent!

We make use of two techniques:

**Data blocking:** to get independent blocks of data out of the configurations

**Statistical bootstrap:** to increase the dataset size to get a reliable estimate of the variance of the expectation values

Finally, we chiral extrapolate to the physical pion mass.

# Approximate analytical expressions for the equilibrium abundances

The chemical potential is approximately

$$\mu_b(T) = T \operatorname{arcsinh} \left( \frac{1}{4} Y_{BS}(T) \left( \frac{2\pi}{T} \right)^{3/2} \left[ \sum_b m_b^{3/2} e^{-m_b/T} \right]^{-1} \right).$$

Then the abundance of sexaquarks in thermal equilibrium is

$$n_S^{\text{eq, high } T}(T) = \left( \frac{m_S T}{2\pi} \right)^{3/2} e^{-m_S/T}$$
$$n_S^{\text{eq, low } T}(T) = \left( \frac{2\pi m_S}{T} \right)^{3/2} \frac{Y_{BS}^2(T) e^{-(m_S - 2m_p)/T}}{4 \left[ m_p^{3/2} + \sum_{b \neq p} m_b^{3/2} e^{-(m_b - m_p)/T} \right]^2}$$

# Scattering with Photons

The cross section between sexaquarks and photons of frequency  $\omega$  due to the electric polarizability is

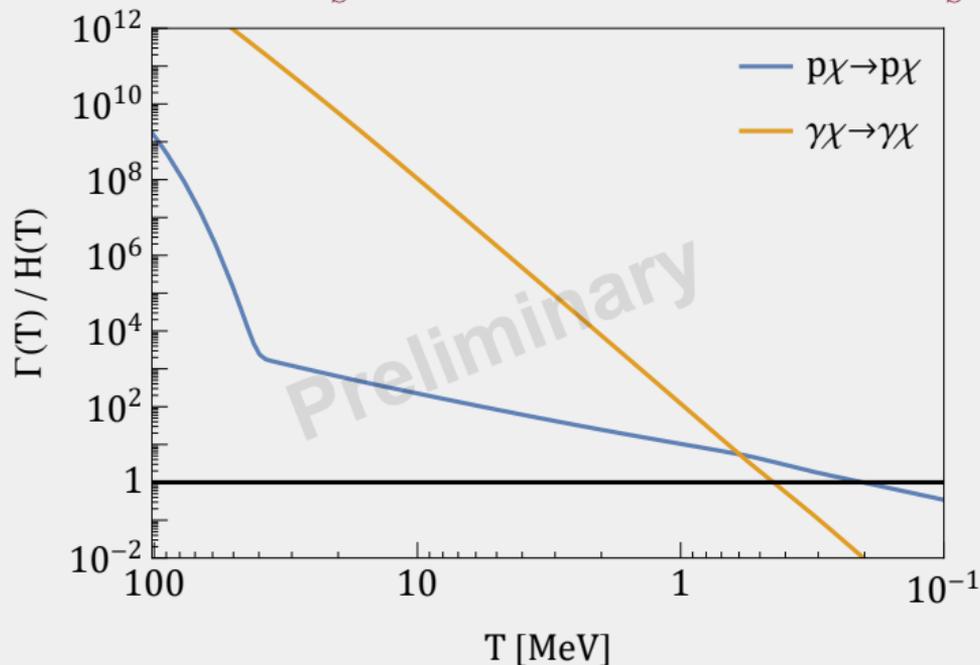
$$\sigma_{S\gamma} = \frac{4}{3\pi} \alpha_S^2 m_S \omega^4 \frac{(m_S + \omega)^2}{(m_S + 2\omega)^3}$$
$$\propto \alpha_S^2 \begin{cases} m_S \omega^3 & m_S \ll \omega \\ \omega^4 & m_S \gg \omega \end{cases} .$$

# Kinetic decoupling

Sexaquarks remain in kinetic equilibrium with the baryon-photon fluid throughout the freeze-out process, even after departing from chemical equilibrium with SM particles.

$$\Gamma_\gamma(T_d) \sim n_\gamma \langle \sigma v \rangle_{S\gamma}^{\text{el}} \frac{T_d}{m_S}$$

$$\Gamma_p(T_d) \sim n_p^{\text{eq}} \langle \sigma v \rangle_{Sp}^{\text{el}} \frac{\mu_{Sp}^2}{m_S m_p} .$$

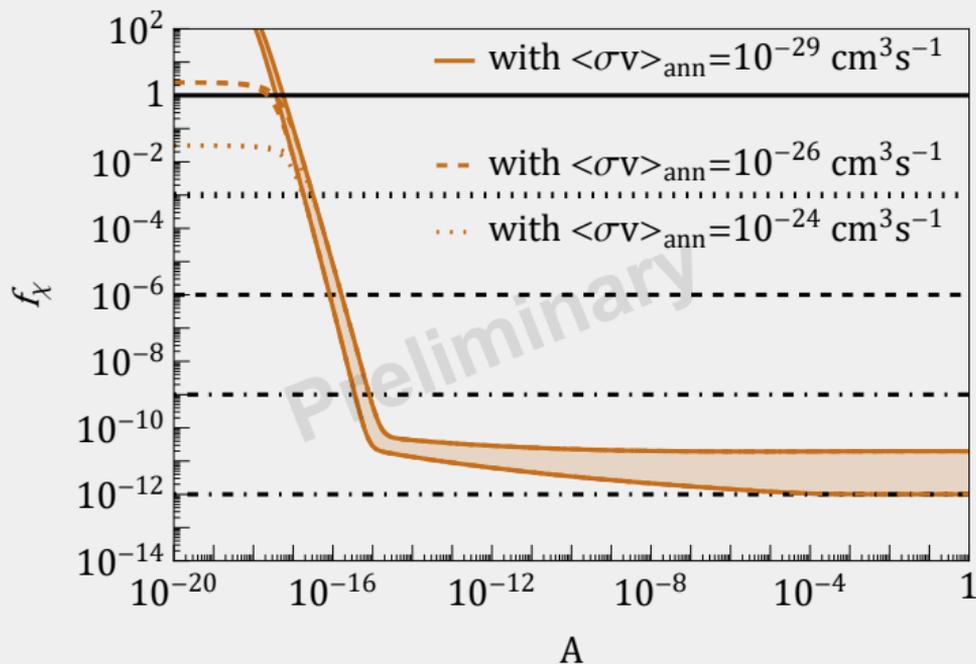


# Sexaquark-anti-sexaquark freeze-out

$$S\bar{S} \rightarrow \{\gamma\gamma, e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \text{etc.}\} \quad \frac{dn_S}{dt} + 3Hn_S = -\langle\sigma v\rangle [n_S n_{\bar{S}} - n_S^{\text{eq}} n_{\bar{S}}^{\text{eq}}]$$

$$\sigma_0 = Am_\pi^{-2}$$

$$\frac{dn_{\bar{S}}}{dt} + 3Hn_{\bar{S}} = -\langle\sigma v\rangle [n_S n_{\bar{S}} - n_S^{\text{eq}} n_{\bar{S}}^{\text{eq}}]$$



$$\Psi_S = \psi_{\text{orbital}} \times \psi_{\text{flavour}} \times \psi_{\text{colour}} \times \psi_{\text{spin}}$$

$$S = S \times ? \times A \times ?$$

We embed colour and spin in  $SU(6)_{cs}$ . For the flavour and colour-spin, we get

$$3 \otimes 3 \otimes 3 \otimes 3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus \bar{10} \oplus 10 \oplus 27 \oplus 35 \oplus 28$$

$$6 \otimes 6 \otimes 6 \otimes 6 \otimes 6 \otimes 6 = 1 \oplus 35 \oplus 189 \oplus 175 \oplus 280 \oplus 896 \oplus 490 \oplus 840'' \oplus 1134'$$

$$\oplus 1050'' \oplus 462 .$$

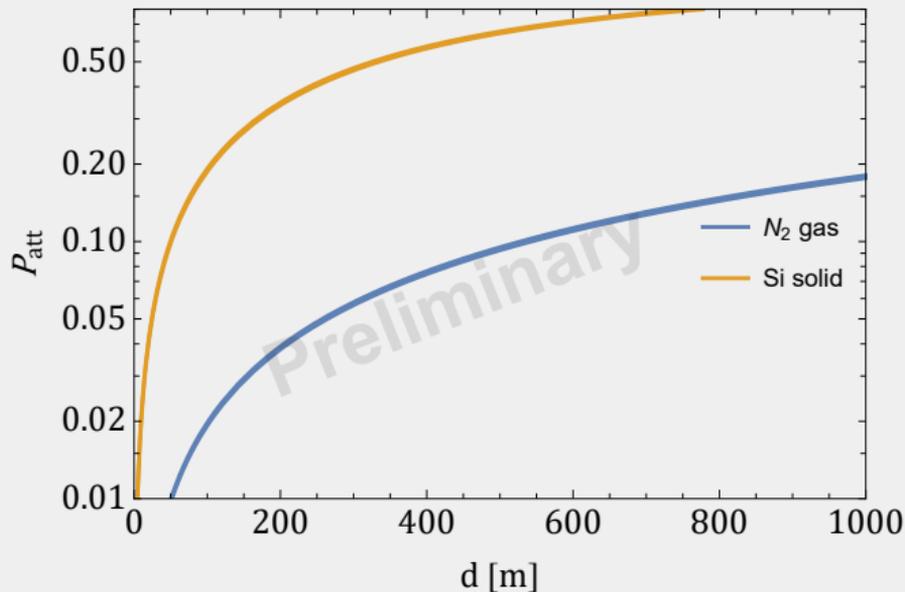
We decompose  $SU(3)_f \times SU(6)_{cs} \rightarrow SU(3)_f \times SU(2)_s \times SU(3)_c$ , keeping only the  $SU(3)_c$  singlets. This gives

$28 \otimes 1 : \mathbf{1} \otimes \mathbf{1}$	$8 \otimes 896 : \{3 \otimes 1, 5 \otimes 1\}$
$35 \otimes 35 : 3 \otimes 1$	$1 \otimes 490 : \mathbf{1} \otimes \mathbf{1}$
$27 \otimes 189 : \{\mathbf{1} \otimes \mathbf{1}, 5 \otimes 1\}$	$\bar{10} \otimes 175 : \{3 \otimes 1, 7 \otimes 1\}$
$10 \otimes 280 : 3 \otimes 1$	

# Sexaquark depletion through Earth's atmosphere and crust

$$\ell_{\text{MFP}} = \frac{1}{n_{\text{T}}\sigma_{\chi N}}$$

$$P_{\text{att}} = 1 - e^{-d/\ell_{\text{MFP}}}$$



# Stability of the sexaquark

Can the sexaquark be a stable bound state? See the following references:

- Lattice QCD studies: PRL **106**, 162002 (2011), PRL **106**, 162001 (2011), PRD **85**, 054511 (2012), Nucl. Phys. A **881**, 28 (2012), PRL **107**, 092004 (2011), JPS Conf. Proc. **1**, 013028 (2014)
- MIT bag model study: PRL **38**, 195 (1977)
- QCD sum rules study: Nucl. Phys. A **580**, 445 (1994)
- holographic QCD study: 2304.10816

# Sexaquark-pion(s) breakup reaction into baryons

Isospin conservation:

$$S\pi^0 : \quad |0, 0\rangle \otimes |1, 0\rangle = |1, 0\rangle$$

$$S\pi^0\pi^0 : \quad |0, 0\rangle \otimes |1, 0\rangle \otimes |1, 0\rangle = -\sqrt{\frac{1}{3}}|0, 0\rangle + \sqrt{\frac{2}{3}}|2, 0\rangle$$

$$S\pi^+\pi^- : \quad |0, 0\rangle \otimes |1, 1\rangle \otimes |1, -1\rangle = \sqrt{\frac{1}{3}}|0, 0\rangle + \sqrt{\frac{1}{2}}|1, 0\rangle + \sqrt{\frac{1}{6}}|2, 0\rangle$$

$$\Lambda\Lambda : \quad |0, 0\rangle \otimes |0, 0\rangle = |0, 0\rangle$$

$$\Lambda\Sigma^0 : \quad |0, 0\rangle \otimes |1, 0\rangle = |1, 0\rangle$$

$$\Sigma^0\Sigma^0 : \quad |1, 0\rangle \otimes |1, 0\rangle = -\sqrt{\frac{1}{3}}|0, 0\rangle + \sqrt{\frac{2}{3}}|2, 0\rangle$$

$$\Sigma^+\Sigma^- : \quad |1, 1\rangle \otimes |1, -1\rangle = \sqrt{\frac{1}{3}}|0, 0\rangle + \sqrt{\frac{1}{2}}|1, 0\rangle + \sqrt{\frac{1}{6}}|2, 0\rangle$$

$$\Xi^0 n : \quad \left|\frac{1}{2}, \frac{1}{2}\right\rangle \otimes \left|\frac{1}{2}, -\frac{1}{2}\right\rangle = \sqrt{\frac{1}{2}}|0, 0\rangle + \sqrt{\frac{1}{2}}|1, 0\rangle$$

$$\Xi^- p : \quad \left|\frac{1}{2}, -\frac{1}{2}\right\rangle \otimes \left|\frac{1}{2}, \frac{1}{2}\right\rangle = -\sqrt{\frac{1}{2}}|0, 0\rangle + \sqrt{\frac{1}{2}}|1, 0\rangle$$