Title: On the cosmology and terrestrial signals of sexaquark dark matter

Speakers: Marianne Moore

Series: Particle Physics

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Abstract: The sexaquark, a hypothetical stable and neutral six-quark state, has been recently proposed as a dark matter candidate. Here, I argue it is very unlikely sexaquarks could consistently compose more than a billionth of the dark matter abundance for a wide range of scattering cross sections and annihilation rates. To draw these conclusions, I will connect several topics, including the sexaquark freeze-out abundance, dark matter direct detection constraints, neutrino experiments, and accumulation mechanisms for sexaquarks in the Earth. I will show how the sexaquark cosmology enforces that a large contribution to dark matter is only possible with a similarly large antisexaquark population. This population, however, would leave a stark annihilation signal in a detector such as Super-Kamiokande. I will summarize with how sexaquarks as a large component of the dark matter is incompatible with current observational data.

Zoom link

On the Cosmology and Terrestrial Signals of Sexaquark Dark Matter

Marianne Moore

Marianne Moore and Tracy R. Slatyer (2402.XXXXX)

January 23, 2023

Fonds de recherche Nature et technologies Québec

NSERC CRSNG

MIT Physics

Outline

Does the sexaquark exist as a stable particle?

Can the sexaquark constitute all of dark matter? If not, what fraction could it consistently make up?

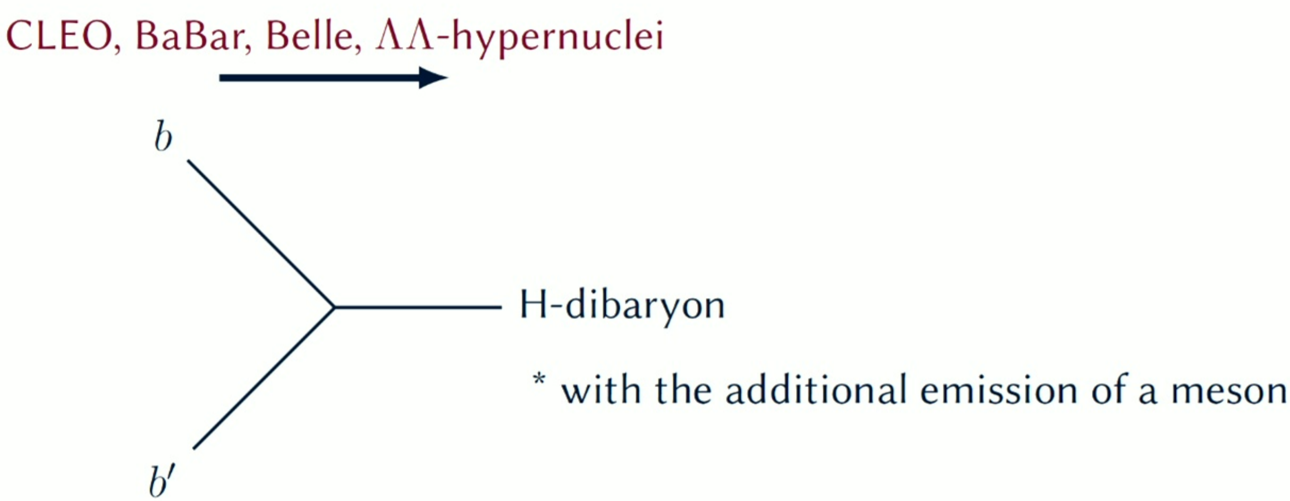
Perhaps a Stable Dihyperon*

R. L. Jaffe†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Department of Physics and Laboratory of Nuclear Science,‡ Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 1 November 1976)

In the quark bag model, the same gluon-exchange forces which make the proton lighter than the $\Delta(1236)$ bind six quarks to form a stable, flavor-singlet (with strangeness of -2) $J^P = 0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H^*) with $J^P = 1^+$ at 2335 MeV should appear as a bump in $\Lambda\Lambda$ invariant-mass plots. Production and decay systematics of the H are discussed.

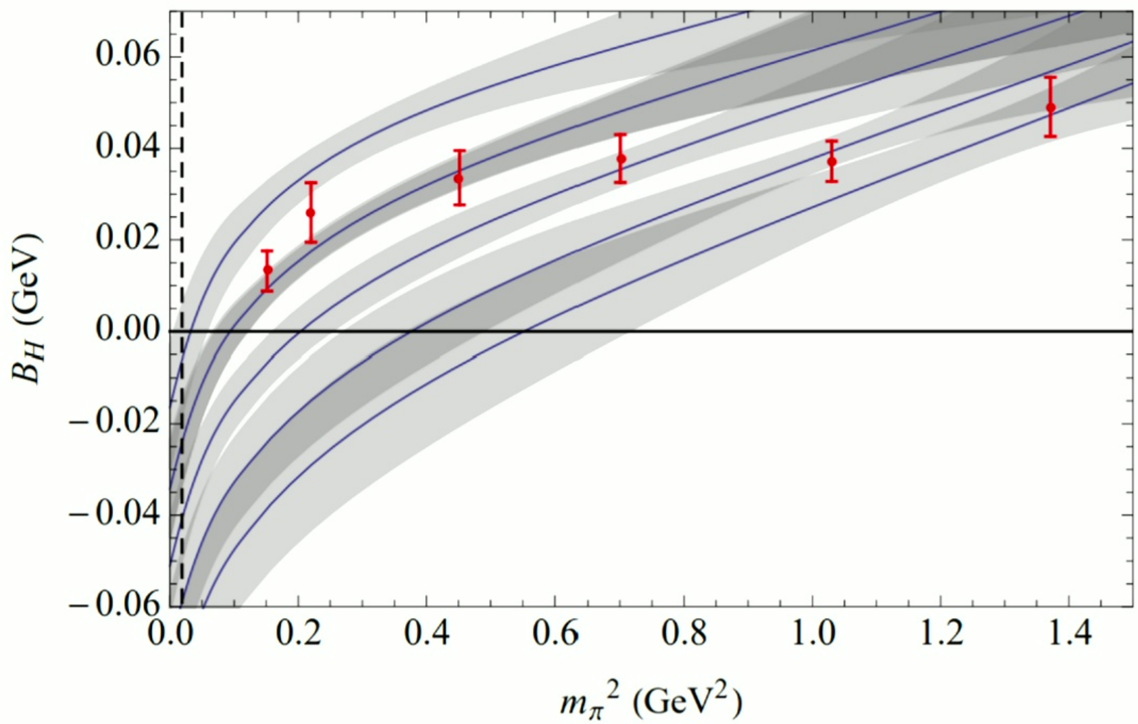
Experimental searches for the H-dibaryon

most searches look for $m > 2$ GeV



Theoretical searches for the H-dibaryon (lattice QCD)

$B_H = 2m_\Lambda - m_H$



bound

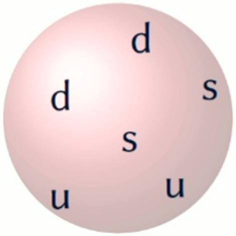
unbound

Shanahan et al. (2013)

From the H-dibaryon to the sexaquark

6-quark bound state

H-dibaryon	loosely bound di-Λ
S	potentially more bound
	what about lattice QCD?



Stable Sexaquark

Glennys R. Farrar
Center for Cosmology and Particle Physics, Department of Physics, New York University, NY, NY 10003, USA

It is proposed that the neutral, B=2, flavor singlet sexaquark (S) composed of $uuddss$ quarks, has mass $m_S \lesssim 2$ GeV. If $m_S < 2(m_p + m_e)$, it is absolutely stable, while for $m_S < m_p + m_e + m_\Lambda$, τ_S can be $> \tau_{\rm Univ}$. Lattice gauge theory cannot yet predict m_S but indirect evidence supports the hypothesis of stability. A stable S is consistent with QCD theory and would have eluded detection in accelerator and non-accelerator experiments. If it exists, the S is a good Dark Matter candidate. Analyses of existing Upsilon decay and LHC data are proposed which could discover it and measure its mass.

1708.08951

The sexaquark as a dark matter candidate

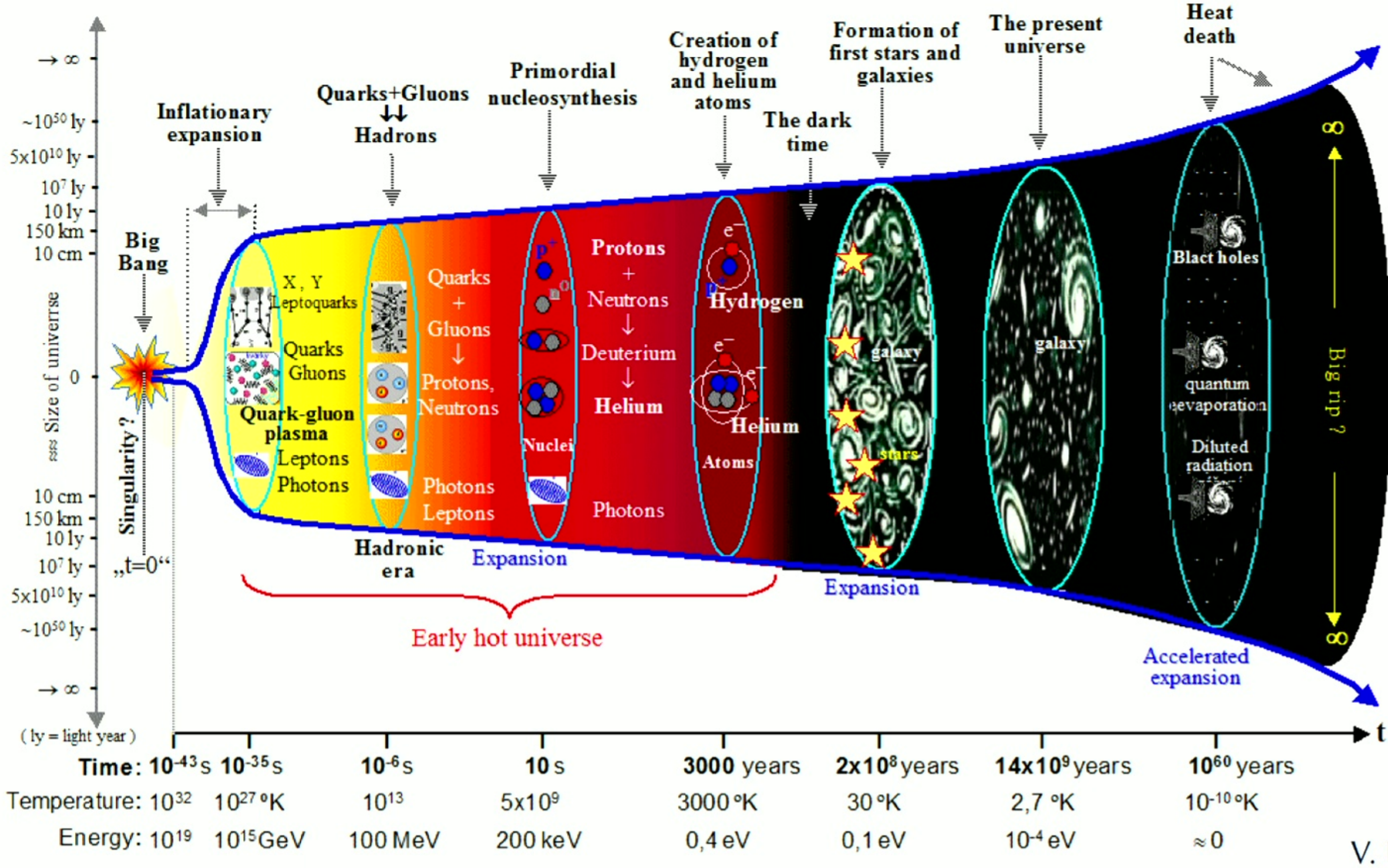
- □ cold
- □ neutral
- □ no net spin
- □ stable for $1860 \lesssim m_S \lesssim 1890$ MeV (**assumption**)
- □ obtain the measured dark matter abundance in the Early Universe
- □ not be already excluded by dark matter experiments, accelerator searches, indirect detection, stability of matter

} if $g_{Sbb} \ll g_{\mathrm{QCD}}$

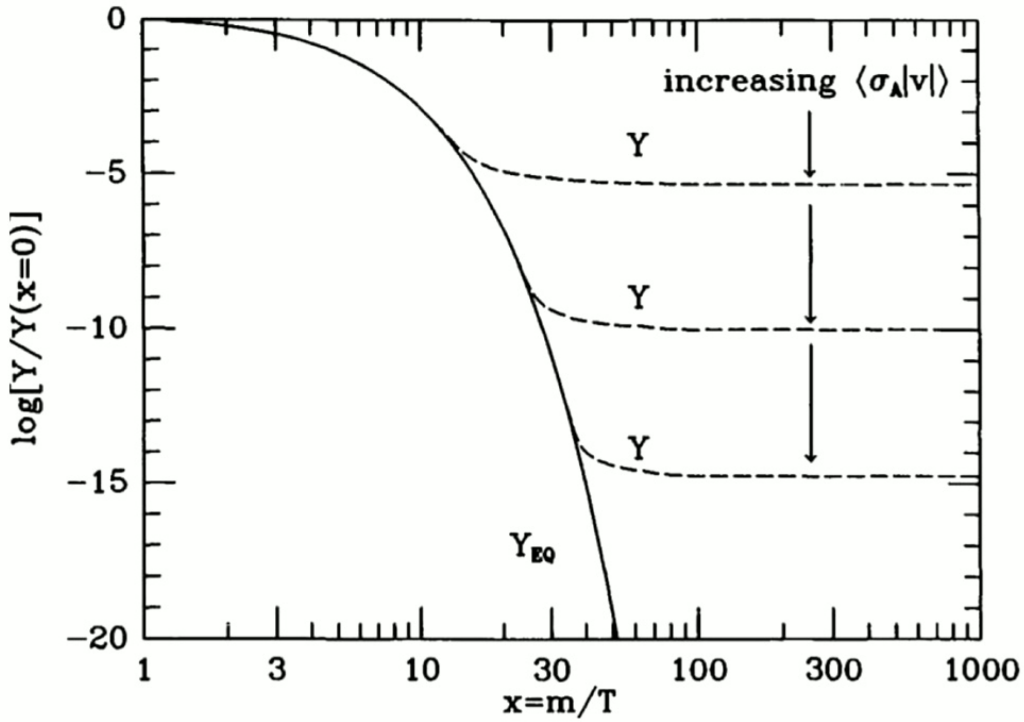
previous studies on the sexaquark:

1708.08951	1803.10242	1804.03073	1805.03723
1809.06003	1809.06765	2007.10378	2112.00707
2201.01334	2202.00652	2306.03123	2310.05194

The history of the Universe



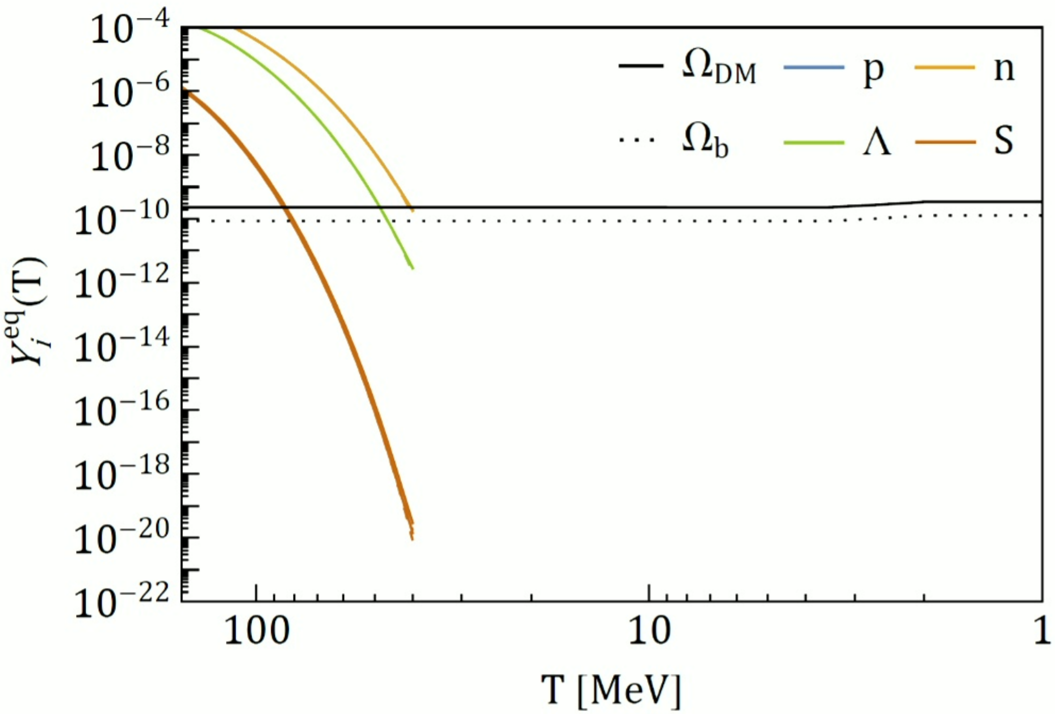
The standard freeze-out scenario



Kolb and Turner (1990)

Suppressed sexaquark equilibrium abundance compared to baryons

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



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

Suppressed sexaquark equilibrium abundance compared to baryons

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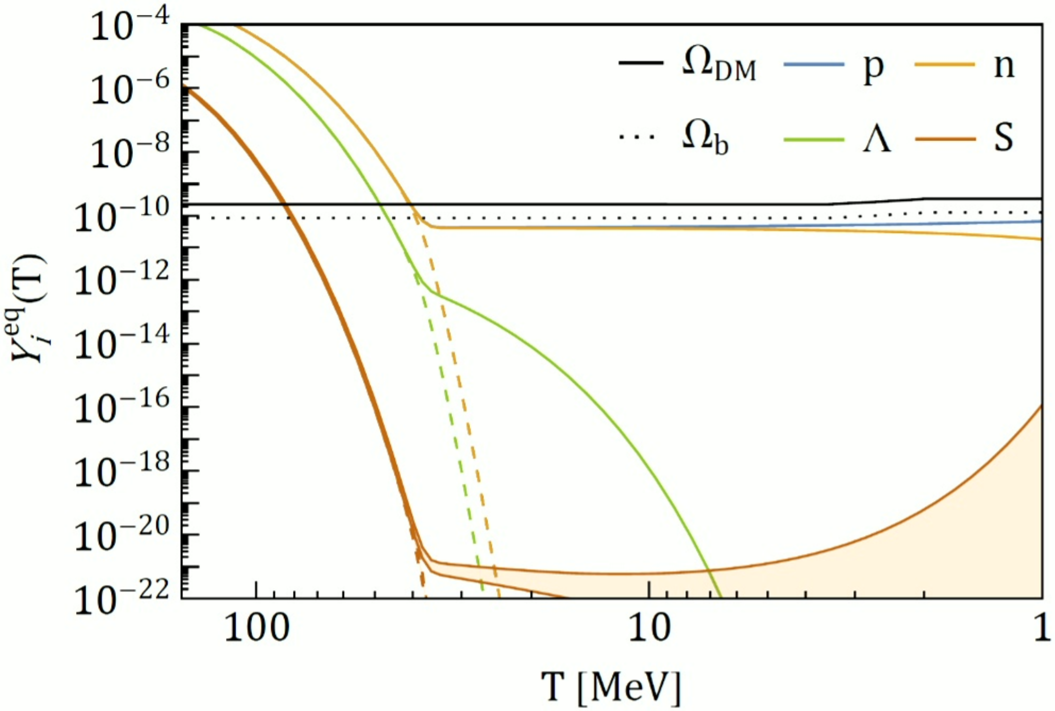

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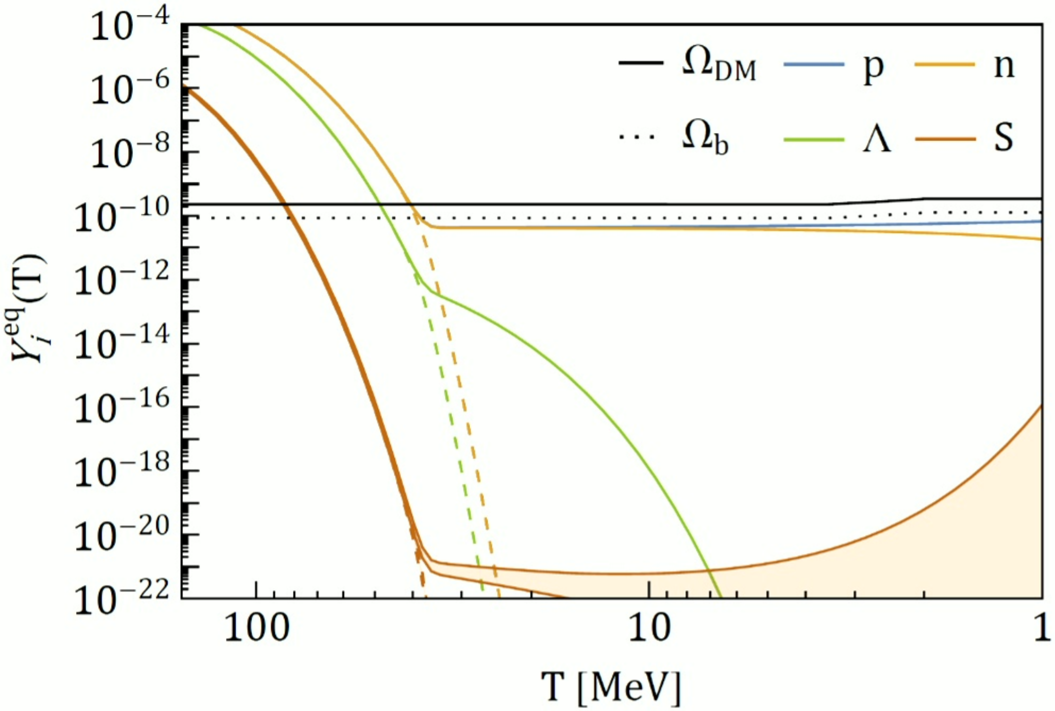


$$n_i^{\mathrm{eq}}(T) = g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-(m_i-\mu_i)/T}$$

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

The freeze-out formalism has 3 different reactions

$S\pi \to bb'$

$$\frac{\mathrm{d}n_S}{\mathrm{d}t} + 3Hn_S = -\langle\sigma v\rangle^{\text{ann}}_{S\bar{S}}\left(n_S n_{\bar{S}} - n_S^{\text{eq}} n_{\bar{S}}^{\text{eq}}\right) - \sum_{b,b'}\left[\Gamma_{S\pi} + \Gamma_{S\bar{b}}\right]\left[n_S - n_S^{\text{eq}}\right]$$

$$\frac{\mathrm{d}n_{\bar{S}}}{\mathrm{d}t} + 3Hn_{\bar{S}} = -\langle\sigma v\rangle^{\text{ann}}_{S\bar{S}}\left(n_S n_{\bar{S}} - n_S^{\text{eq}} n_{\bar{S}}^{\text{eq}}\right) - \sum_{b,b'}\left[\Gamma_{\bar{S}\pi} + \Gamma_{\bar{S}b}\right]\left[n_{\bar{S}} - n_{\bar{S}}^{\text{eq}}\right]$$

$S\bar{S} \to$ SM particles

$S\bar{b} \to b'\pi$
$\bar{S}b \to \bar{b}'\pi$

parameterize $\Gamma_{S\pi} \propto Am_\pi^{-2}$

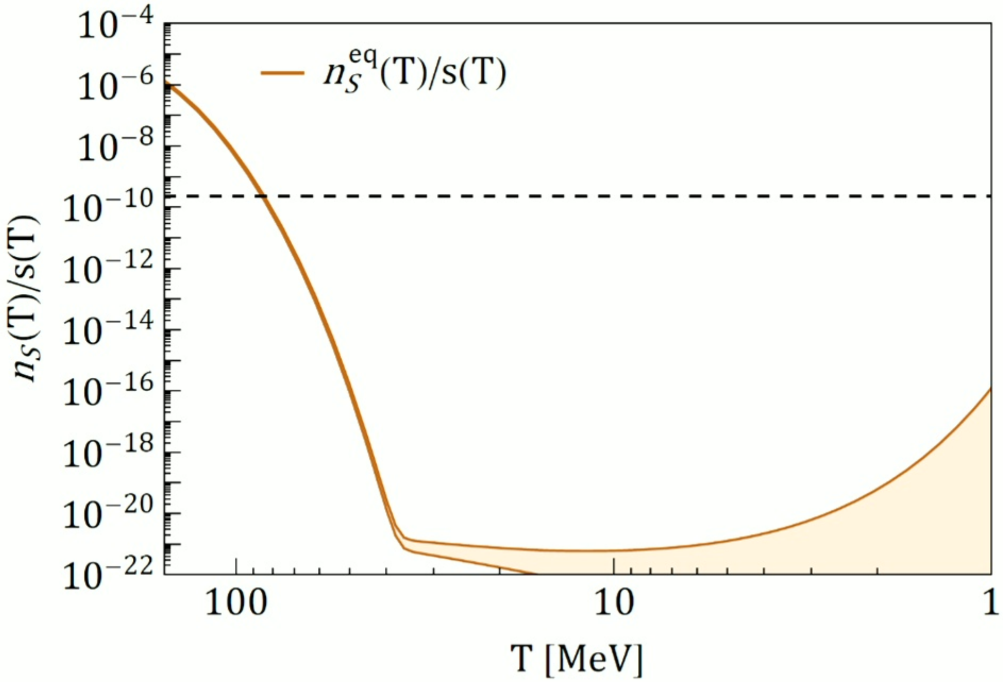
parameterize $\Gamma_{S\bar{b}} \propto Bm_\pi^{-2}$

The sexaquark freeze-out yield plateaus for large interaction strength

$S\pi\pi \to \Lambda\Lambda$

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

$$\frac{dn_S}{dt} + 3Hn_S = -\Gamma_{S\pi}\left[n_S - n_S^{eq}\right]$$



The sexaquark freeze-out yield plateaus for large interaction strength

$$S\pi\pi \to \Lambda\Lambda$$

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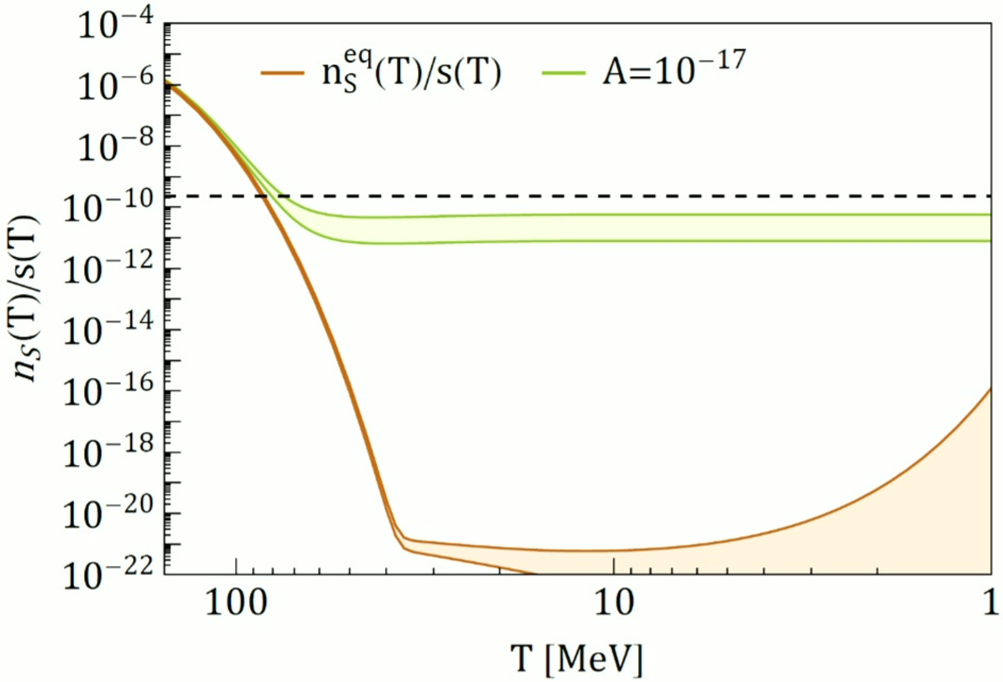


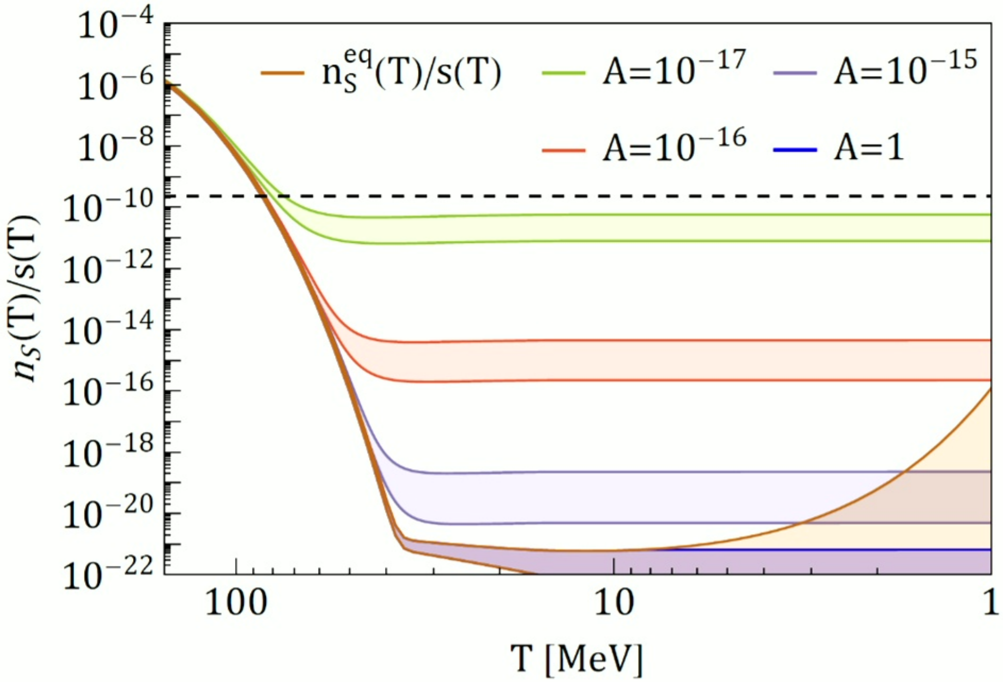
$$\Gamma_{S\pi} \propto A m_\pi^{-2}$$

The sexaquark freeze-out yield plateaus for large interaction strength

$S\pi\pi \to \Lambda\Lambda$

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

$$\frac{\mathrm{d}n_S}{\mathrm{d}t} + 3Hn_S = -\Gamma_{S\pi}\left[n_S - n_S^{\mathrm{eq}}\right]$$



$$\Gamma_{S\pi} \propto A m_\pi^{-2}$$

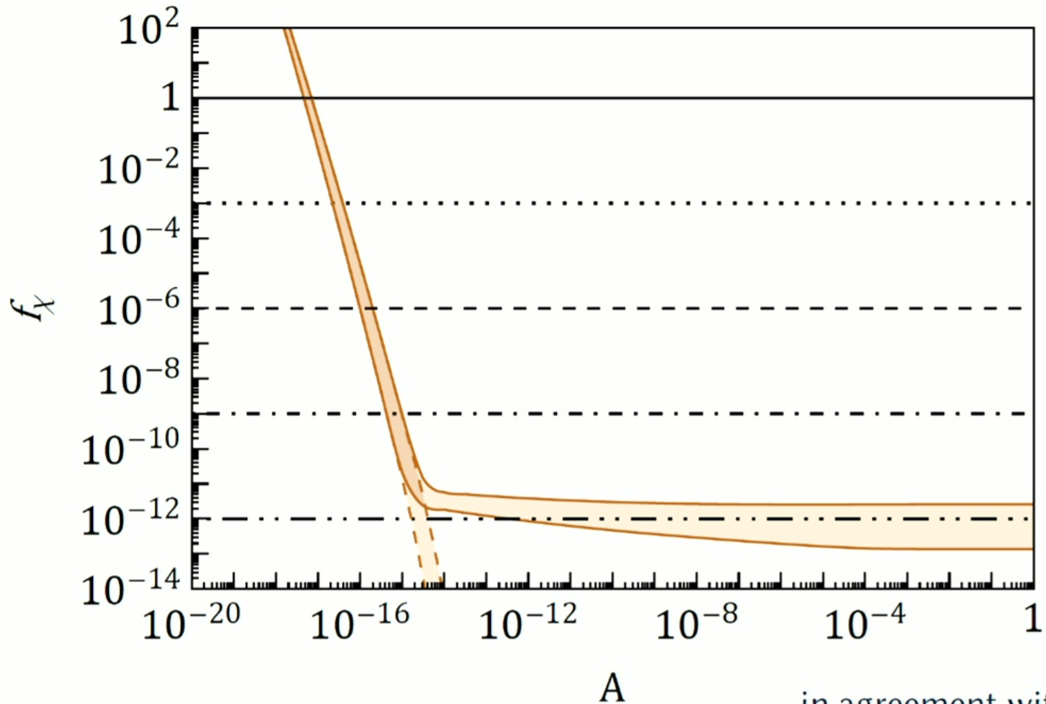
Sexaquark and antisexaquark freeze-out ($S\pi \to bb'$)

$S\pi\pi \to \Lambda\Lambda$

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

$$\frac{\mathrm{d}n_S}{\mathrm{d}t} + 3Hn_S = -\Gamma_{S\pi}\left[n_S - n_S^{\mathrm{eq}}\right]$$

$$\frac{\mathrm{d}n_{\bar{S}}}{\mathrm{d}t} + 3Hn_{\bar{S}} = -\Gamma_{\bar{S}\pi}\left[n_{\bar{S}} - n_{\bar{S}}^{\mathrm{eq}}\right]$$



$$\Gamma_{S\pi} \propto A m_\pi^{-2}$$

Glennys Farrar claims that $A \lesssim 10^{-12}$ gives $f_\chi \sim 1$ (1805.03723)

in agreement with Kolb and Turner, 1809.06003

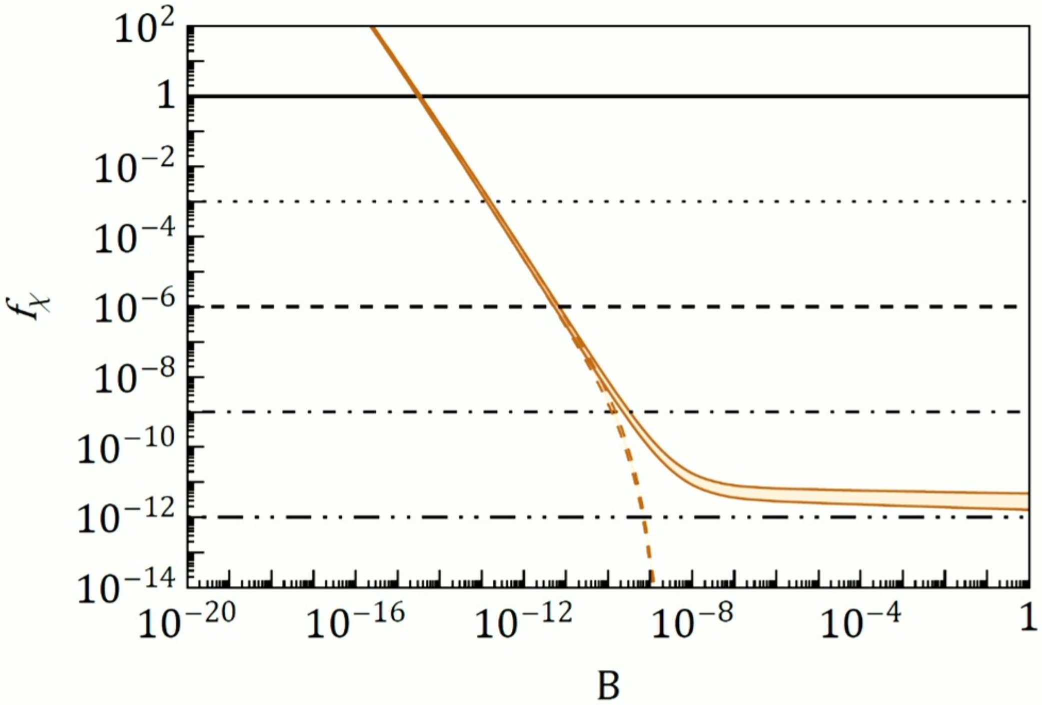
Sexaquark and antisexaquark freeze-out ($\bar{S}b \to \bar{b}'\pi$)

$\{S\bar{p}, S\bar{n}\} \to \Xi\pi$

$$\frac{dn_S}{dt} + 3Hn_S = -\Gamma_{S\bar{b}}\left[n_S - n_S^{eq}\right]$$

$\{S\bar{p}, S\bar{n}\} \to \{\Sigma K, \Lambda K\}$

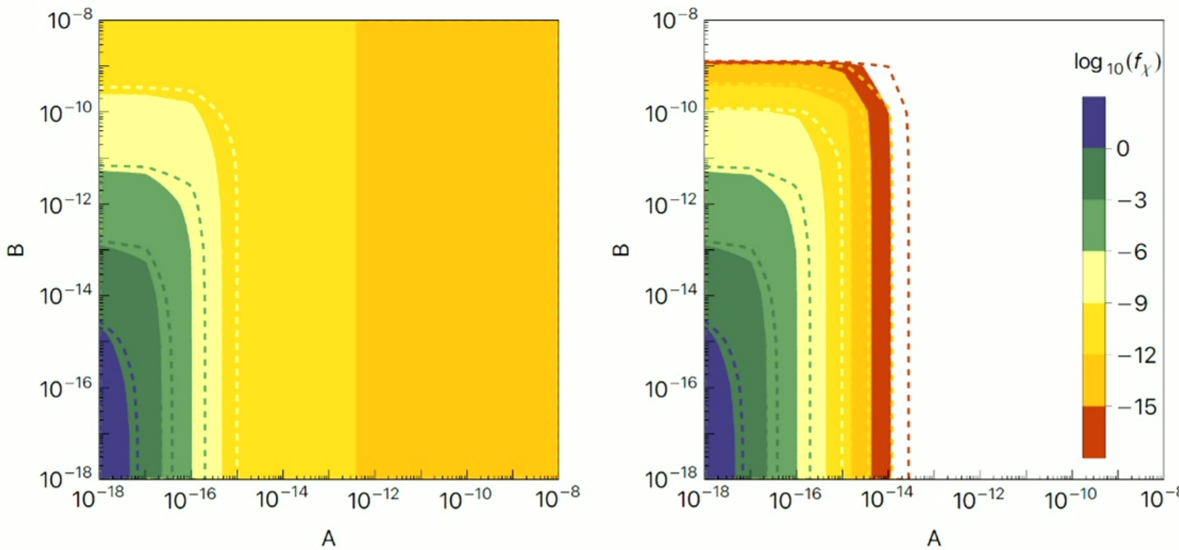
$$\frac{dn_{\bar{S}}}{dt} + 3Hn_{\bar{S}} = -\Gamma_{\bar{S}b}\left[n_{\bar{S}} - n_{\bar{S}}^{eq}\right]$$



$$\Gamma_{S\bar{b}} \propto B m_\pi^{-2}$$

Sexaquark and antisexaquark freeze-out (summary)

- $f_\chi = 1$ is possible with all 3 mechanisms, at the expense of a **symmetric** population
- Both strong force freeze-out require a **large suppression** of the cross section
- If all rates are very small, S **doesn't equilibrate** with the baryon-photon bath



- If no large suppression, the S abundance **plateaus** at $f_\chi \sim 10^{-11}$

Outline

Introduction to the sexaquark

Can the sexaquark constitute all of dark matter? If not, what fraction could it consistently make up?

- Three mechanisms for freeze-out abundance
- Direct detection via polarizability interaction
- Accumulation in the Earth
- Annihilation signatures

Summary

The sexaquark probably has a large polarizability

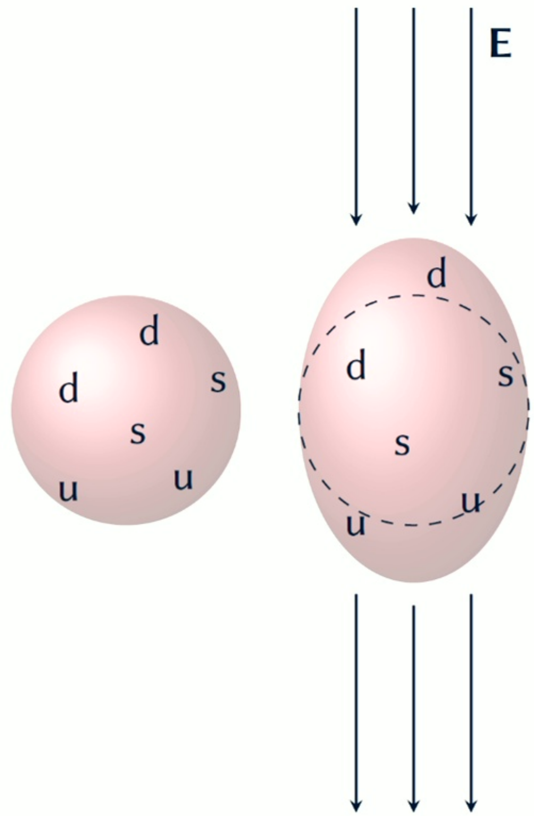
S-nucleus interactions: $\pi\pi$, ω/ϕ, $\gamma\gamma$

Measured polarizability of nucleons:

$$\alpha_p = 11.2(0.4) \times 10^{-4}\ \text{fm}^3$$
$$\alpha_n = 11.8(1.1) \times 10^{-4}\ \text{fm}^3$$

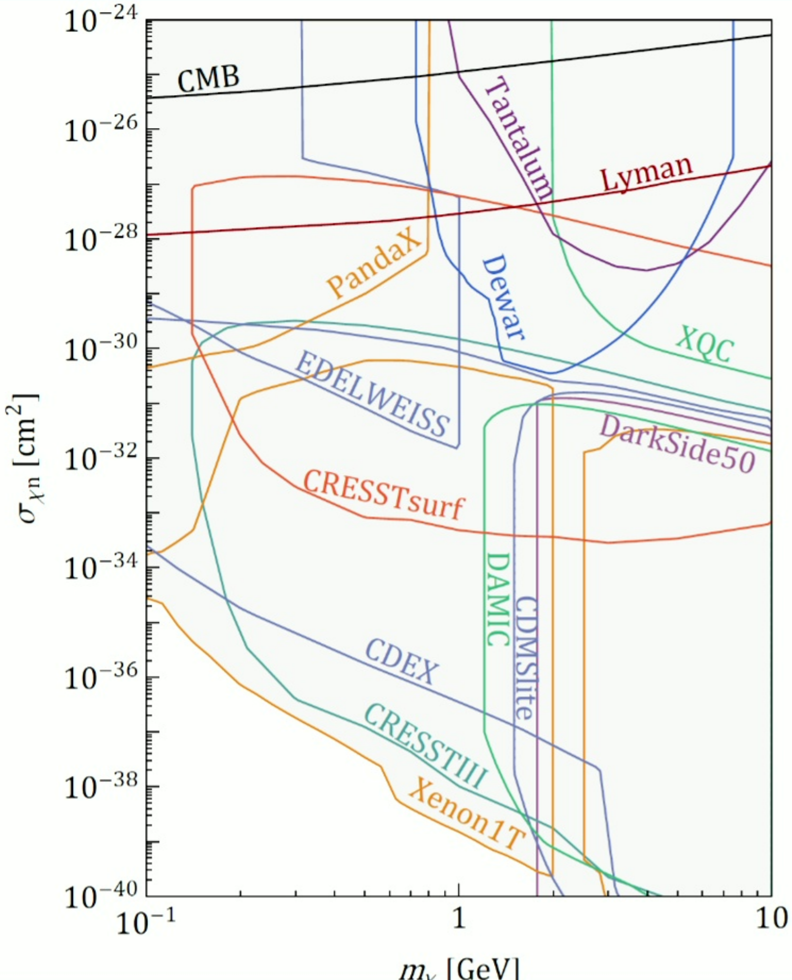
Estimate of the sexaquark polarizability:

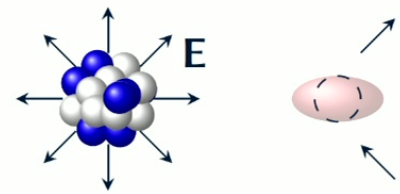
$$\alpha_S \simeq [0.1, 1]\alpha_n$$



PDG 2022

Direct detection through the polarizability





Nucleon cross section due to the **E**-field of a nucleus:

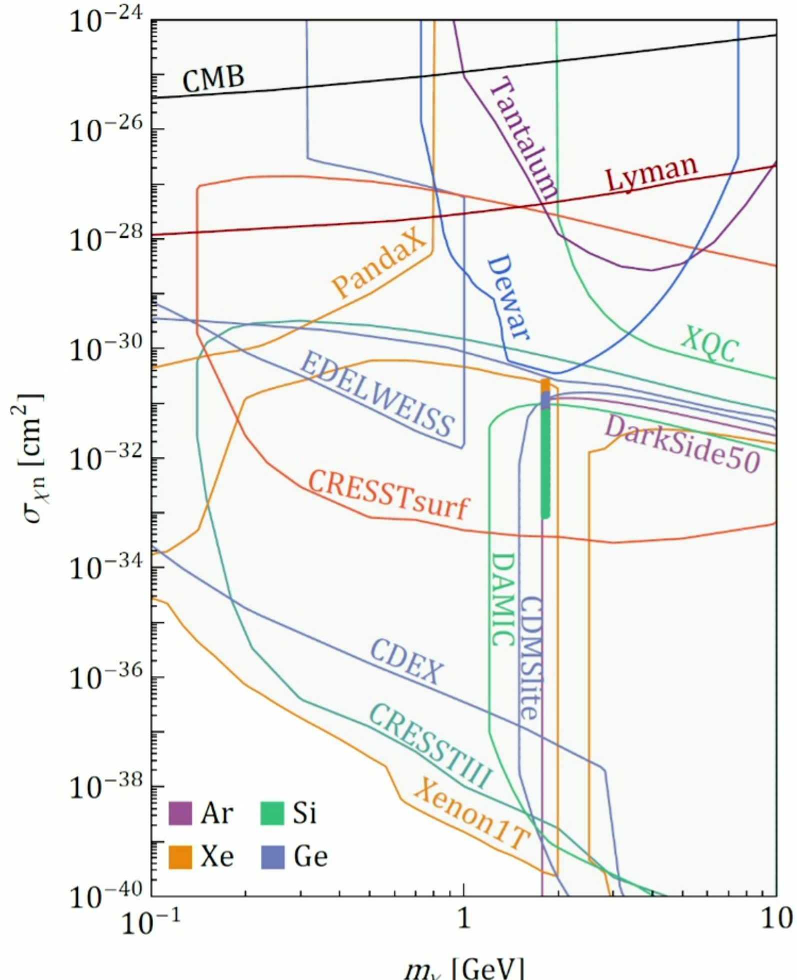
polarizability

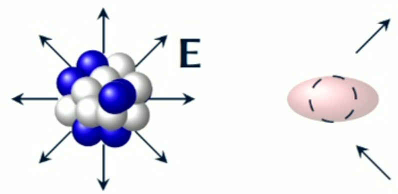
$$\sigma_{Sn} = \frac{144\pi}{25}\mu_{Sn}^2\alpha_S^2\alpha^2\frac{Z^4}{r_0^2 A^2}$$

reduced mass   nucleus properties

Pospelov and ter Veldhuis, hep-ph/0003010

Direct detection through the polarizability





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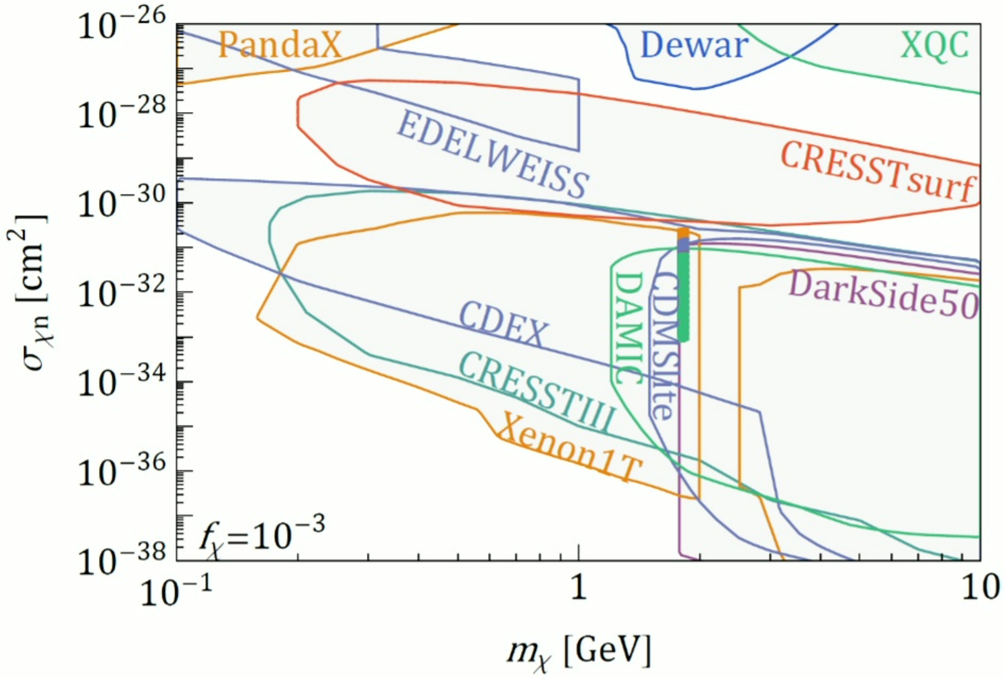
reduced mass   nucleus properties

Pospelov and ter Veldhuis, hep-ph/0003010

Probing a subcomponent of dark matter

The ceiling depends on f_χ: the probability to reach the detector with high velocity is small.



Direct detection cannot constrain $f_\chi \ll 1$, especially if $\alpha_S \simeq \alpha_n$.

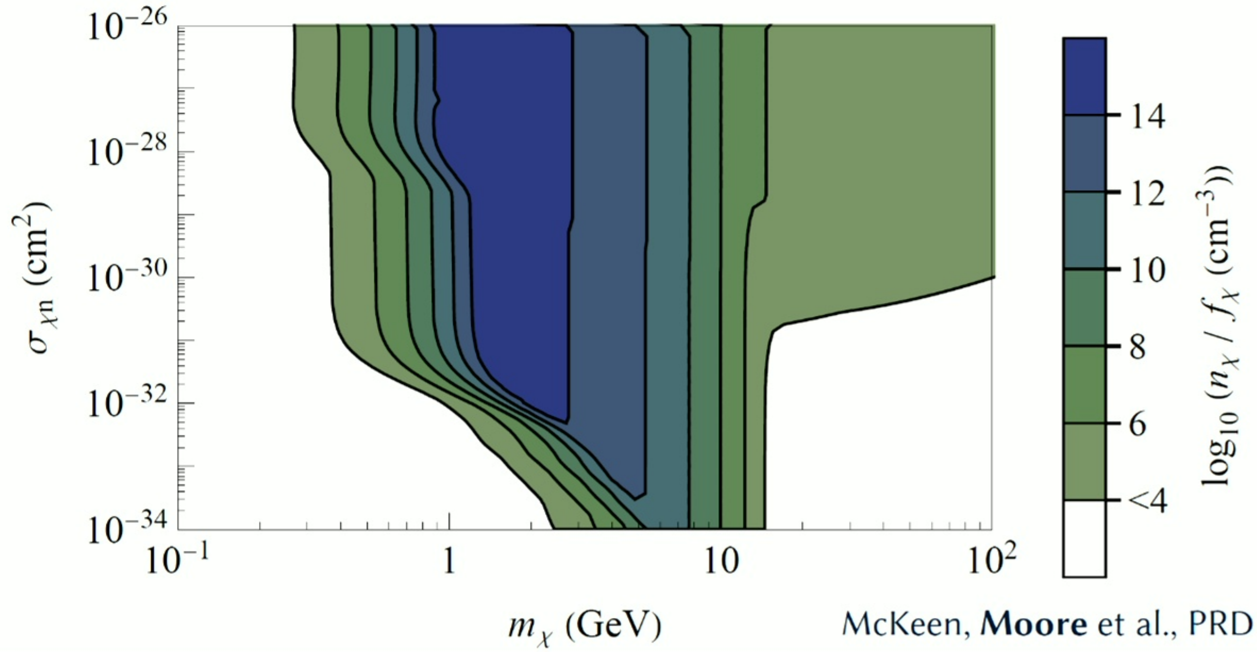
Sexaquarks can reach a large overabundance in the Earth (framework)

$$\frac{\mathrm{d}N_S}{\mathrm{d}t} = f_S \Gamma^{\mathrm{cap}} - N_S \Gamma^{\mathrm{evap}} - N_S N_{\bar{S}} \Gamma^{\mathrm{ann}}_{S\bar{S}}$$
$$\frac{\mathrm{d}N_{\bar{S}}}{\mathrm{d}t} = f_{\bar{S}} \Gamma^{\mathrm{cap}} - N_{\bar{S}} \Gamma^{\mathrm{evap}} - N_S N_{\bar{S}} \Gamma^{\mathrm{ann}}_{S\bar{S}} - N_{\bar{S}} N_n \Gamma^{\mathrm{ann}}_{\bar{S}n}$$

Γ^{cap} (Bramante *et al.* 2210.01812, Neufeld *et al.* 1805.08794)
Γ^{evap} (Neufeld *et al.* 1805.08794)
Γ^{ann} (Pospelov and Ray 2309.10032)

Sexaquarks can reach a large overabundance in the Earth ($\Gamma^{\rm ann} = 0$)

$$\frac{\mathrm{d}N_S}{\mathrm{d}t} = f_S \Gamma^{\rm cap} - N_S \Gamma^{\rm evap}$$
$$\frac{\mathrm{d}N_{\bar{S}}}{\mathrm{d}t} = f_{\bar{S}} \Gamma^{\rm cap} - N_{\bar{S}} \Gamma^{\rm evap}$$



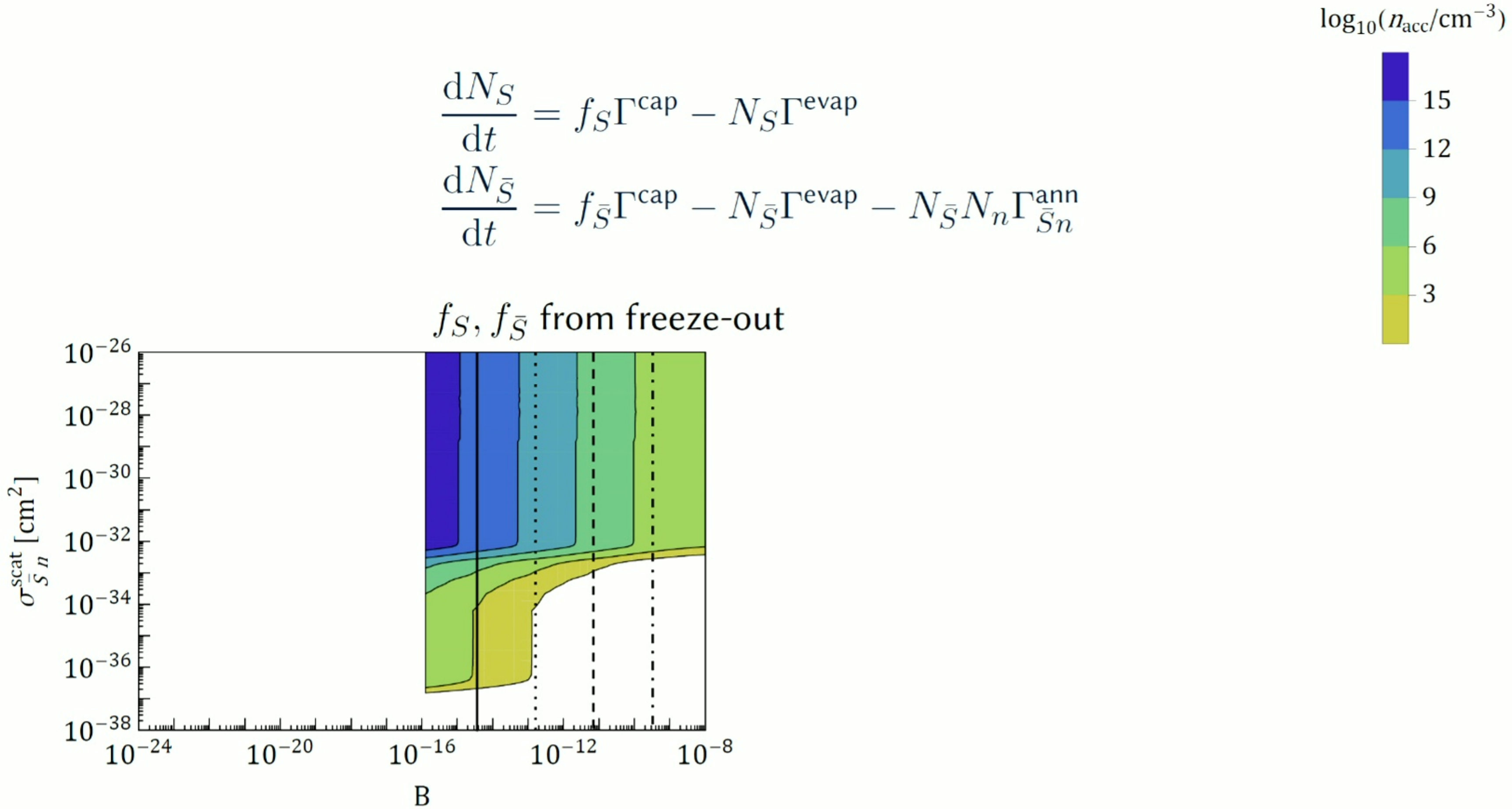
McKeen, **Moore** et al., PRD **106**, 035011 (2022)

Sexaquarks can reach a large overabundance in the Earth ($\bar{S}n \to \bar{b}\pi$)

$$\frac{dN_S}{dt} = f_S\Gamma^{\text{cap}} - N_S\Gamma^{\text{evap}}$$

$$\frac{dN_{\bar{S}}}{dt} = f_{\bar{S}}\Gamma^{\text{cap}} - N_{\bar{S}}\Gamma^{\text{evap}} - N_{\bar{S}}N_n\Gamma^{\text{ann}}_{\bar{S}n}$$

$f_S, f_{\bar{S}}$ from freeze-out



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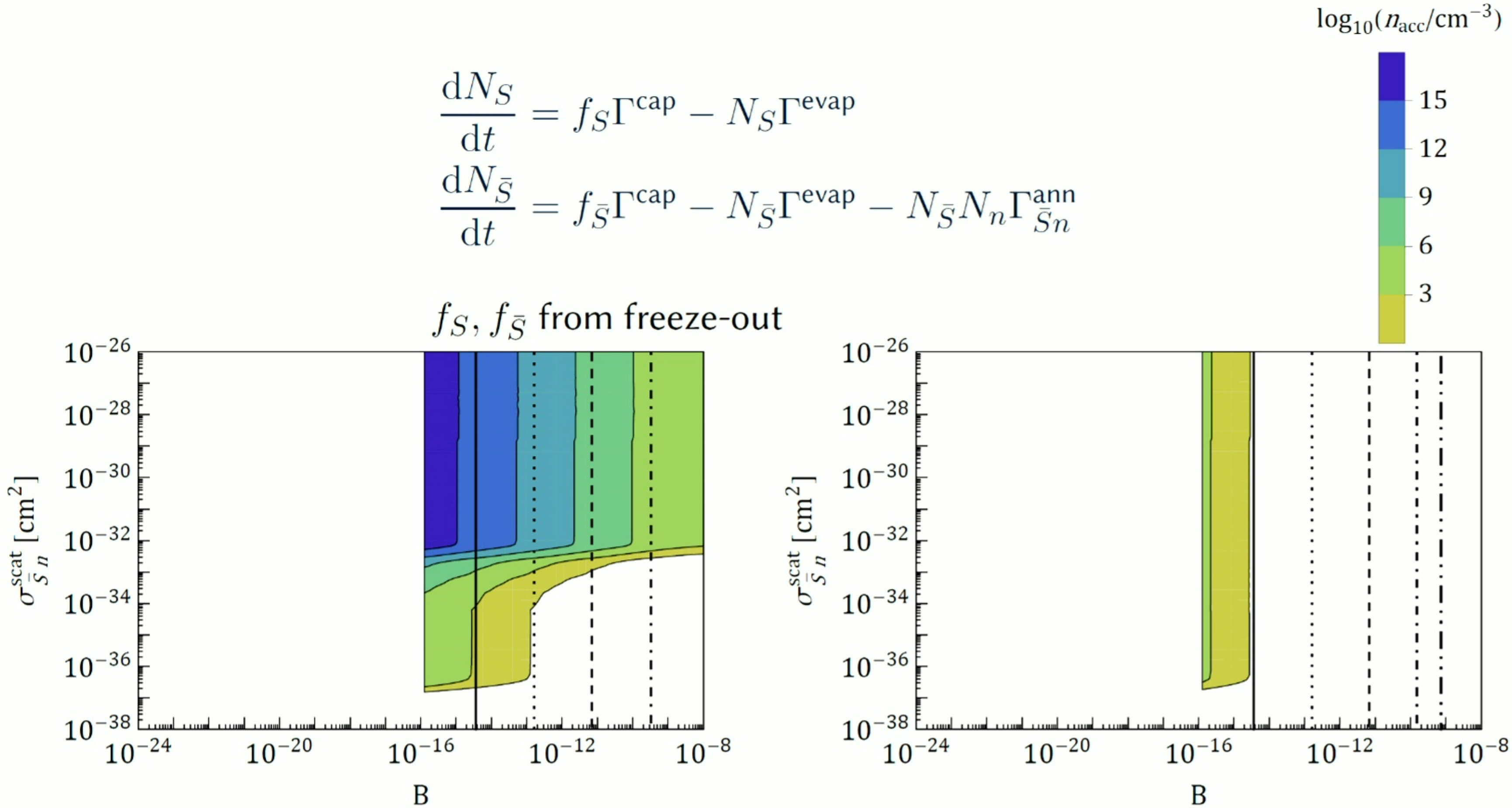
$f_S, f_{\bar{S}}$ from freeze-out



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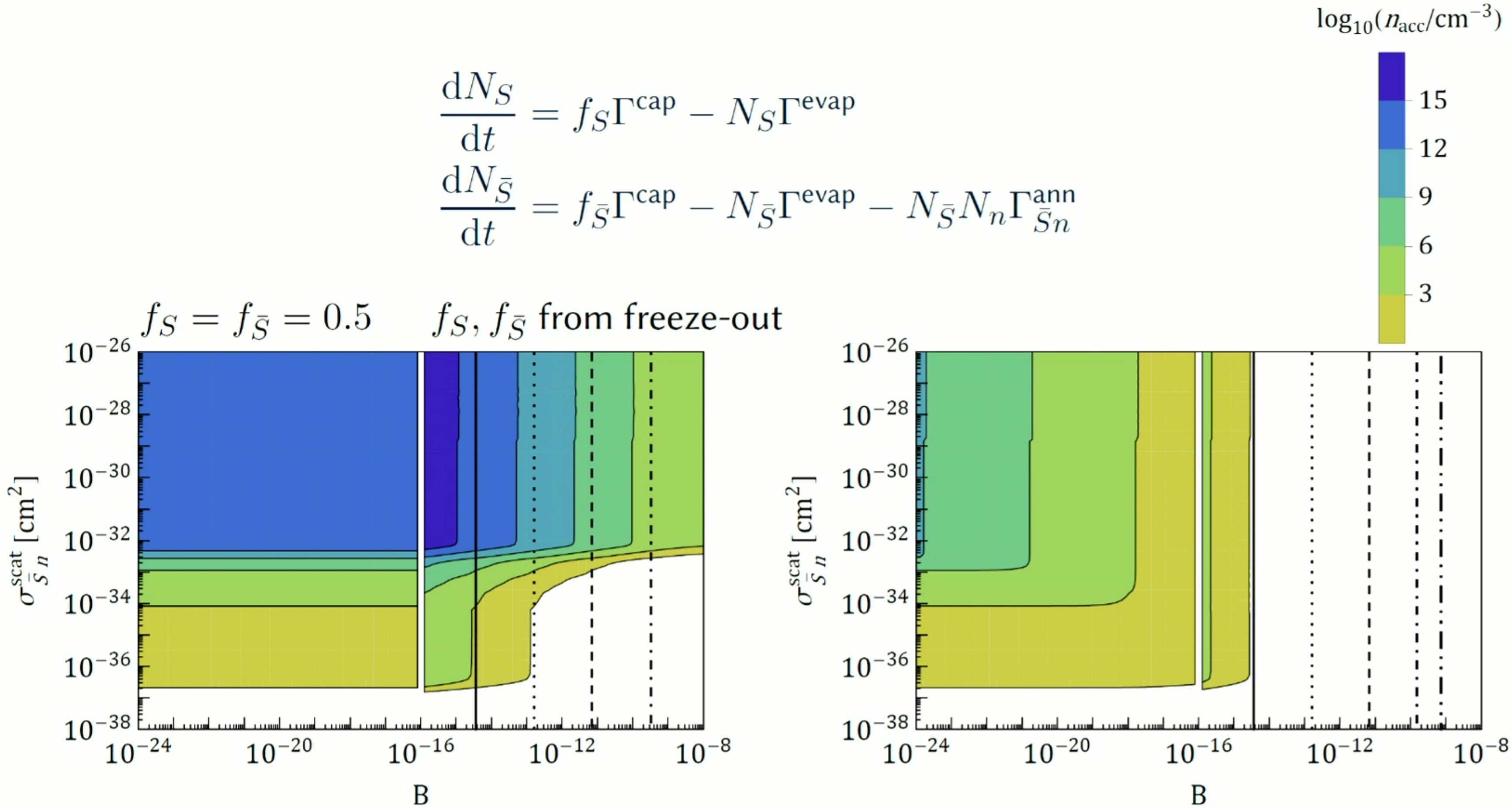
$f_S = f_{\bar{S}} = 0.5$ $f_S, f_{\bar{S}}$ from freeze-out

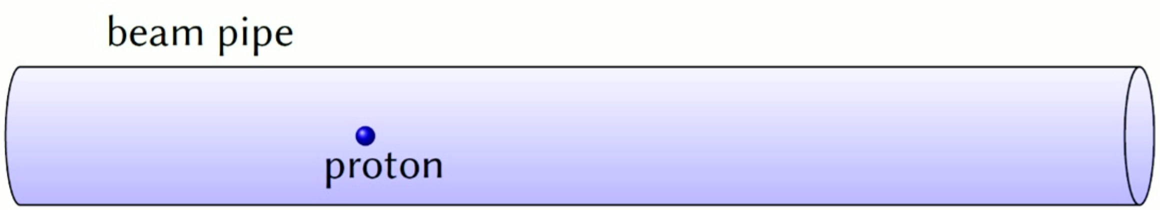


How to discover an overabundance of thermalized dark matter?

- **Upscatter dark matter** ($\propto \sigma^2_{Sn}$)
- **Look for annihilation signals** ($\propto B, \langle \sigma v \rangle_{S\bar{S}}$)
  - *Earth core heating* (e.g. 0705.4298, 1909.11683)
  - *Detecting neutrinos from annihilating dark matter* (e.g. 2309.10032)
  - *Annihilating directly in detectors* (e.g. 2303.03416)

A setup to upscatter dark matter using nuclear accelerators

energy: 400 keV to 3.5 MeV
current: $1 - 10$ mA
location: Gran Sasso, Jinping, SURF



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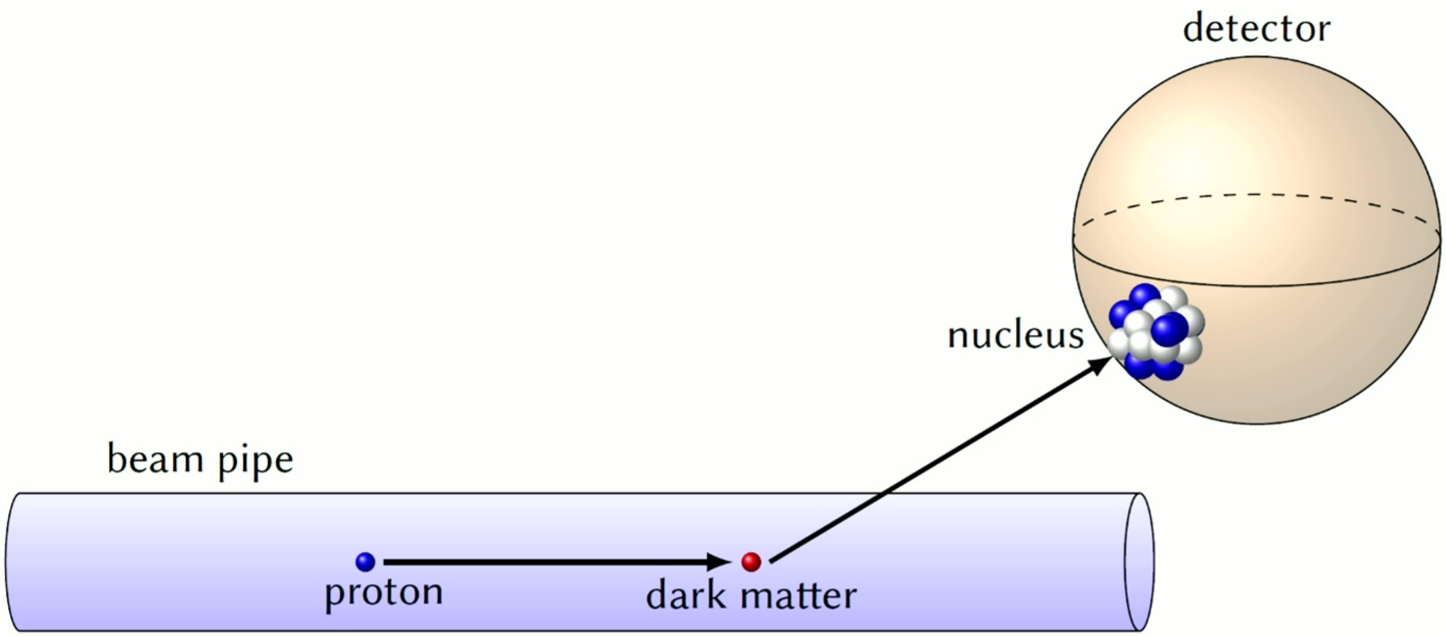
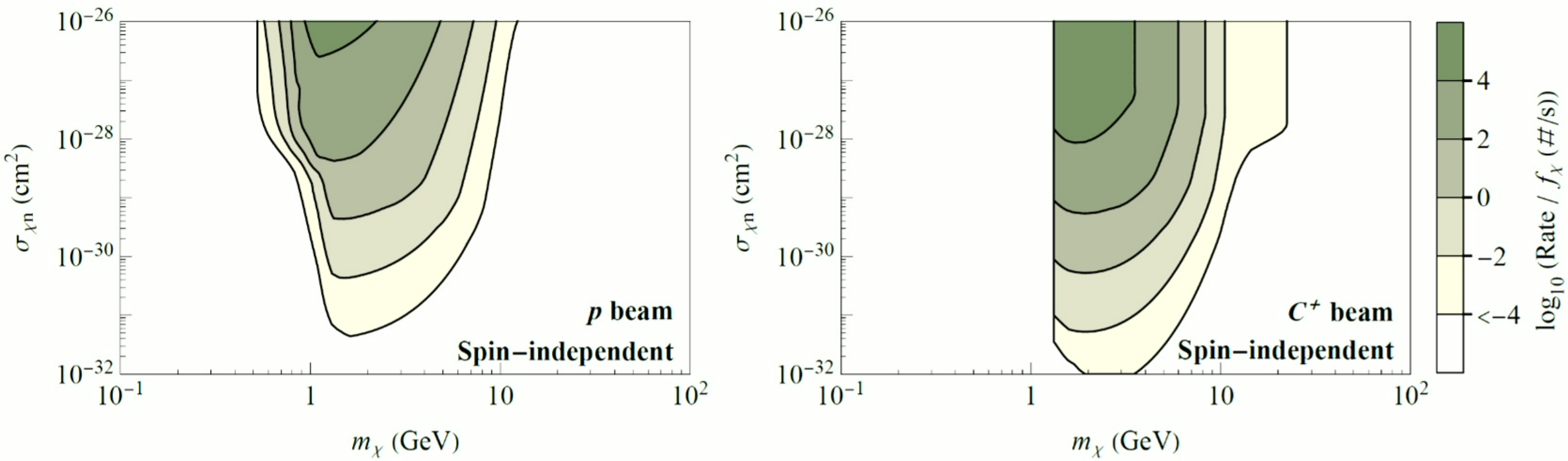


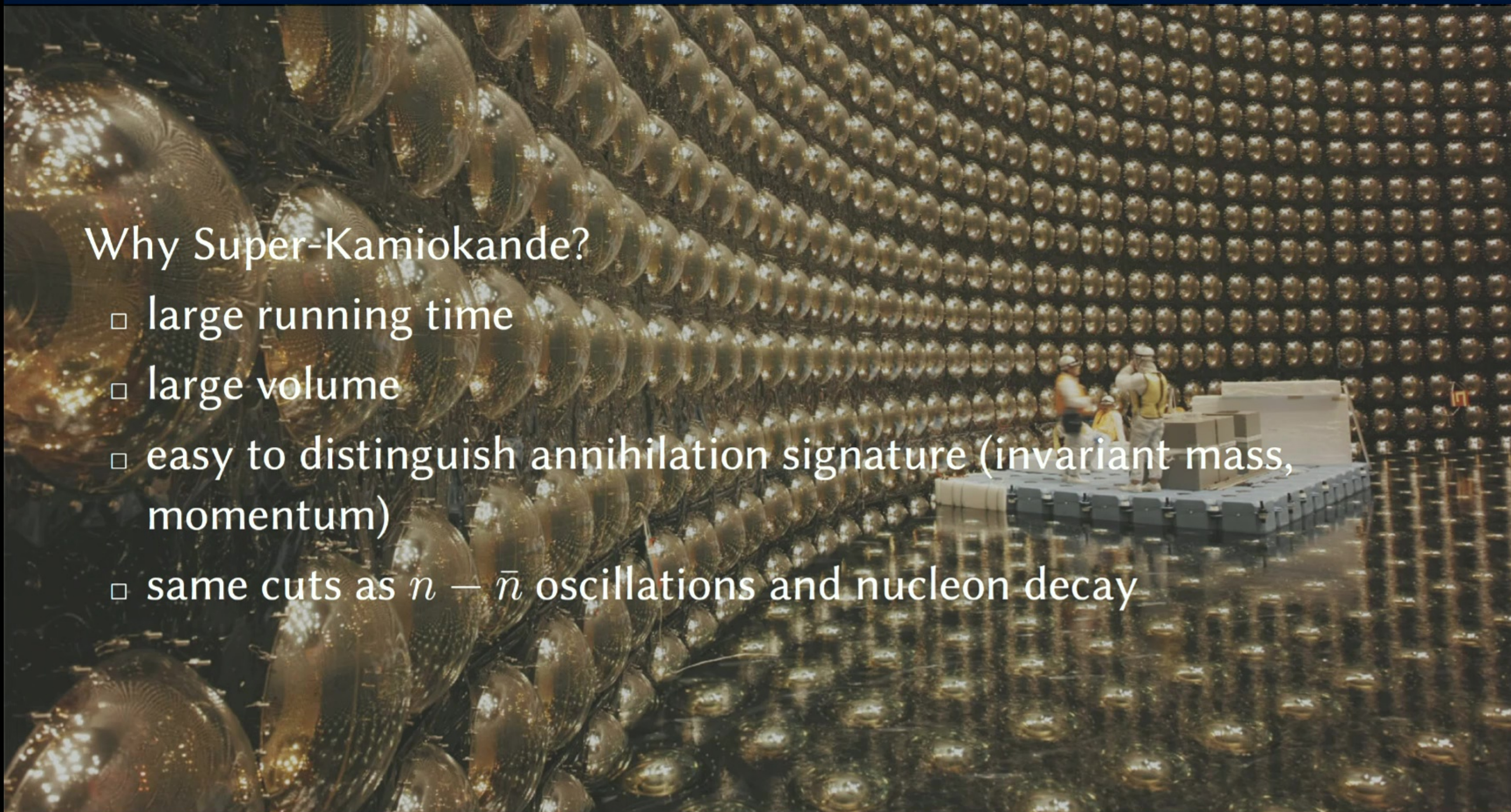
McKeen, **Moore** et al., PRD **106**, 035011 (2022)

Detection prospects from nuclear accelerators



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

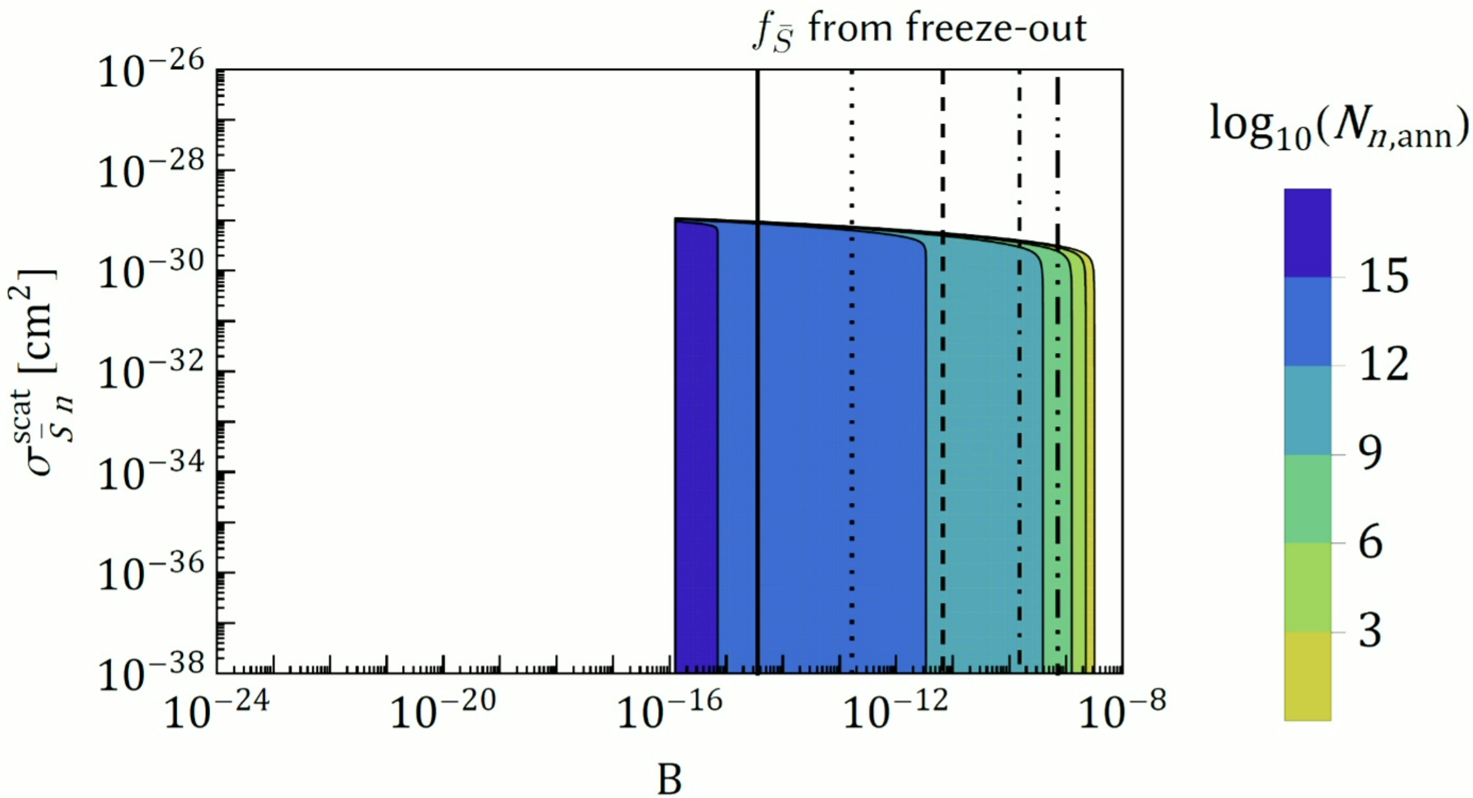
Antisexaquarks would annihilate in Super-Kamiokande



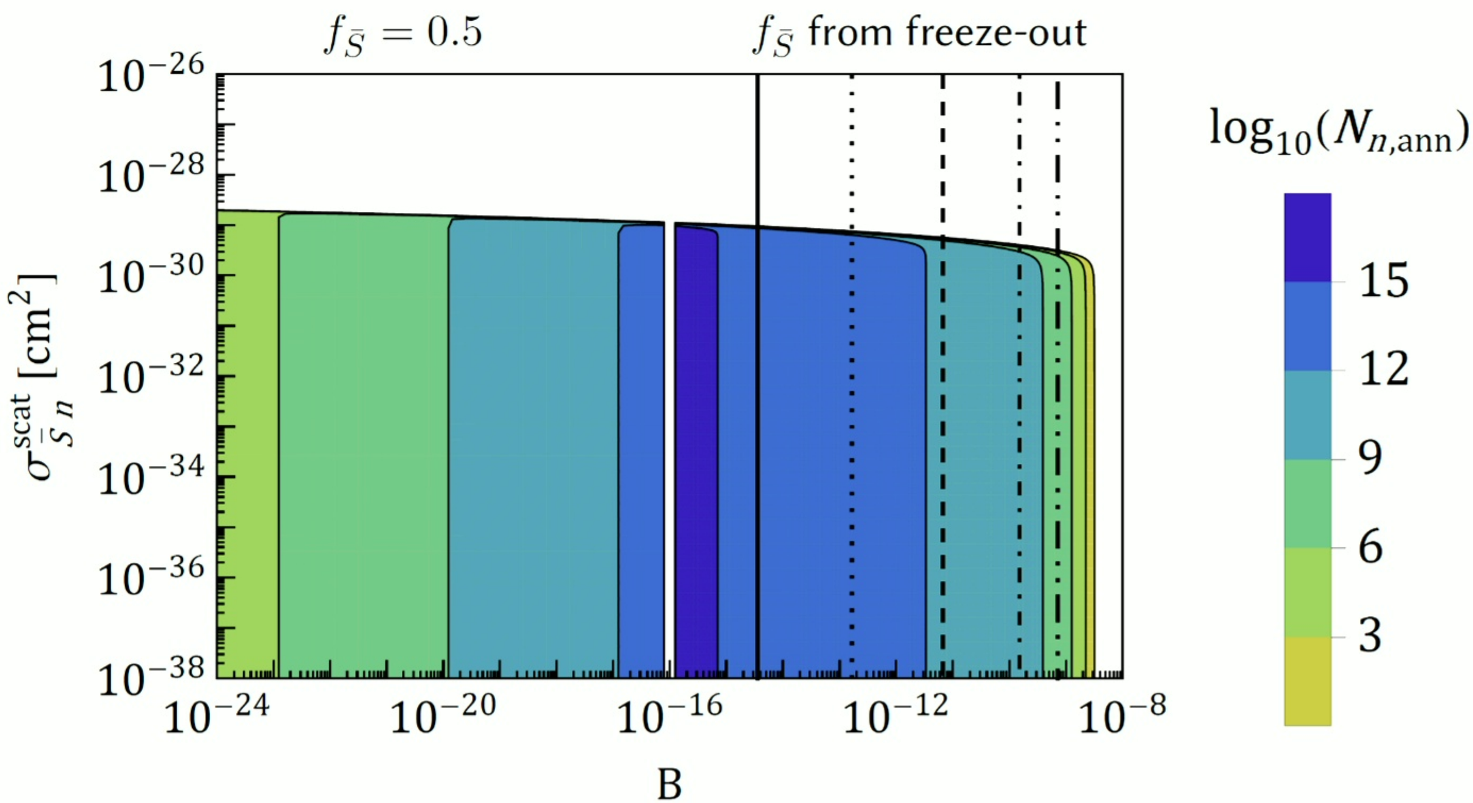
Why Super-Kamiokande?

- large running time
- large volume
- easy to distinguish annihilation signature (invariant mass, momentum)
- same cuts as $n - \bar{n}$ oscillations and nucleon decay

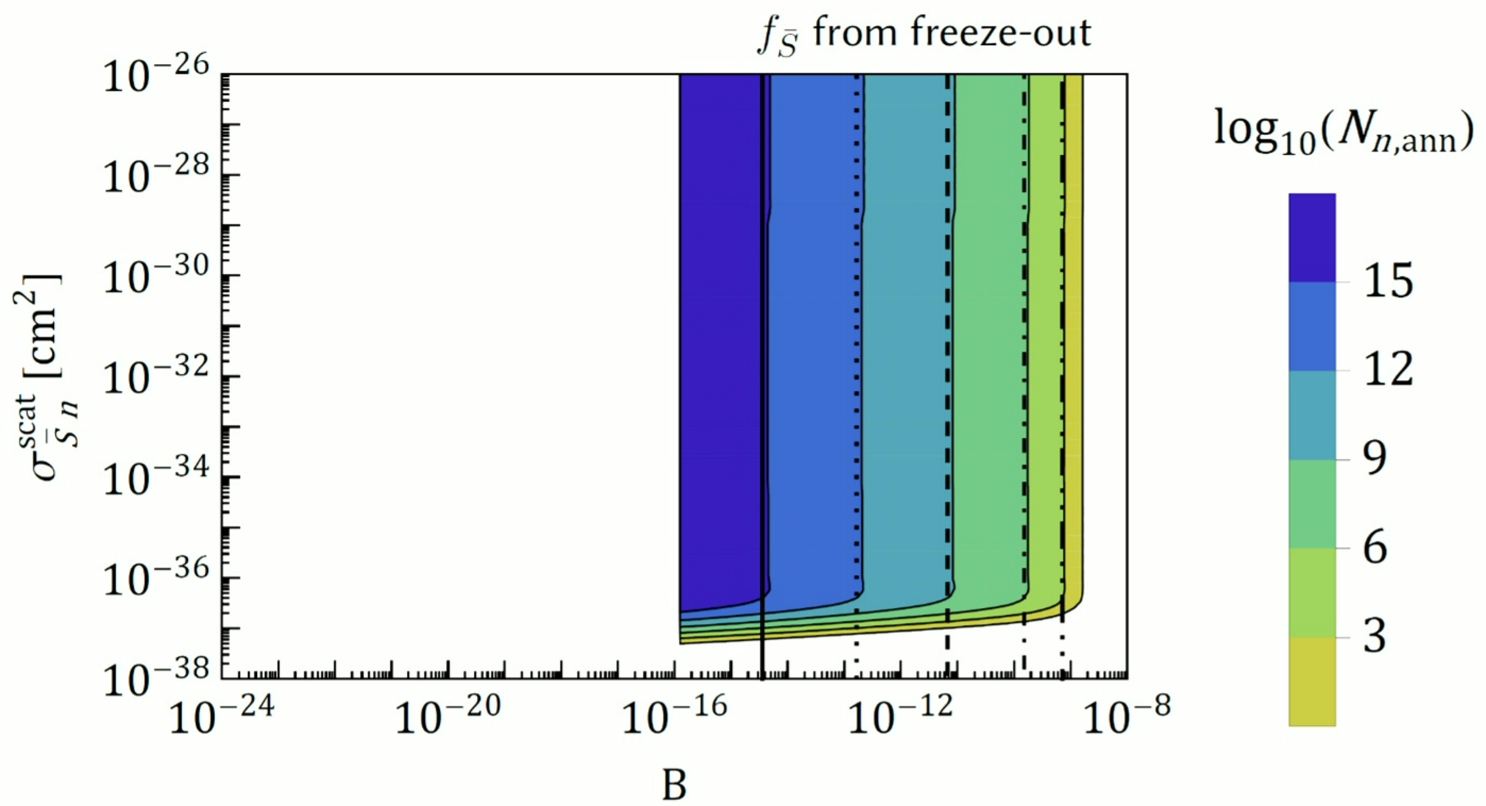
Wind antisexaquarks would annihilate in Super-Kamiokande



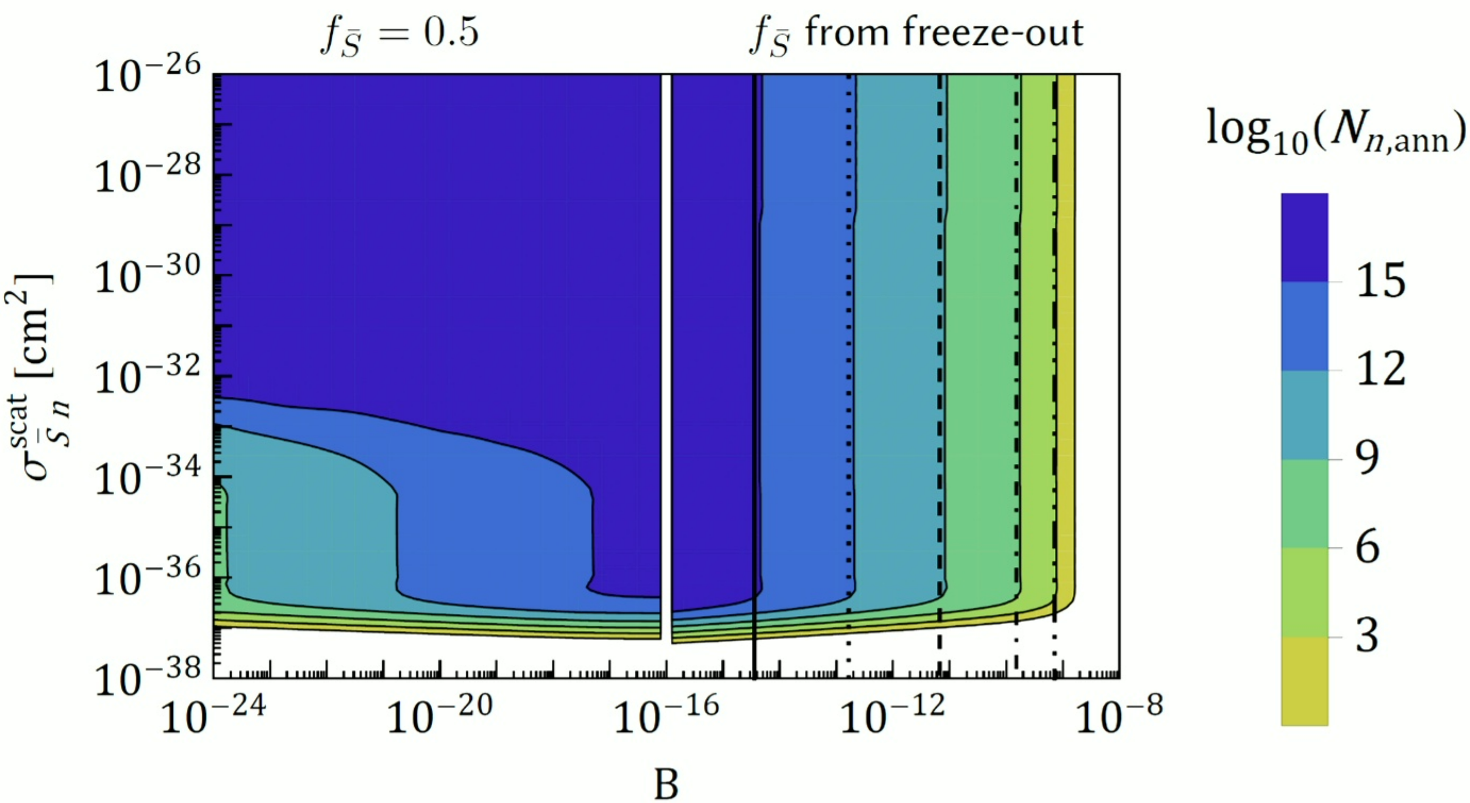
Wind antisexaquarks would annihilate in Super-Kamiokande



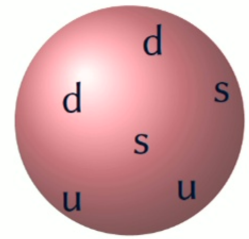
Accumulated antisexaquarks would annihilate in Super-Kamiokande



Accumulated antisexaquarks would annihilate in Super-Kamiokande



Summary



→ **Freeze-out**

- An early freeze-out is the only way to obtain $f_\chi = 1$, at the expense of a symmetric S-$\bar{S}$ population.
- all freeze-out rates must be small to give a non-negligible f_χ

→ **Direct detection**

- excludes $f_\chi = 1$ but not a subcomponent

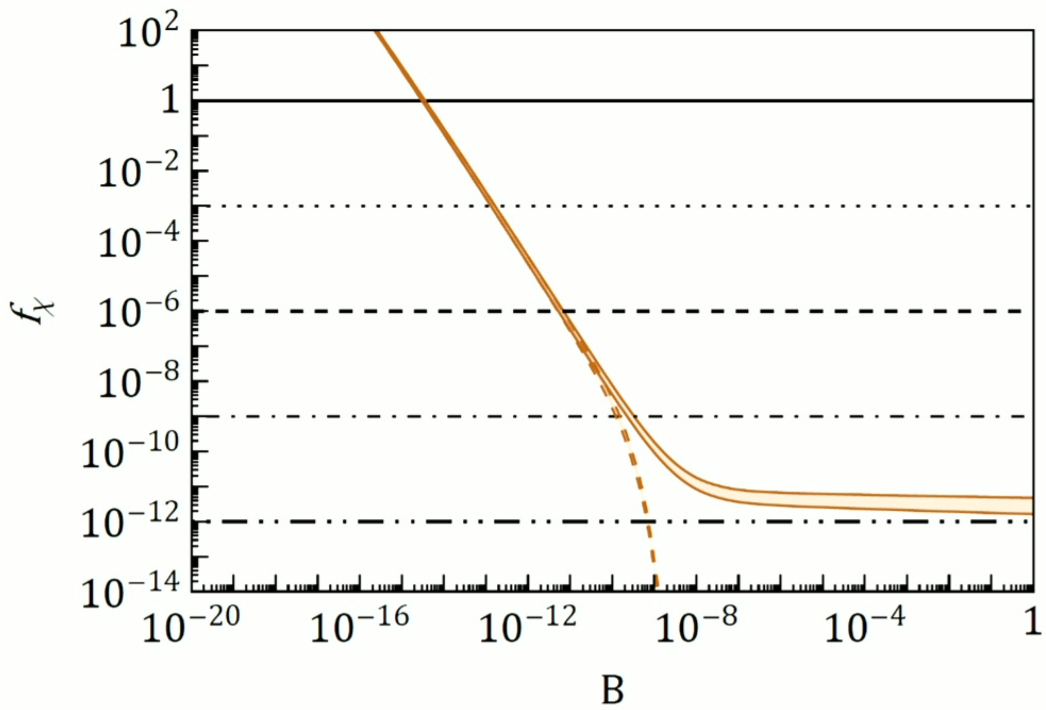
→ **Accumulation**

- a large S overabundance can be reached

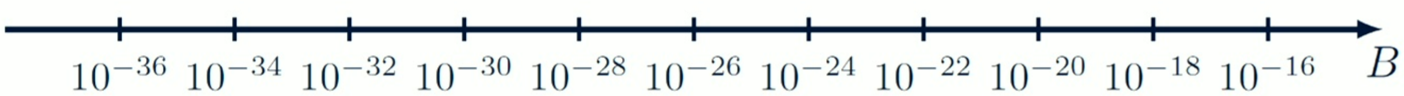
→ **Annihilation signature**

- $B > 10^{-9}$ giving $f_\chi \sim 10^{-11}$ remains viable
- $B < 10^{-33}$ and $f_\chi = 1$ cannot yet be probed by Super-Kamiokande

Summary



$f_S = f_{\bar{S}} = 0.5$

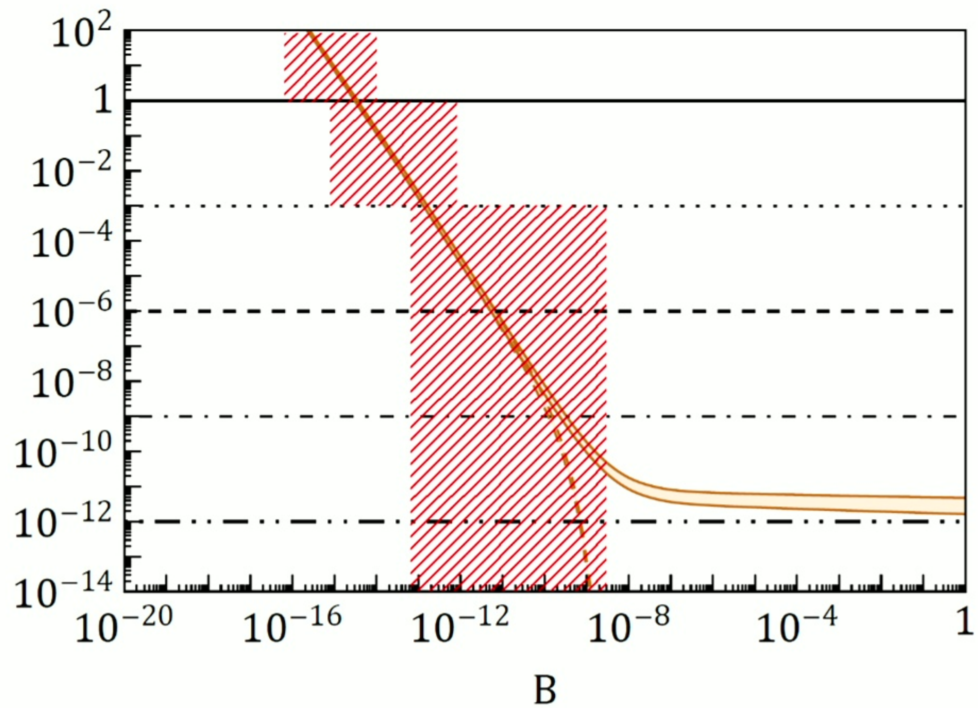


Summary

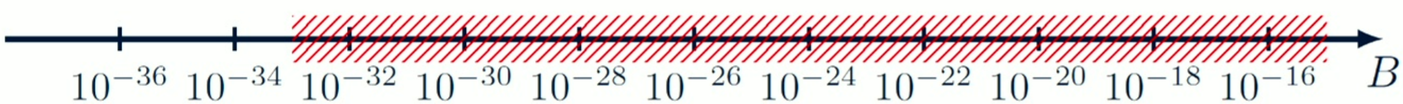
ruled out by cosmology

ruled out by direct detection

ruled out by Super-Kamiokande



$f_S = f_{\bar{S}} = 0.5$



Summary

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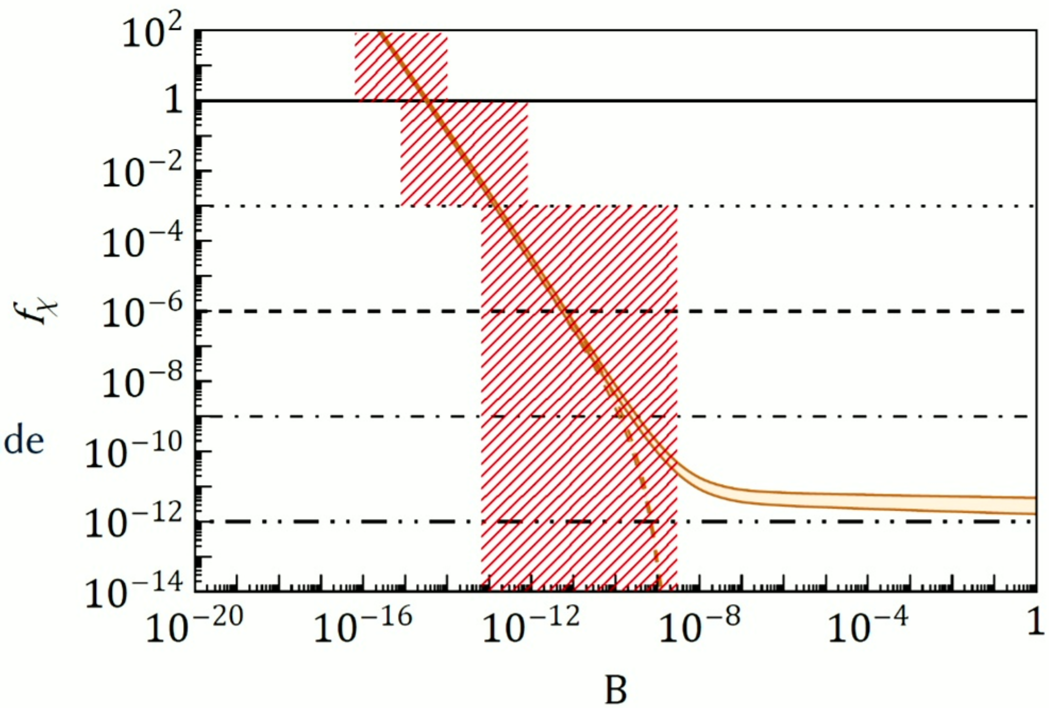

requires $A \sim 10^{-17}$

$f_S = f_{\bar{S}} = 0.5$