A dark matter candidate in the Standard Model?

Marianne Moore

BNL High Energy Theory seminar

March 5, 2026

based on

2403.03972 with Tracy R. Slatyer, 2512.14838 with Stefano Profumo

The possible dark matter mass range is huge

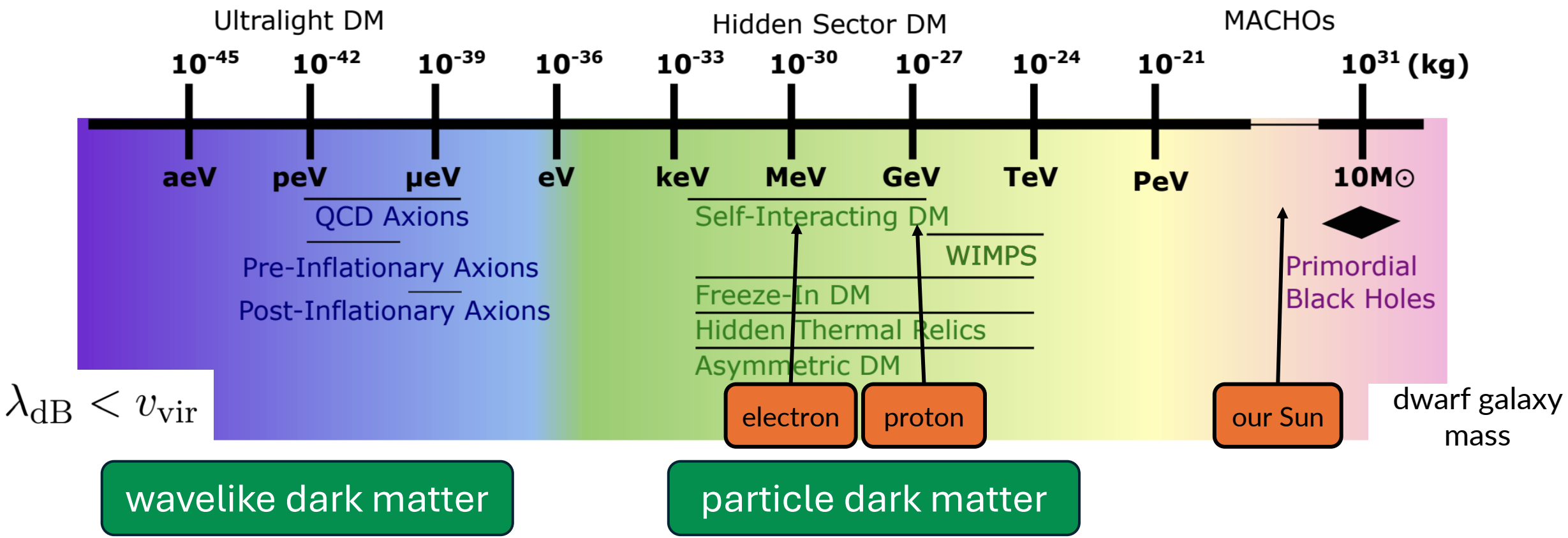
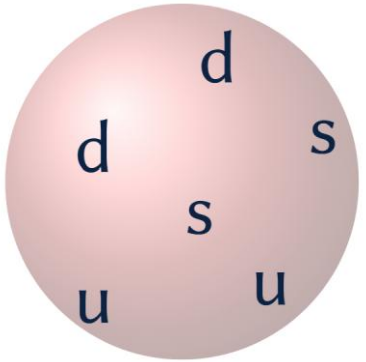


Figure from UCL

Are dark matter and baryons related?

- $\rho_{\text{dark matter}} \simeq 5\rho_{\text{baryons}}$
- This motivates baryogenesis (leptogenesis) connected to dark matter genesis
- The **only** reason to expect dark matter to have non-gravitational couplings
- $\frac{n_{\text{baryons}} - n_{\text{antibaryons}}}{n_\gamma} \simeq 6 \times 10^{-10}$

The sexaquark history



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.

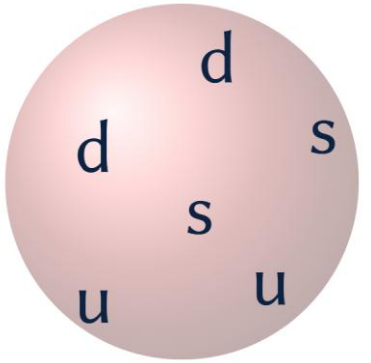
Stable Sexaquark

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.

no net spin nor charge
$B = 2$

The sexaquark mass range



$$m_S \gtrsim 1860\ \mathrm{MeV}$$

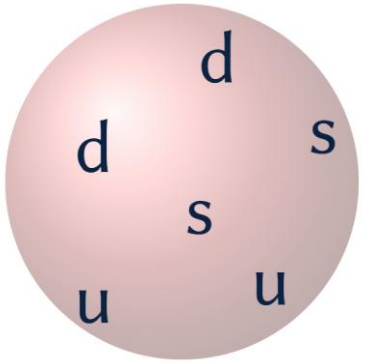
- to guarantee nuclear stability (${}^{A}_{Z}X \rightarrow {}^{A-2}_{Z-1}Y + S$)
- $1860 \simeq m_p + m_n - m_e - 2BE$ ($BE \sim 8$ MeV is the binding energy of a nucleon in a nucleus)

$$m_S \lesssim 1890\ \mathrm{MeV}$$

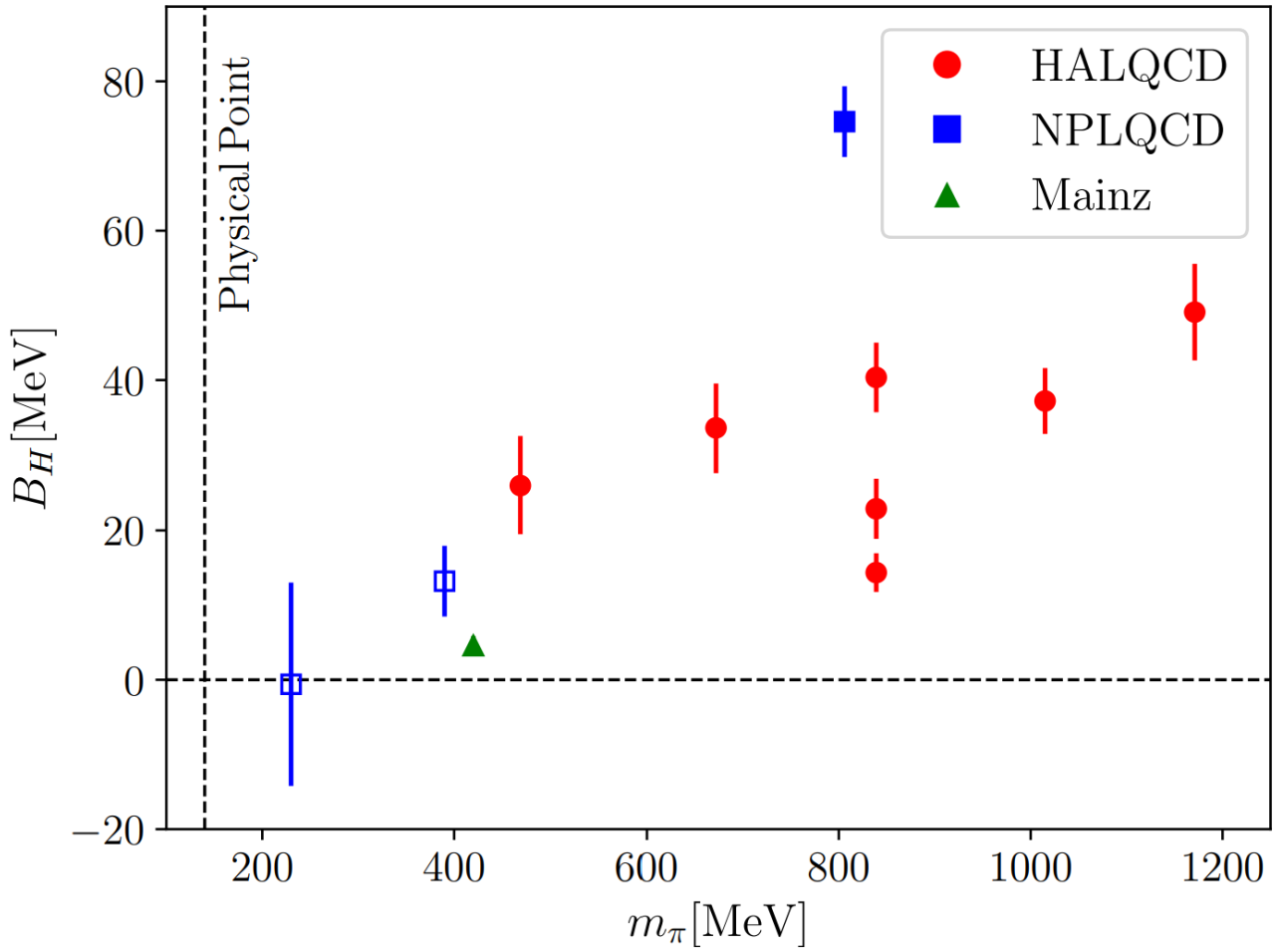
- to guarantee sexaquark stability ($S \rightarrow 2m_p + 2m_e$)
- it is a doubly weak process

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

Binding energy using lattice QCD

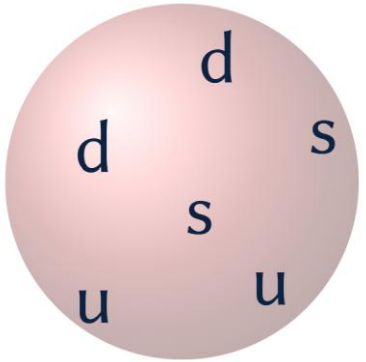


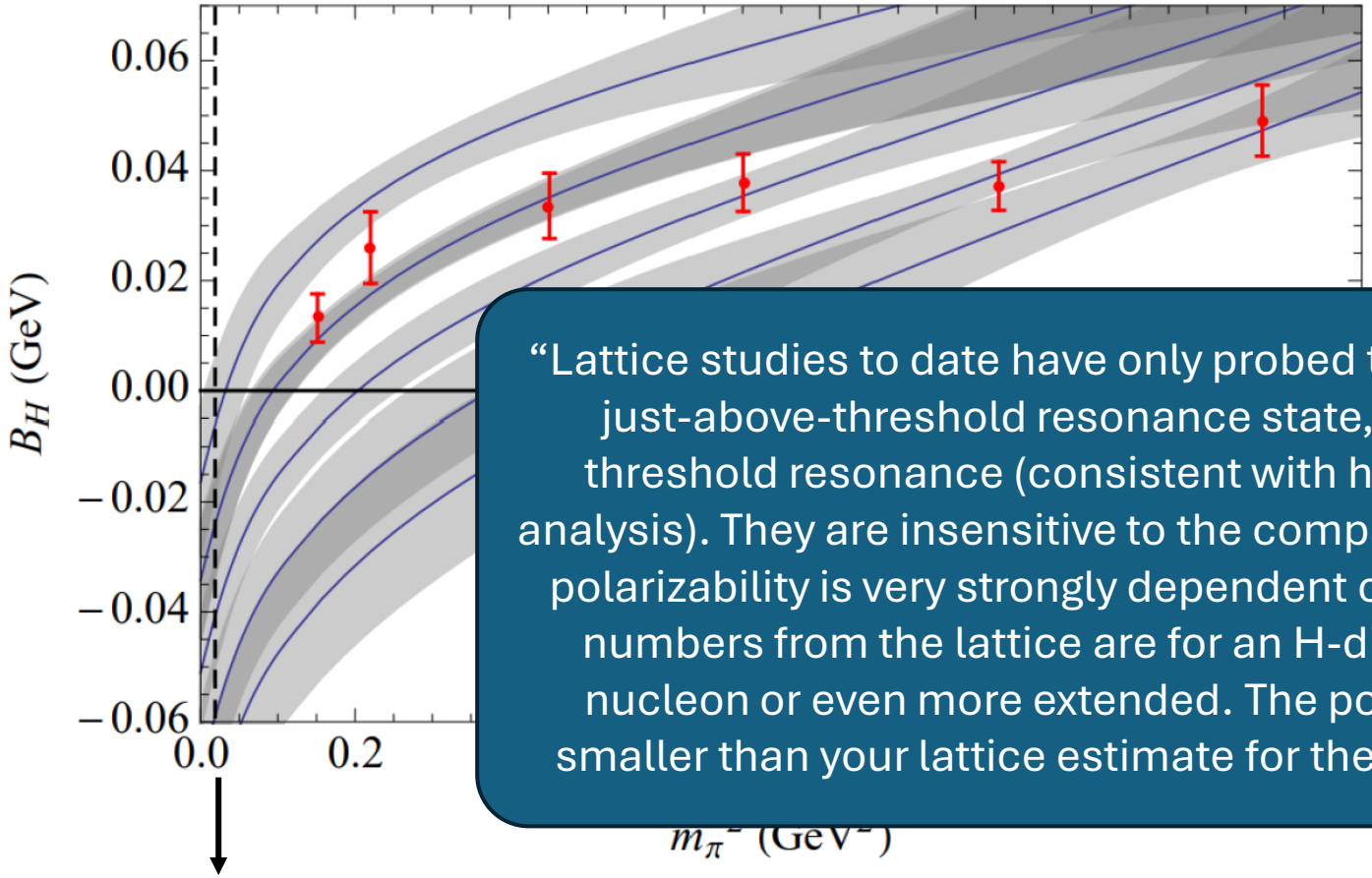
filled: SU(3) symmetric
empty: SU(3) broken



Baião Raposo *et al.*, 2603.00698

Lattice QCD extrapolation



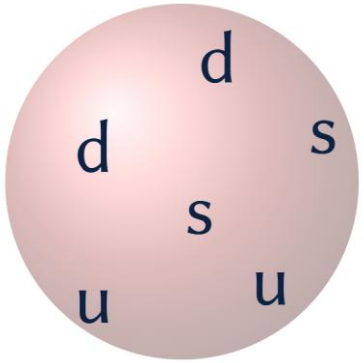


physica pion mass

"Lattice studies to date have only probed the weakly bound molecule or just-above-threshold resonance state, with BE < ~5 MeV, or near-threshold resonance (consistent with hints from ALICE phase shift analysis). They are insensitive to the compact Sexaquark system [...]. The polarizability is very strongly dependent on the spatial extent and your numbers from the lattice are for an H-dibaryon state which is like a nucleon or even more extended. The polarizability of the S is much smaller than your lattice estimate for the H-dibaryon would indicate."

Shanahan *et al.*, 1308.1748

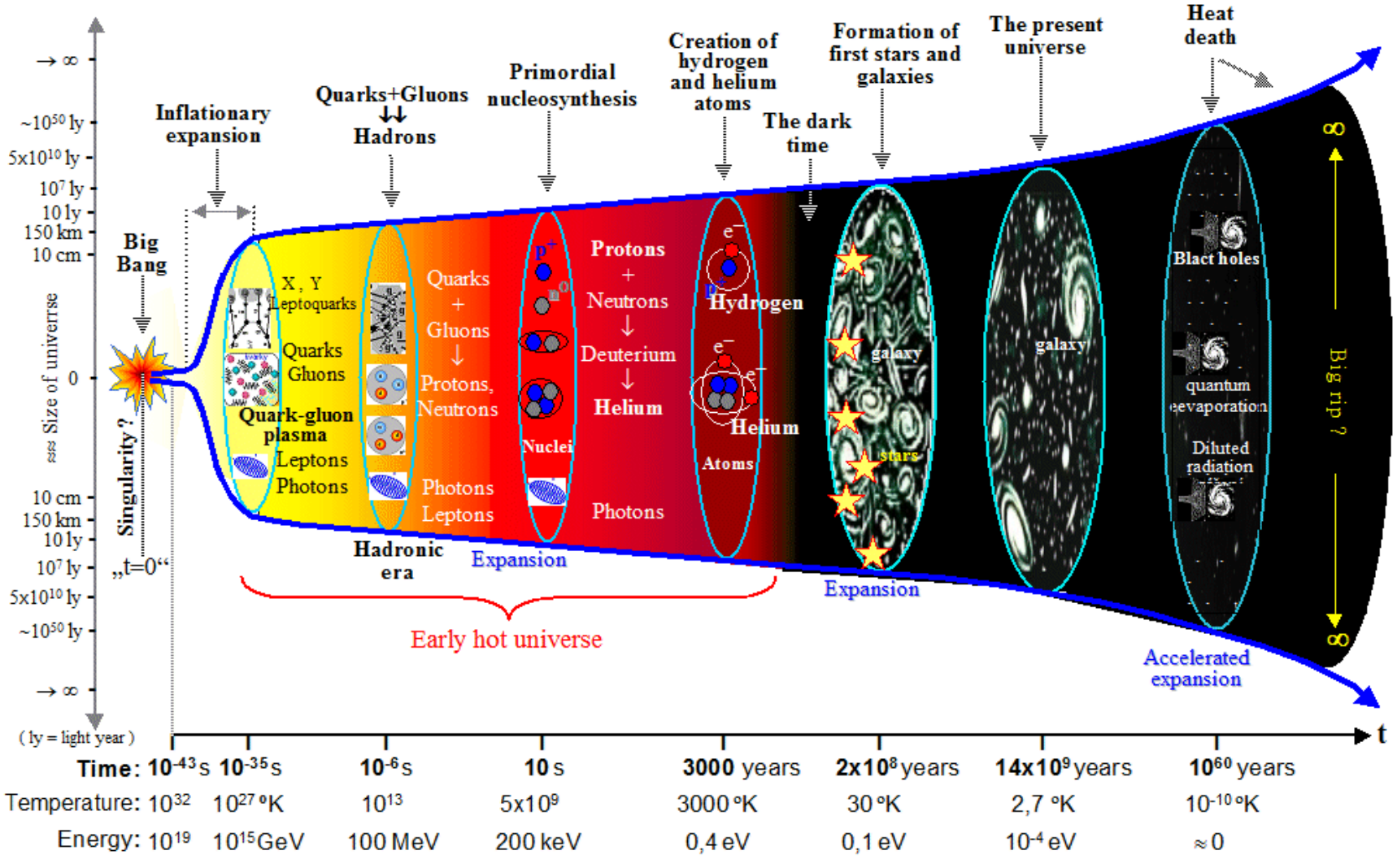
Sexaquark properties



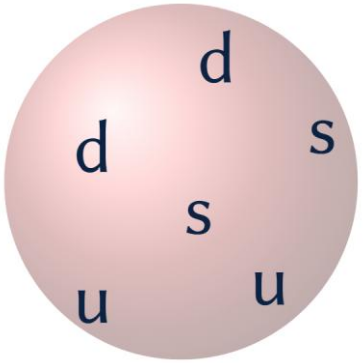
- Dark/Neutral ✓
- Cold/Non-relativistic ✓
- Stable on cosmological timescales
  - very long lifetime $\tau \gtrsim 10^9 \times \tau_{\text{universe}}$
- Can obtain the measured dark matter abundance in the Early Universe ?
- Not be already excluded ?

Claim: possible if its Standard Model coupling is much smaller than naïve QCD

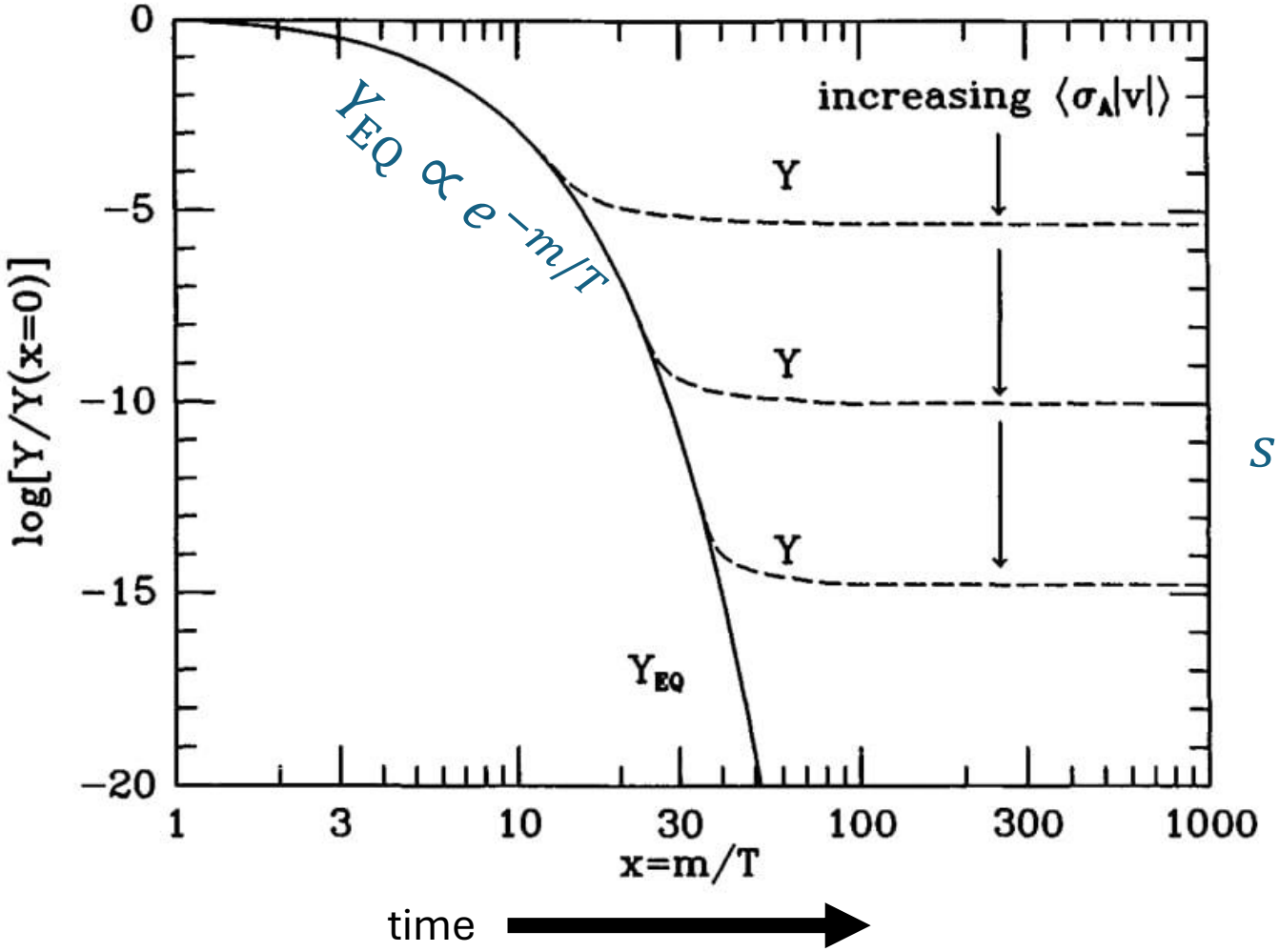
The history of the Universe



Freeze out of WIMPs



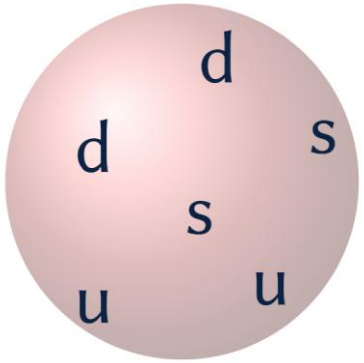
no chemical potential

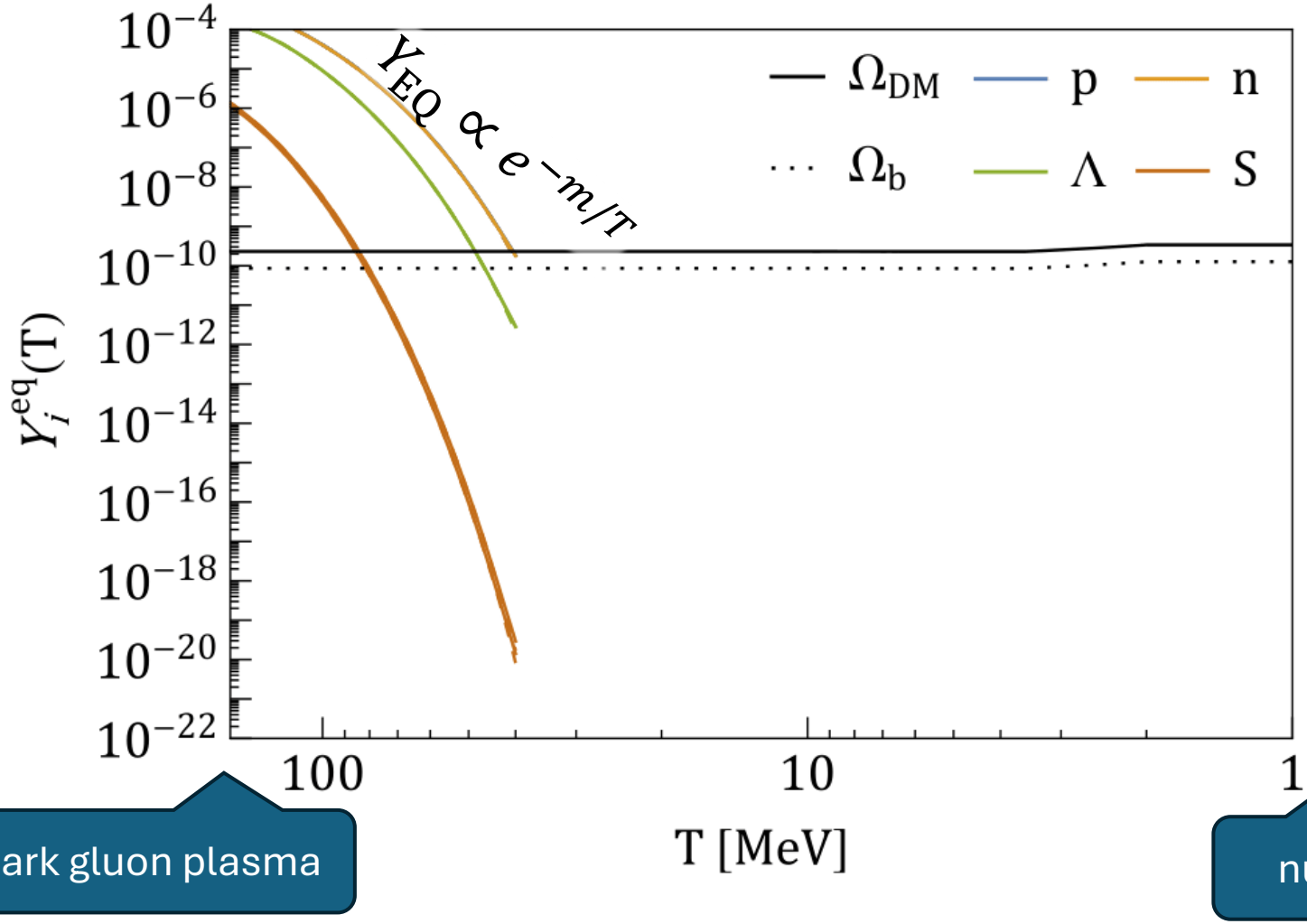


$$s\,Y\,\langle\sigma v\rangle \simeq H$$

Kolb & Turner 1990

Equilibrium abundance of the sexaquark





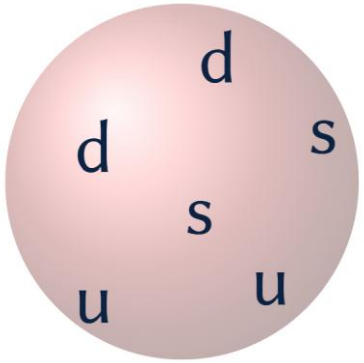
with chemical potential (not answering where it comes from)

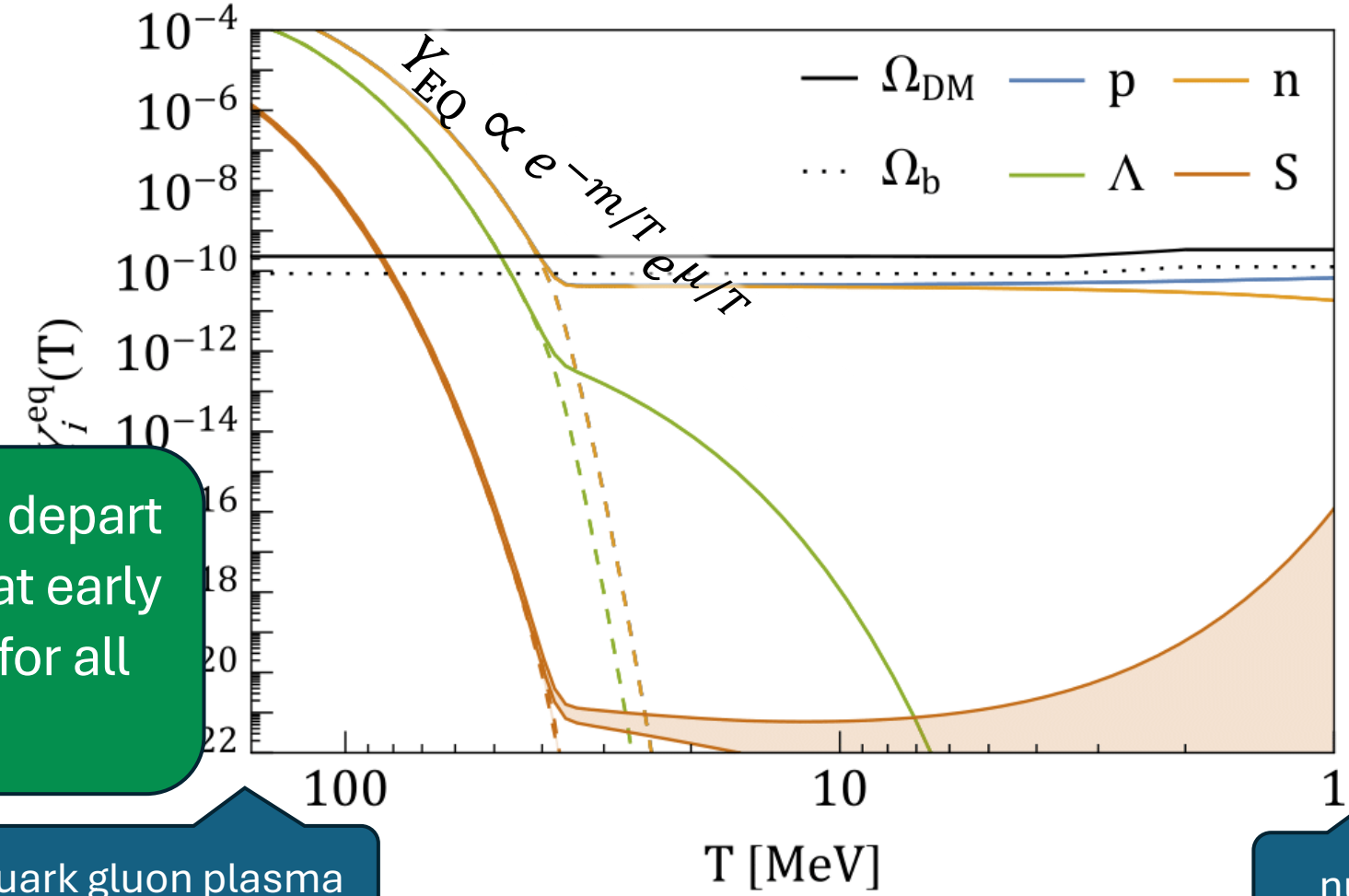
quark gluon plasma

nucleosynthesis

MM+ 2403.03972

Equilibrium abundance of the sexaquark





with chemical potential (not answering where it comes from)

1860 MeV

↓

heavier

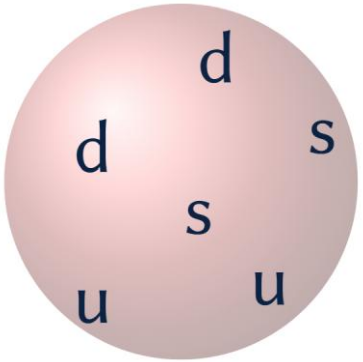
Sexaquarks must depart from equilibrium at early times to account for all of dark matter

quark gluon plasma

nucleosynthesis

MM+ 2403.03972

Freeze out of the sexaquark



Three main processes can lead to freeze out

0 $S\bar{S} \to \text{SM particles}$

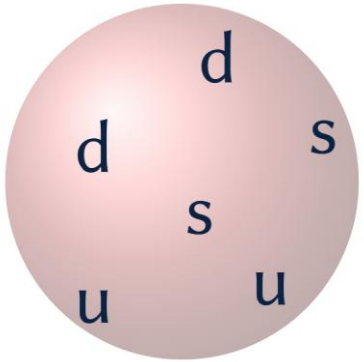
$$\frac{\mathrm{d}n_S}{\mathrm{d}t} + 3Hn_S = -\langle\sigma v\rangle^{\text{ann}}_{S\bar{S}} \left(n_S n_{\bar{S}} - n_S^{\text{eq}} n_{\bar{S}}^{\text{eq}}\right)$$

$$\frac{\mathrm{d}n_{\bar{S}}}{\mathrm{d}t} + 3Hn_{\bar{S}} = -\langle\sigma v\rangle^{\text{ann}}_{S\bar{S}} \left(n_S n_{\bar{S}} - n_S^{\text{eq}} n_{\bar{S}}^{\text{eq}}\right)$$

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

MM+ 2403.03972

Freeze out of the sexaquark



Three main processes can lead to freeze out

0	$S\bar{S} \to \text{SM particles}$
2	$S\pi \to bb'$
1	$S\bar{b} \to b'\pi$

$\propto B m_\pi^{-2}, \text{ with } B \leq 1$

investigated by Kolb & Turner in 2018 for $B \in [10^{-11}, 1]$, but claims by Glennys that $B \leq 10^{-12}$

$S\pi \to bb'$

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

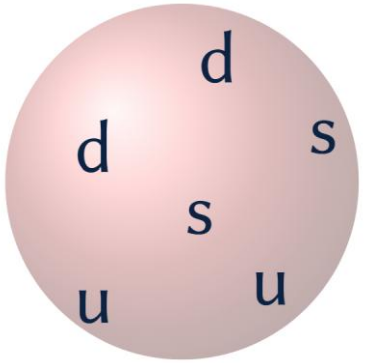
$$\frac{\mathrm{d}n_{\bar{S}}}{\mathrm{d}t} + 3Hn_{\bar{S}} = -\langle\sigma v\rangle^{\text{ann}}_{S\bar{S}} (n_S n_{\bar{S}} - n_S^{\text{eq}} n_{\bar{S}}^{\text{eq}}) - \sum_{b,b'} [\Gamma_{\bar{S}\pi} + \Gamma_{\bar{S}b}] [n_{\bar{S}} - n_{\bar{S}}^{\text{eq}}]$$

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

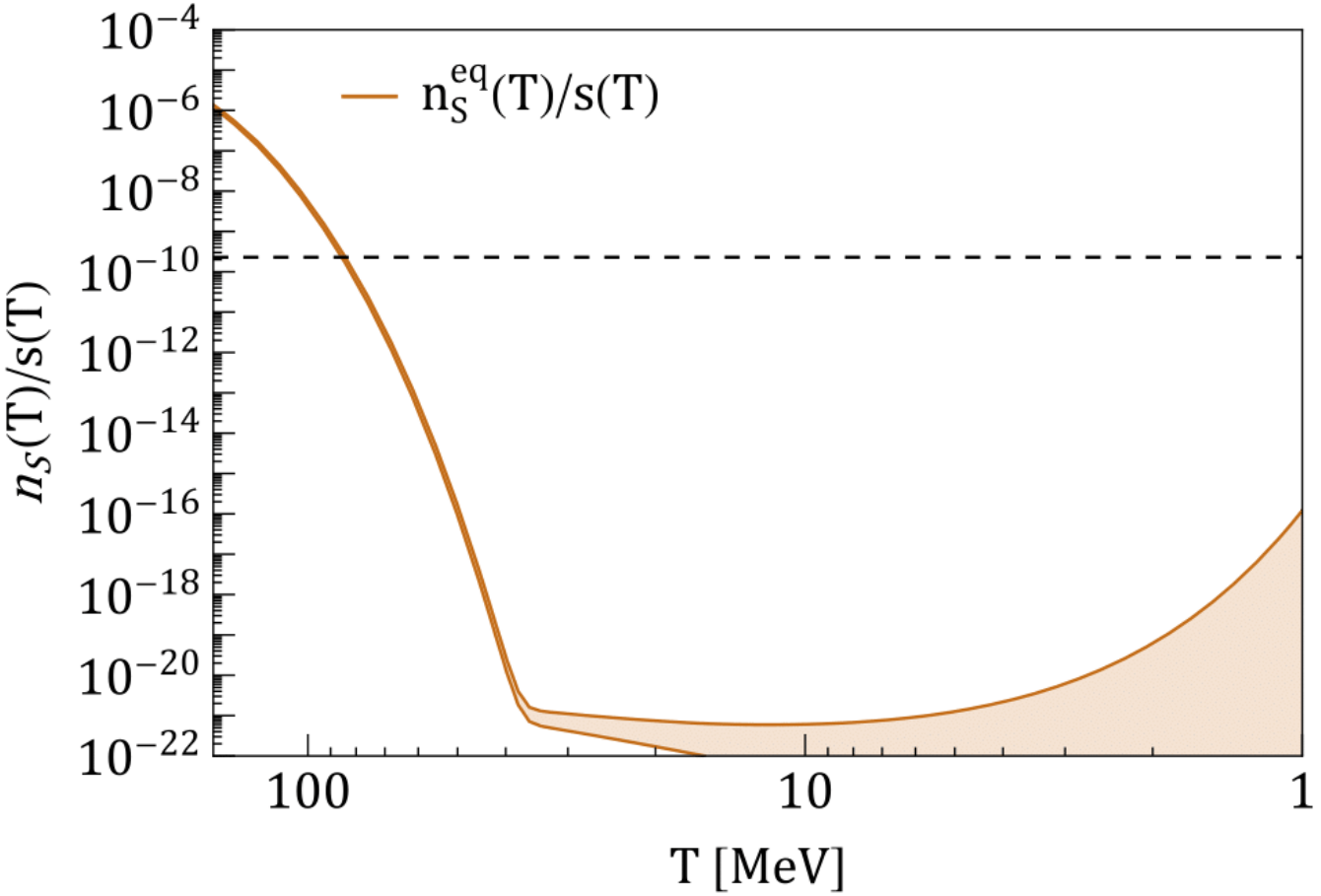
$S\bar{b} \to b'\pi$
$\bar{S}b \to \bar{b}'\pi$

MM+ 2403.03972

Freeze out of the sexaquark



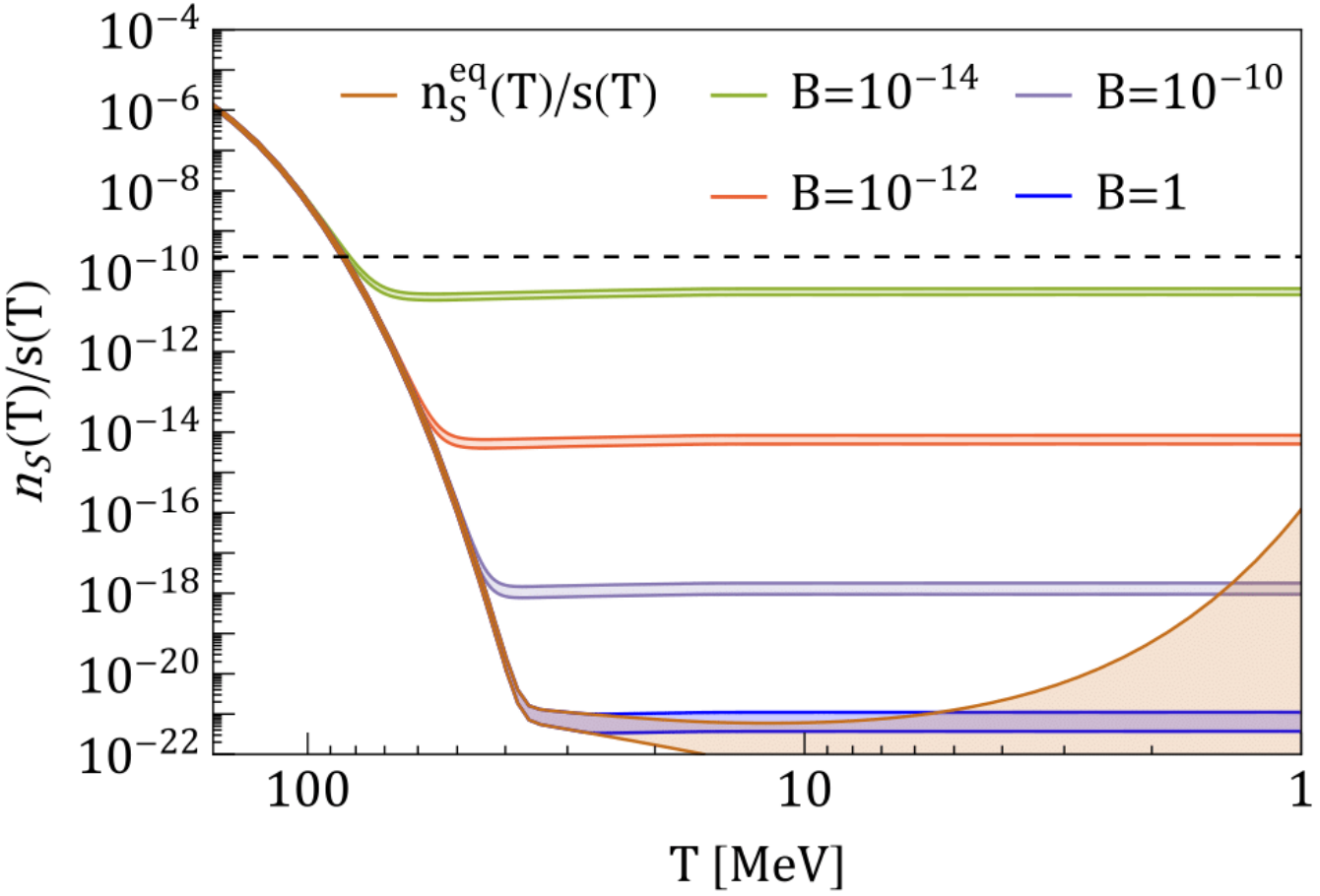
$\langle \sigma \mathrm{v} \rangle = B m_\pi^{-2}$



MM+ 2403.03972

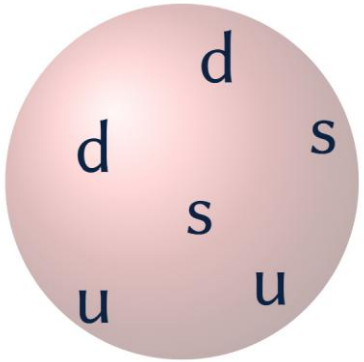
Freeze out of the sexaquark

$$\langle \sigma v \rangle = B m_\pi^{-2}$$



MM+ 2403.03972

Freeze out of the sexaquark



Three main processes can lead to freeze-out

$$\left.\begin{array}{ll} 0 & S\bar{S} \to \text{SM particles} \\ 2 & S\pi \to b b' \\ 1 & S\bar{b} \to b'\pi \end{array}\right\} \propto B m_\pi^{-2}, \text{ with } B \leq 1$$

$\langle \sigma v \rangle \simeq 10^{-26}\ \text{cm}^2$
$B \simeq 10^{-17}$
$B \simeq 10^{-15}$

$S\pi \to b b'$

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

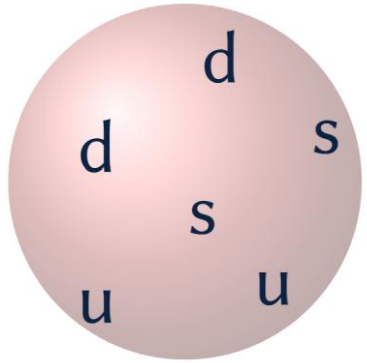
$$\frac{\mathrm{d}n_{\bar{S}}}{\mathrm{d}t} + 3Hn_{\bar{S}} = -\langle \sigma v \rangle^{\text{ann}}_{S\bar{S}} \left(n_S n_{\bar{S}} - n_S^{\text{eq}} n_{\bar{S}}^{\text{eq}}\right) - \sum_{b,b'} \left[\Gamma_{\bar{S}\pi} + \Gamma_{\bar{S}b}\right]\left[n_{\bar{S}} - n_{\bar{S}}^{\text{eq}}\right]$$

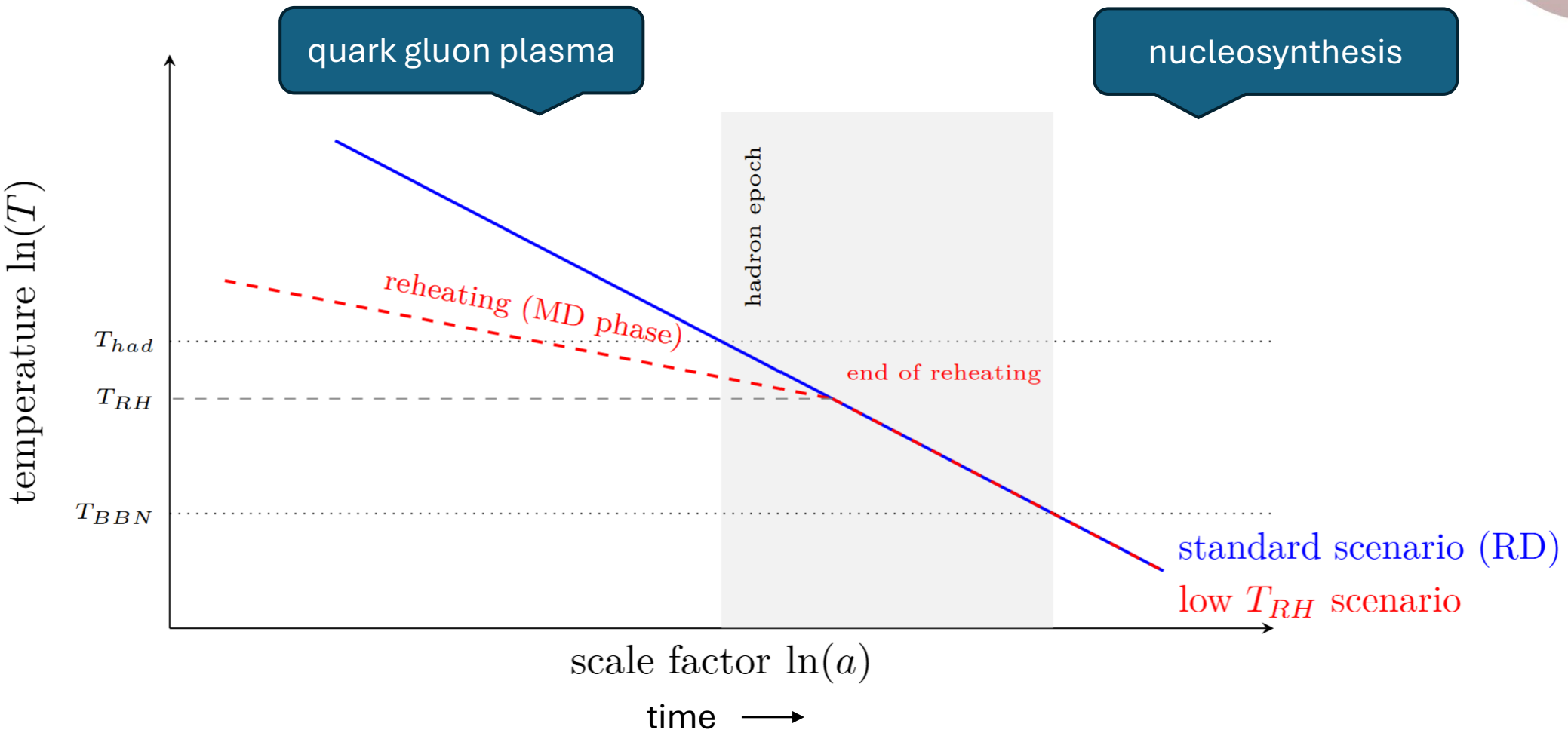
$S\bar{S} \to$ SM particles

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

MM+ 2403.03972

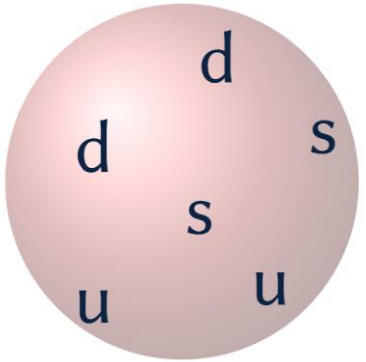
Alternate cosmological history

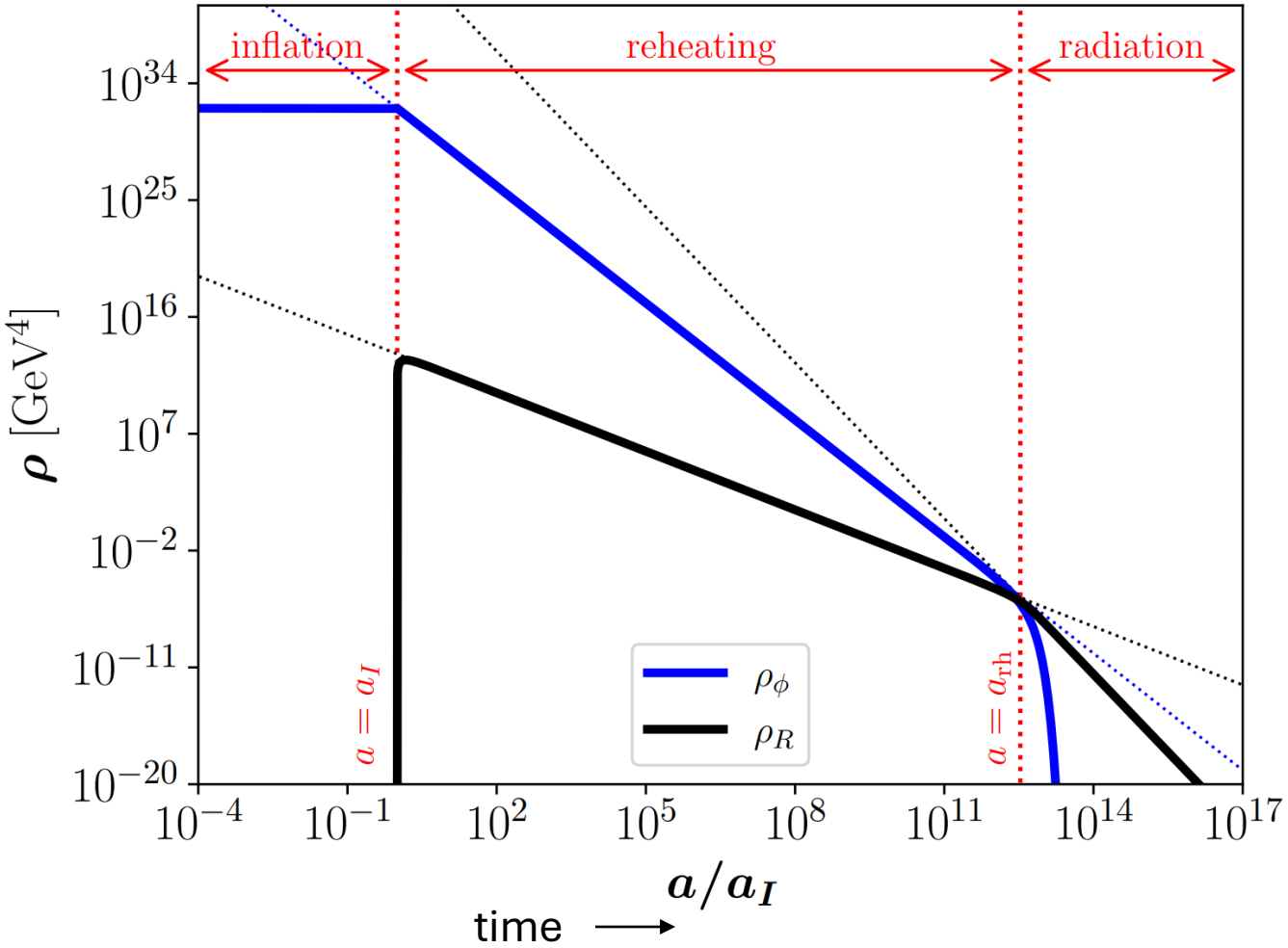




MM+ 2512.14838

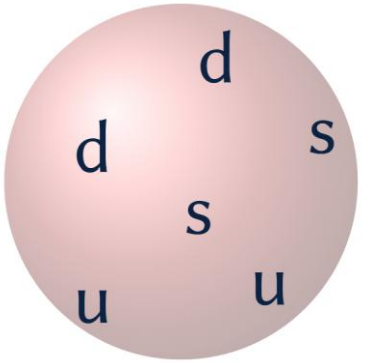
Evolution of energy densities





Bernal *et al.*, 2406.17039

Sexaquarks from a late-decaying reheaton



For $m_\phi \gg \Lambda_{\rm QCD}$, a couple of parameters set the abundance:

$$Y_S \simeq f_S \times \frac{T_{\rm RH}}{m_\phi} \text{ where } f_S \equiv B_{\rm strange} \times P_{\rm coal}$$

coalescence probability

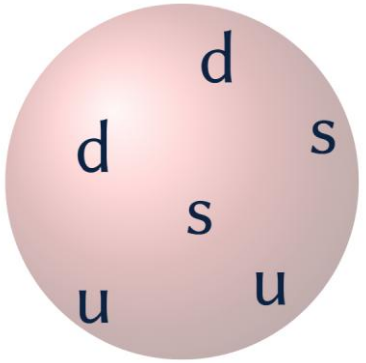
sexaquark survival efficiency from reheaton decay

branching fraction of reheaton decays into strange quarks

$T_{\rm BBN} \ll T_{\rm RH} \ll T_{\rm had}$ requires $f_S \simeq 10^{-7}$ for sexaquarks to be all of dark matter

MM+ 2512.14838

Reheaton decaying into quark matter



Pairs of quarks can be produced from the decay of

- spin-0 (scalar) reheatons
- spin-1 (vector) reheatons

$$\mathcal{L}_1 = \phi(g_s \bar{q} q + i g_p \bar{q} \gamma^5 q)$$

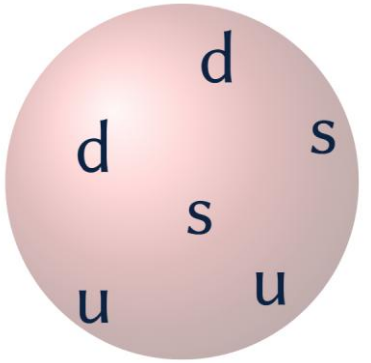
$$\mathcal{L}_2 = \frac{c}{\Lambda} \phi G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$\mathcal{L}_3 = Z'_\mu \left(g_{\mathrm{v}} \bar{q} \gamma^\mu q + i g_{\mathrm{a}} \bar{q} \gamma^{\mu\gamma^5} q \right)$$

evaluated with the Lund string model

MM+ 2512.14838

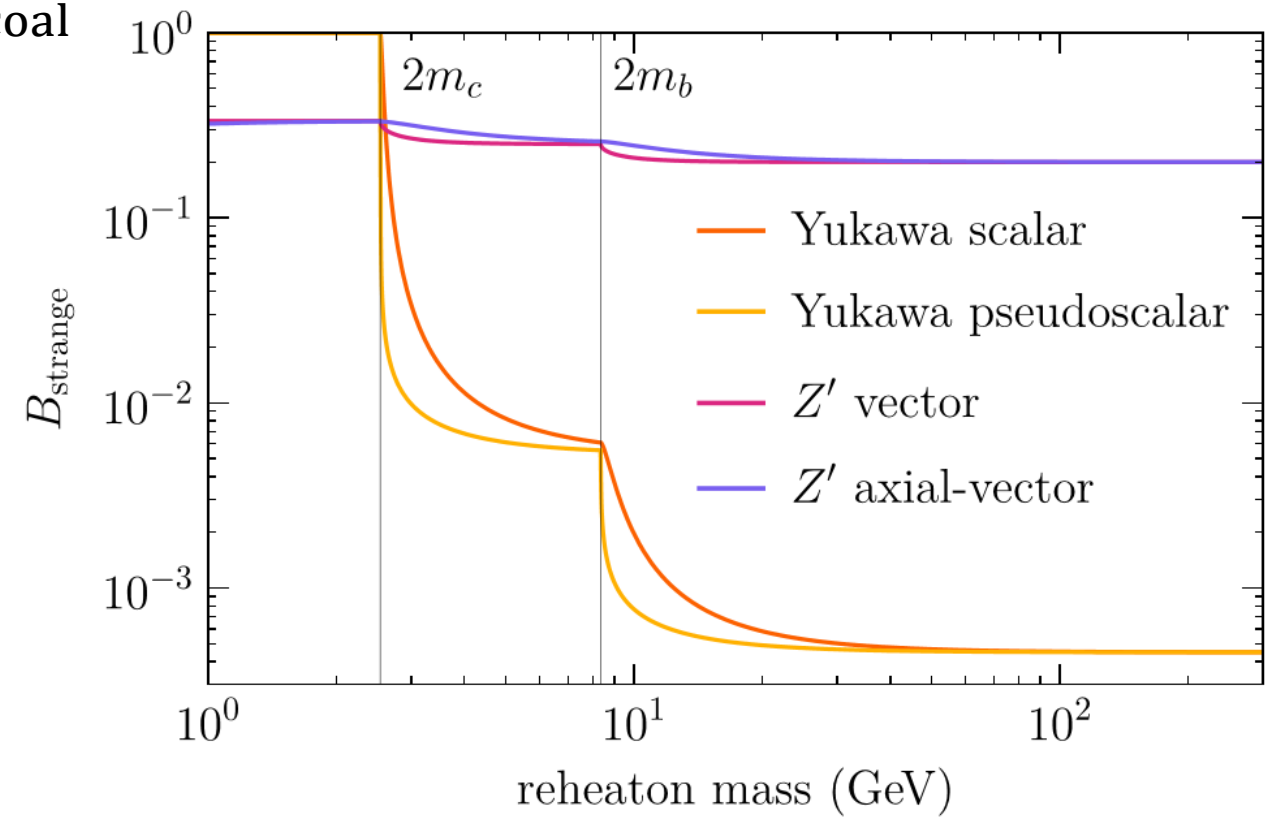
Strange branching fraction of reheaton decay



$$f_S \equiv B_{\text{strange}} \times P_{\text{coal}}$$

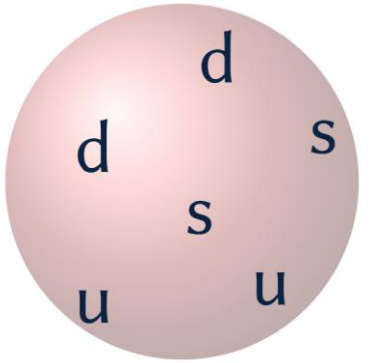
$\phi \to q\bar{q}$
$Z' \to q\bar{q}$

also
$\phi \to gg$



MM+ 2512.14838

Coalescence probability of quark matter into sexaquarks



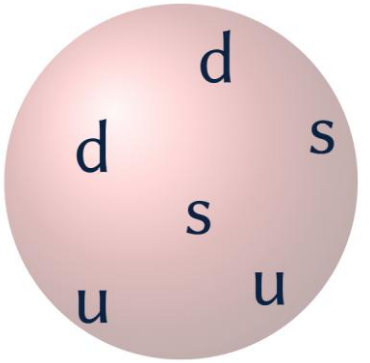
$$f_S \equiv B_{\text{strange}} \times P_{\text{coal}}$$

How do two strange baryons coalesce into a sexaquark? It depends approximately on

- quantum numbers
- strange-baryon fraction within a correlation volume
- relative momentum of the baryons
- probability of the baryons to combine rather than scatter

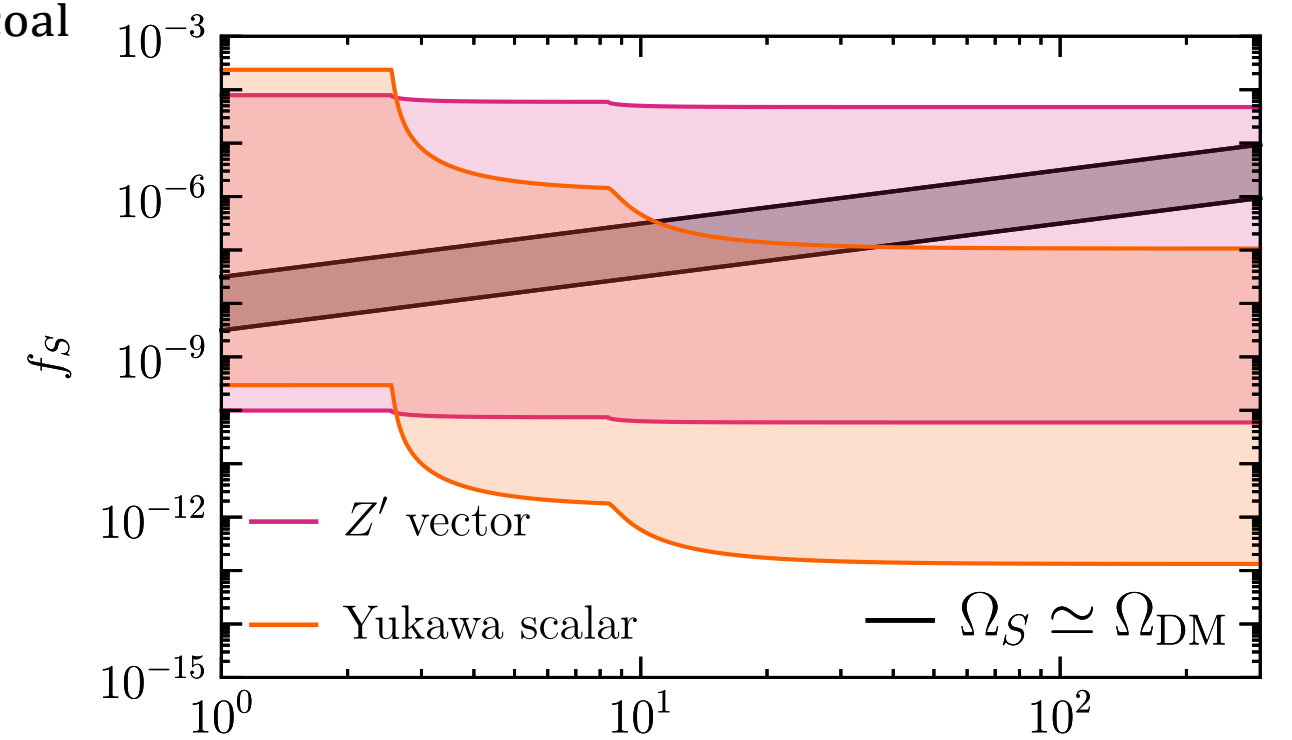
MM+ 2512.14838

Fraction of reheaton decay producing sexaquarks



$$f_S \equiv B_{\text{strange}} \times P_{\text{coal}}$$

$$\phi \to q\bar{q}$$
$$Z' \to q\bar{q}$$
$$\phi \to gg$$



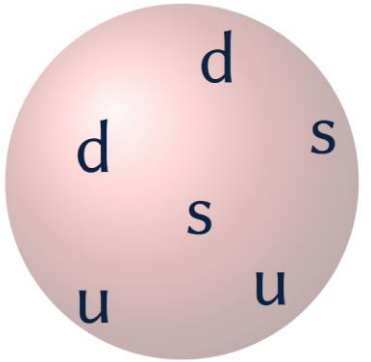
spread in T_{RH}

The factors entering P_{coal} are poorly constrained (width of coloured regions)

It is hard to get sexaquarks as more than 10^{-3} of dark matter without fine tuning reheaton interactions

MM+ 2512.14838

Constraints on reheaton decay to SM states



$f_S \equiv B_{\text{strange}} \times P_{\text{coal}}$

$\phi \to q\bar{q}$
$Z' \to q\bar{q}$
$\phi \to gg$

To decay between the QGP and BBN:

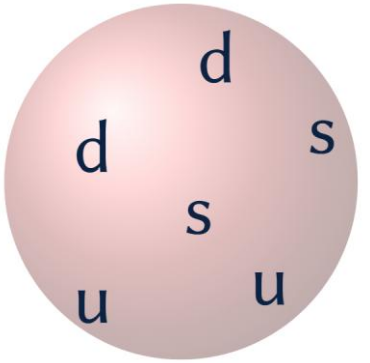
$$\tau \sim 10^{-5} - 1\ \text{s}$$

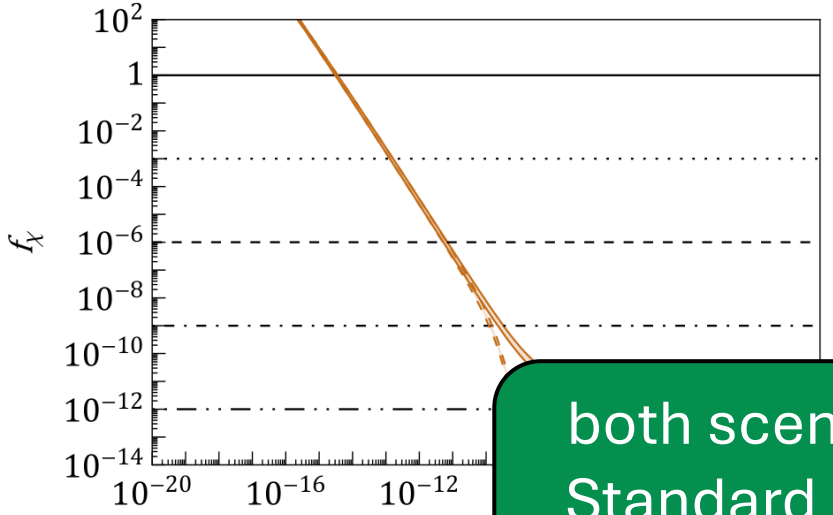
→ hard to look for in collider and long-lived particle experiments

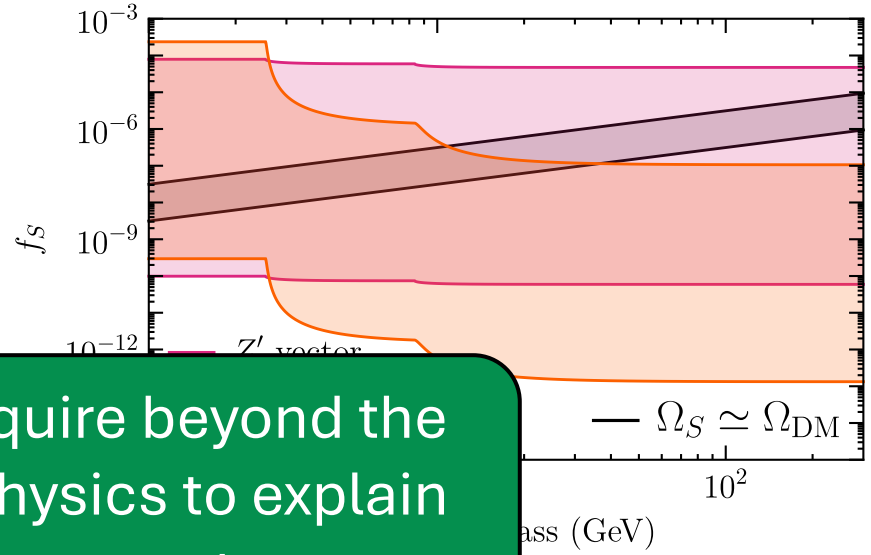
ϕ-Higgs mixing: $m_\phi \not\approx m_h$

MM+ 2512.14838

Producing sexaquarks in the early Universe







both scenarios require beyond the Standard Model physics to explain the baryon asymmetry

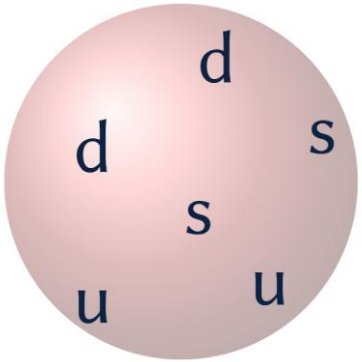
- Sexaquarks must depart from equilibrium early
- At the expense of also producing antisexaquarks
- Requires *all* cross sections to be strongly suppressed (small B's)

- need beyond the Standard Model physics to explain the existence of a reheaton
- tune the reheaton mass or introduce flavor-nonuniversal couplings to favor strange

MM+ 2403.03972

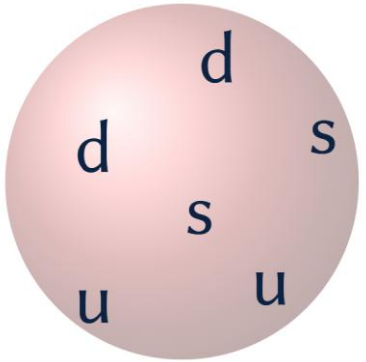
MM+ 2512.14838

Sexaquark properties

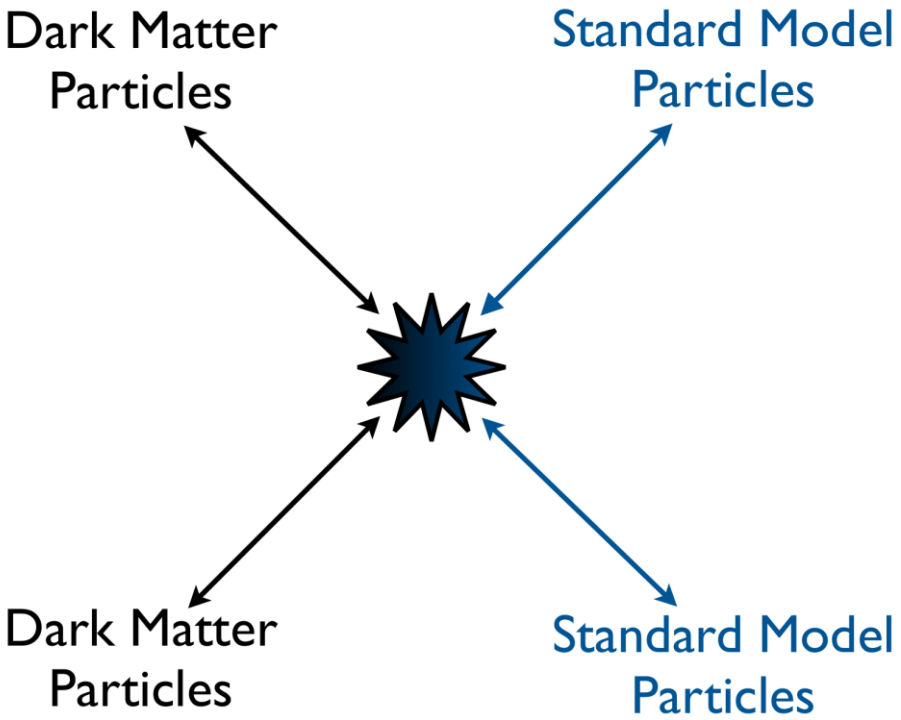


- Dark/Neutral ✓
- Cold/Non-relativistic ✓
- Stable on cosmological timescales
  - very long lifetime $\tau \gtrsim 10^9 \times \tau_{\text{universe}}$
- Can obtain the measured dark matter abundance in the Early Universe ?
- Not be already excluded ?

Dark matter detection mechanisms



$$f_\chi, f_{\bar{\chi}} \leq 10^{-3}$$



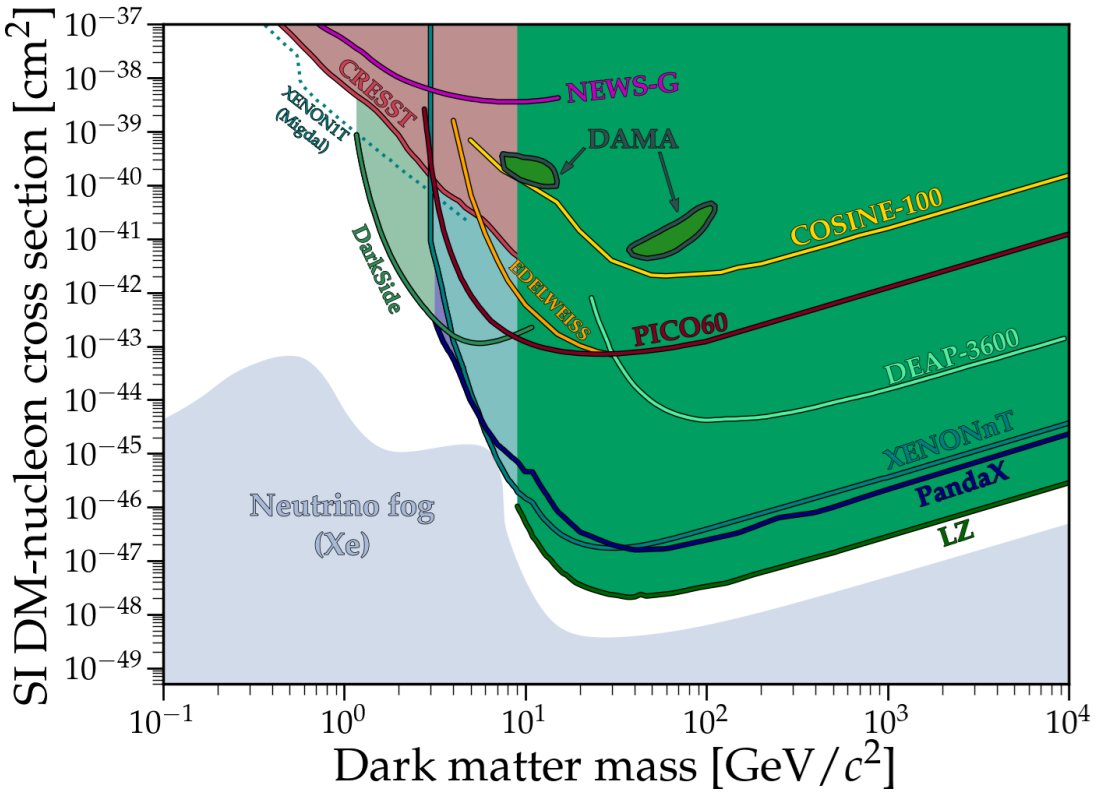
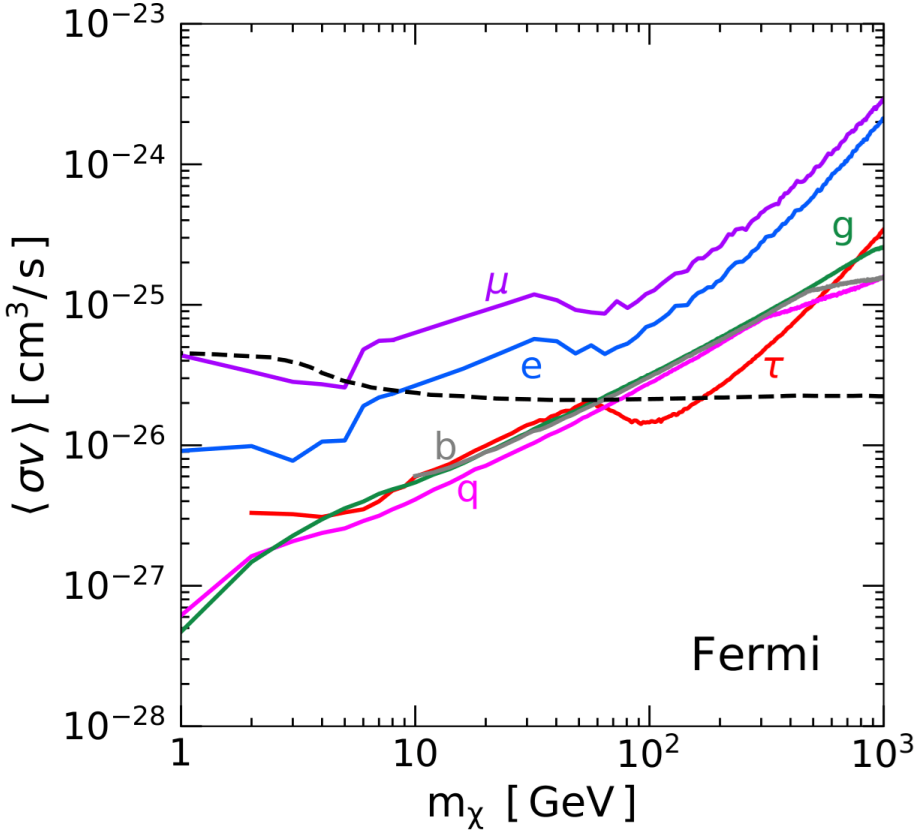


Figure from https://particleastro.brown.edu/dark-matter/

Annihilation $S\bar{S} \rightarrow$ SM (hadronic)

- The best constraints come from *Planck* (CMB energy injection) and *Fermi-LAT* (γ-rays from dwarf spheroidal galaxies)

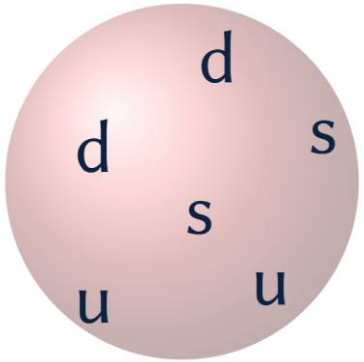


$$f_\chi f_{\bar{\chi}} \lesssim 10^{-7}$$

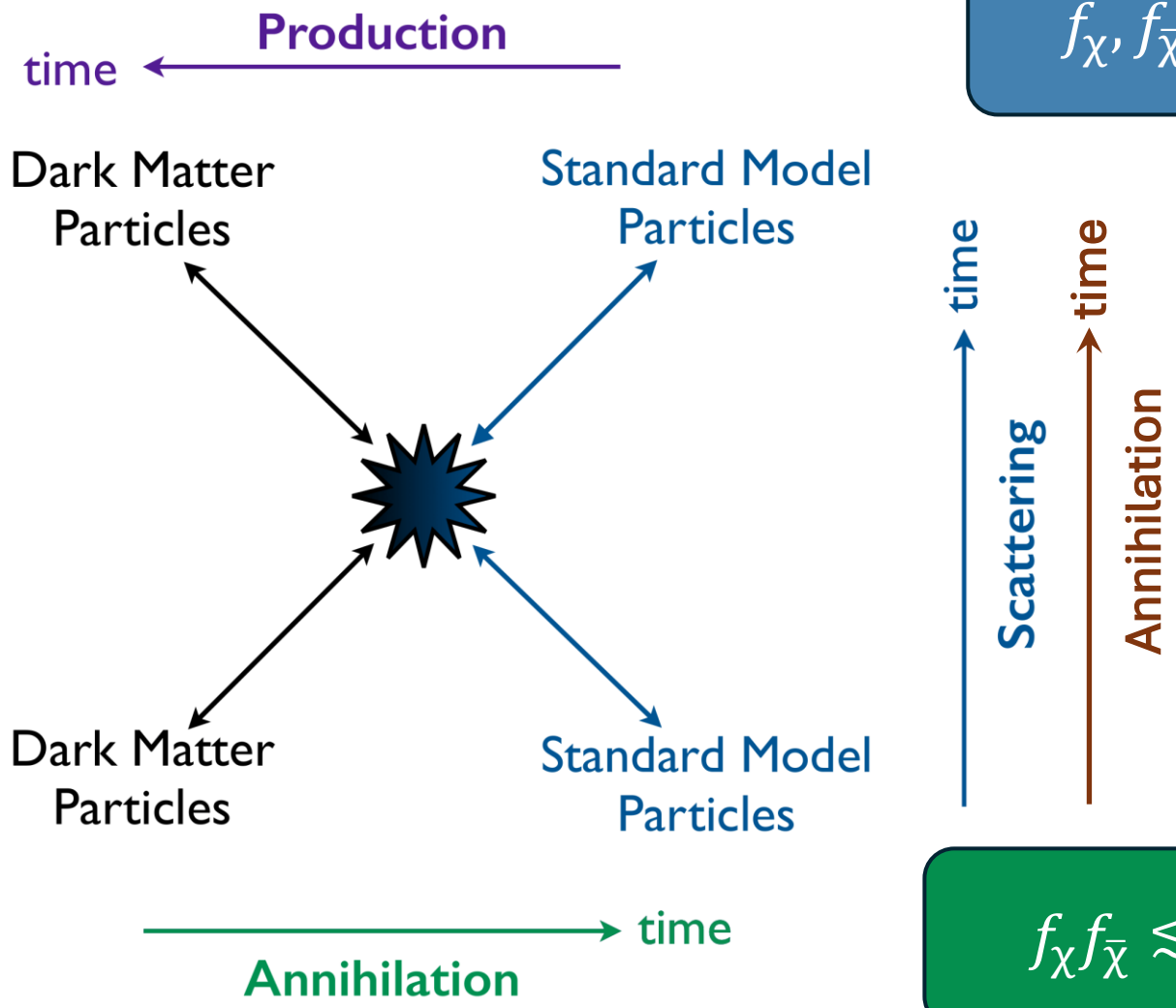
MM+ 2512.14838

Leane+ 1805.10305

Dark matter detection mechanisms



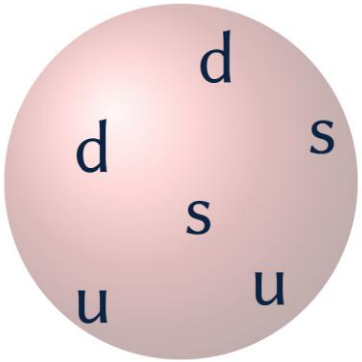
$f_\chi, f_{\bar{\chi}} \leq 10^{-3}$



$f_\chi f_{\bar{\chi}} \lesssim 10^{-7}$

Figure from https://particleastro.brown.edu/dark-matter/

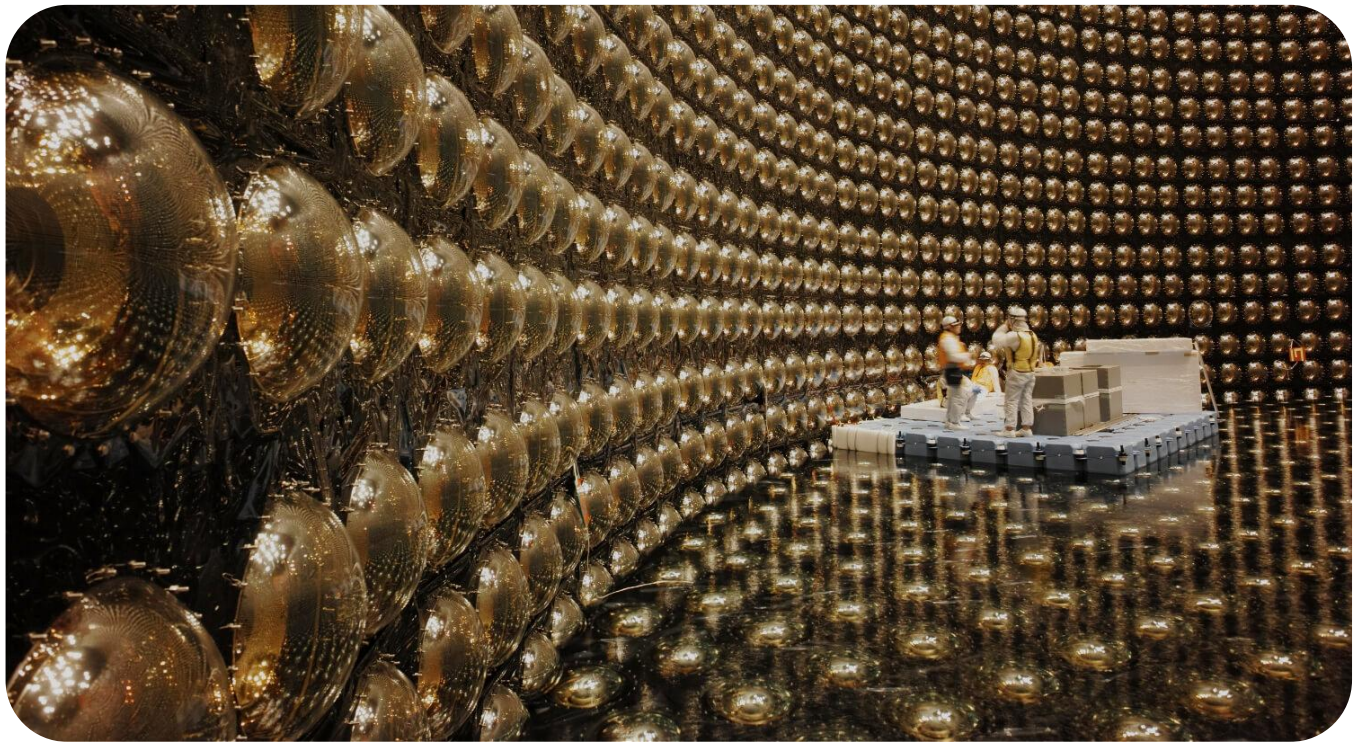
Annihilation in Super-Kamiokande



Why Super-Kamiokande?

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

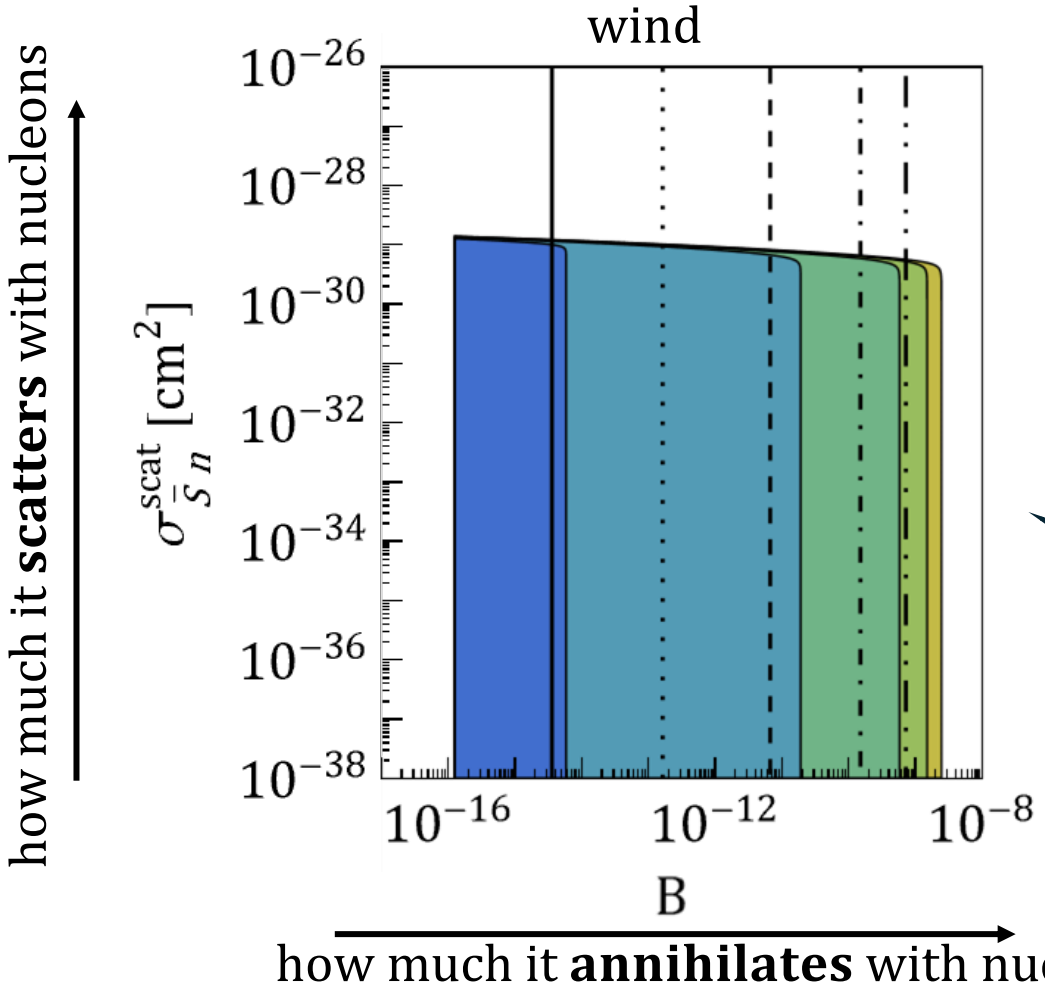
$$S\bar{b} \to b'\pi$$

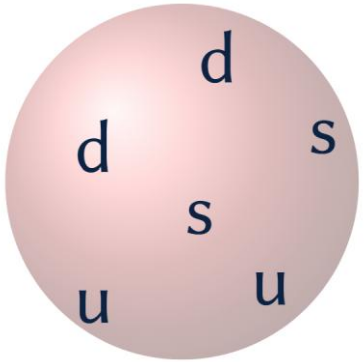


MM+ 2403.03972

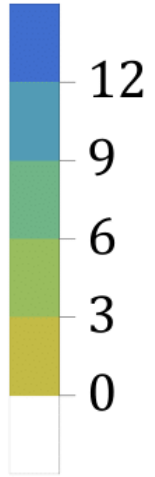
Annihilation in Super-Kamiokande

$f_{\bar{s}}$ from freeze-out





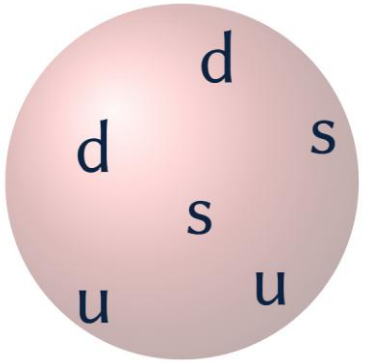
$\log_{10}(N_{n,\rm ann})$



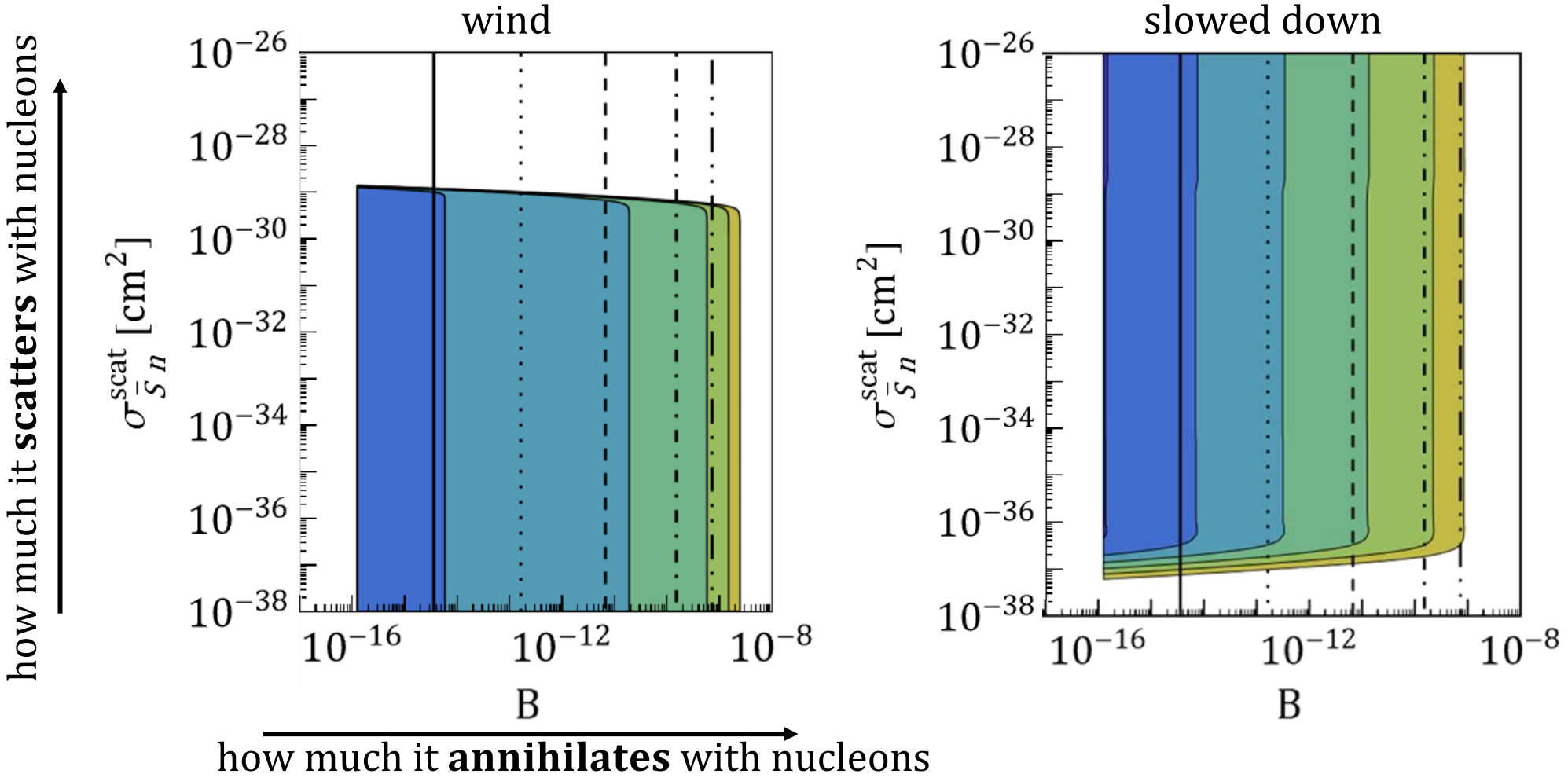
two factors of depletion: annihilates before reaching the detector, and small relic abundance

MM+ 2403.03972

Annihilation in Super-Kamiokande

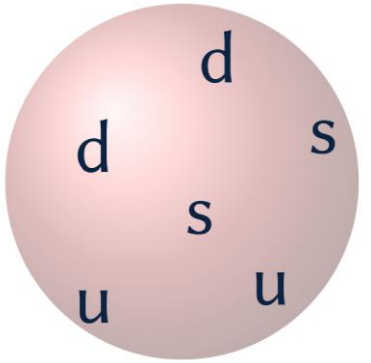


$f_{\bar{s}}$ from freeze-out

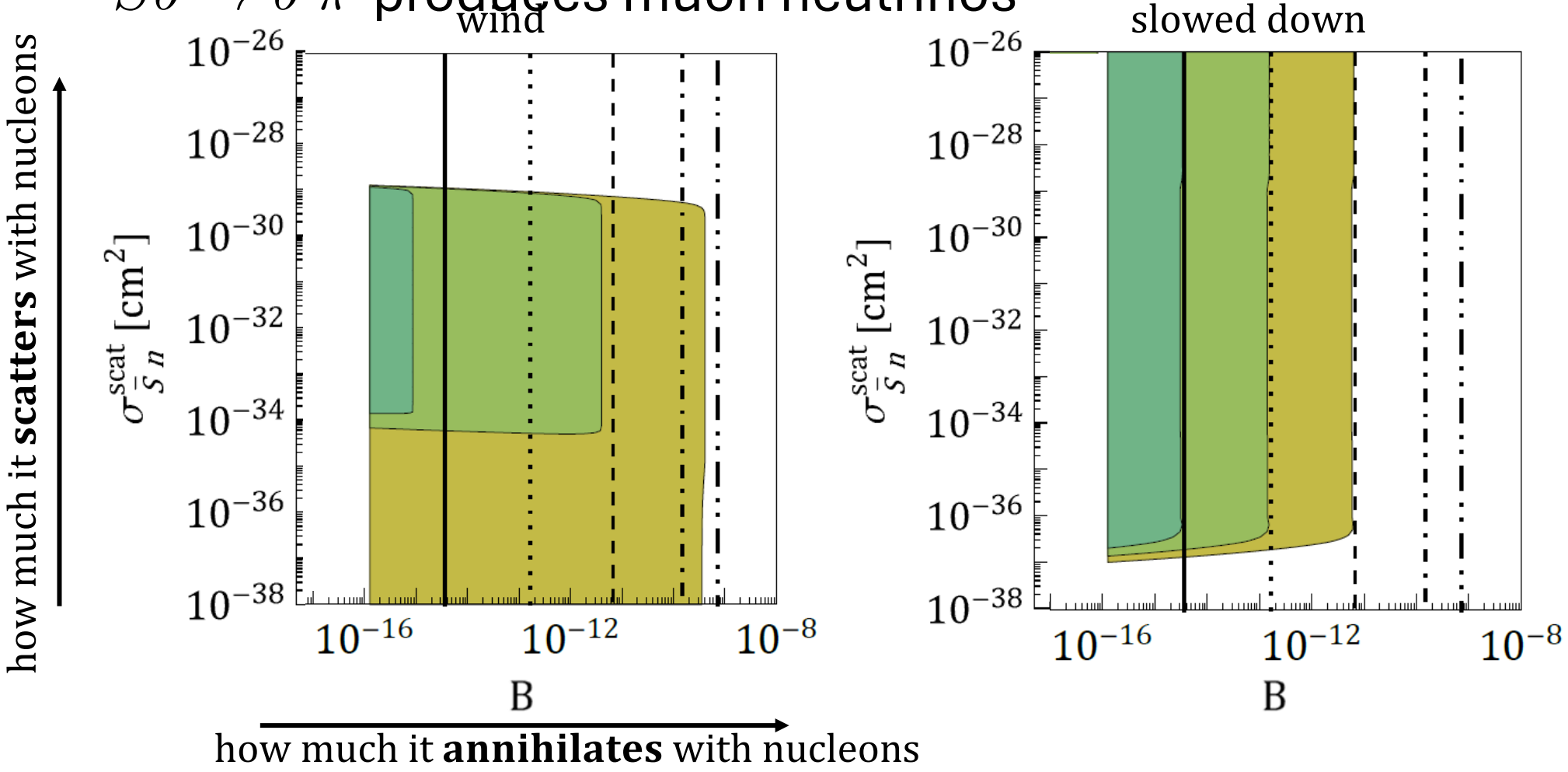


MM+ 2403.03972

Annihilation in the Earth to neutrinos

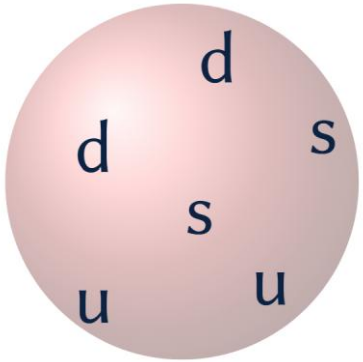


$S\bar{b} \to b'\pi$ produces muon neutrinos $f_{\bar{s}}$ from freeze-out

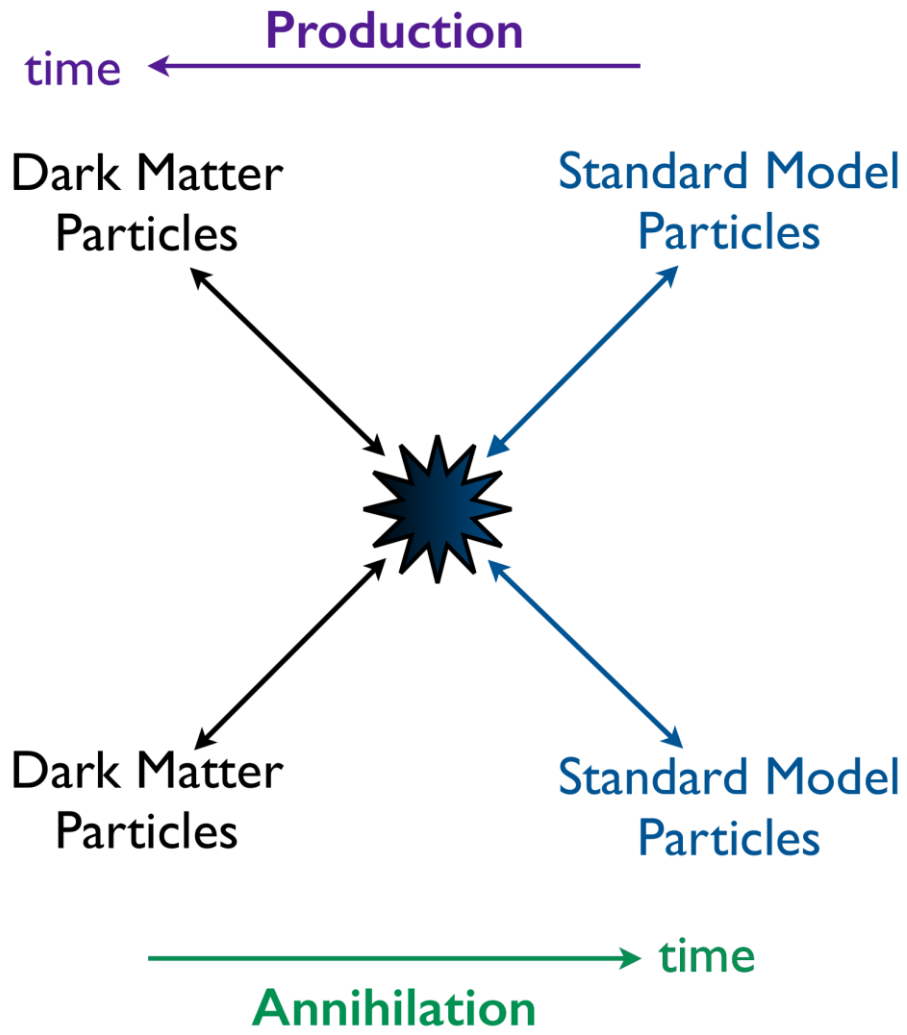


MM+ 2403.03972

Dark matter detection mechanisms



$f_\chi, f_{\bar{\chi}} \leq 10^{-3}$

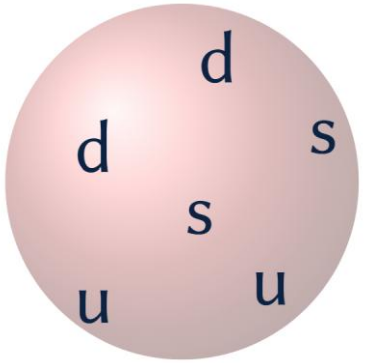


$f_{\bar{\chi}} \leq 10^{-10}$

$f_\chi f_{\bar{\chi}} \lesssim 10^{-7}$

Figure from https://particleastro.brown.edu/dark-matter/

Summary



Genesis:

- *all* freeze-out rates must be small (~15 orders of magnitude) or reheaton branching ratio large to give a non-negligible abundance (fine-tuning)

Direct detection and annihilation signatures:

- prevent the existence of a non-negligible abundance

The sexaquark is an **unlikely** candidate to make up a large fraction of dark matter

MM+ 2403.03972 & 2512.14838