Composite Dark Matter

Part	DM theory	Interest	Craziness
1	SM	!!!	???
2	SM + heavy $\mathcal{Q}$	!!	??
3	SM + heavy $\mathcal{Q}$ + new force	!	?

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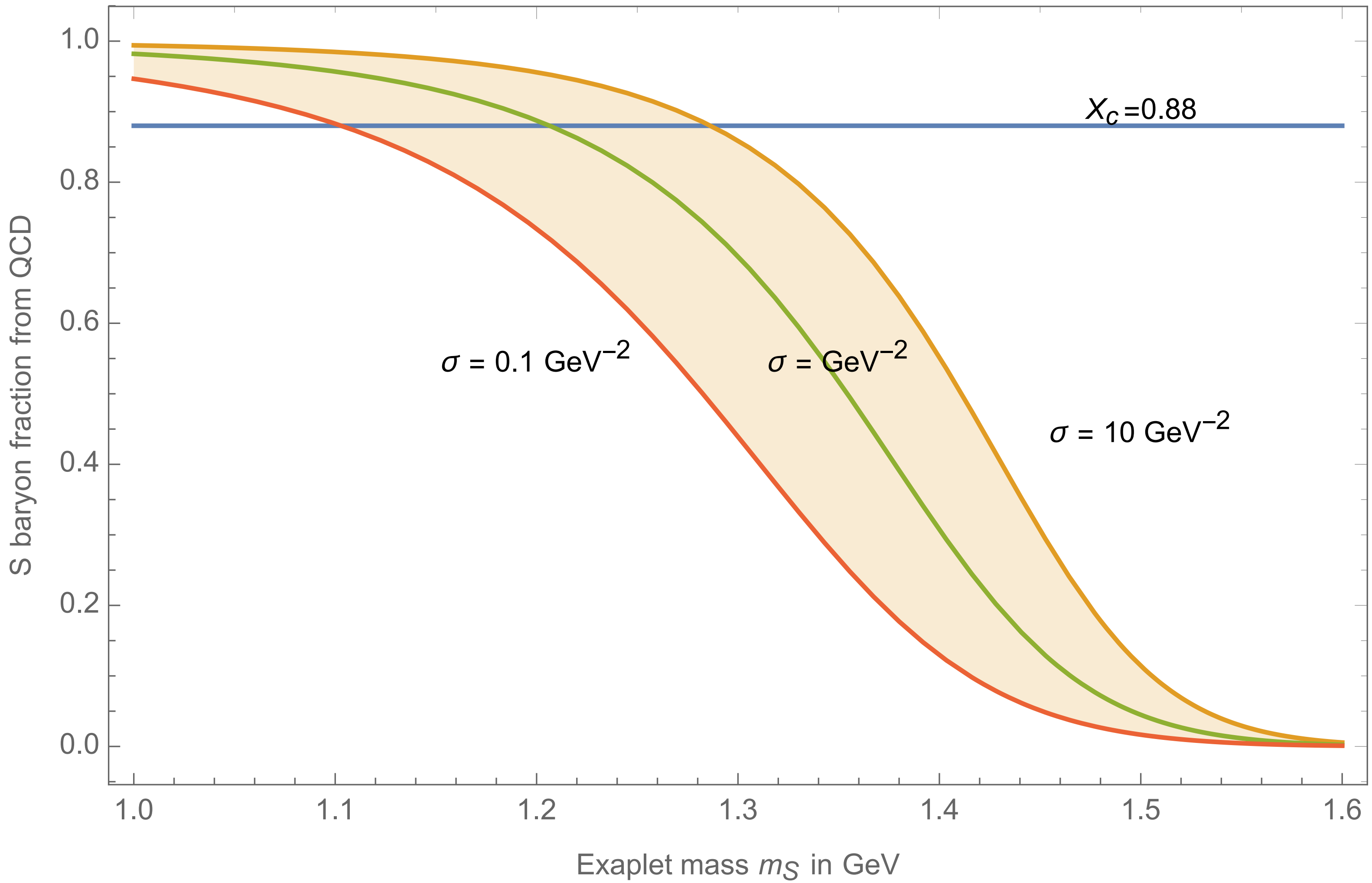
1) DM within the SM???

Jaffe: the spin 0 iso-singlet di-baryon $\mathcal{S} = uuddss$ should have a large binding.

Farrar: it could be stable DM if $E_B \gtrsim 2m_s$ such that $M_{\mathcal{S}} < 2(M_p + M_e)$.

Thermal abundance

Interactions with strange hadrons (e.g. $\Lambda\Lambda \leftrightarrow \mathcal{S}X$) keep $\mathcal{S}$ in thermal equilibrium until Λ get Boltzmann suppressed at $T \sim M_\Lambda - M_p$: $\Omega_\mathcal{S} \sim 5\Omega_b$ for $M_\mathcal{S} \approx 1.3\,\mathrm{GeV}$:

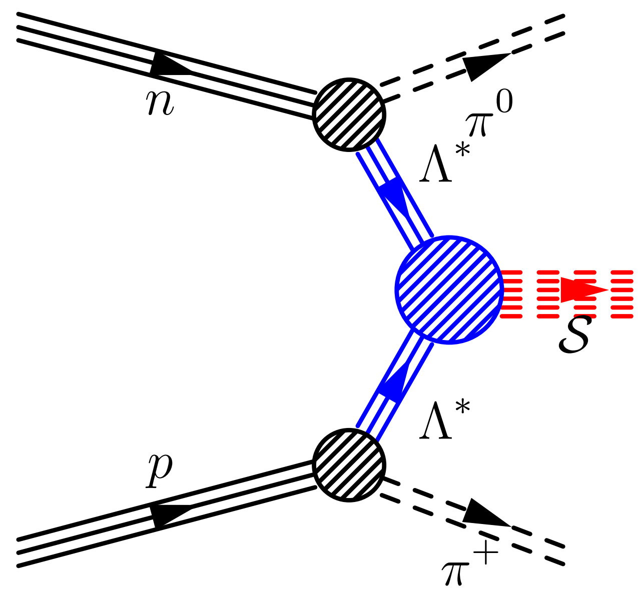


Nuclear decay

If stable, $\mathcal{S}$ makes nuclei unstable.
Excluded by SuperKamiokande

$$\tau(\mathrm{O} \to \mathcal{S}X) > 10^{26-29}\,\mathrm{yr}$$

where $X = \{\pi\pi, \pi, e, \gamma\}$. The decay dominantly proceeds trough double β production of virtual Λ^*.
Recent fits of nucleon potentials and O wave-function imply a too fast decay.



Excluded also by balloon direct detection, unless interactions reduce $\mathcal{S}$ speed.

2) Colored DM??

Uh? Everybody knows it's excluded

Theory

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\mathcal{Q}}(i\not{D} - M_{\mathcal{Q}})\mathcal{Q}.$$

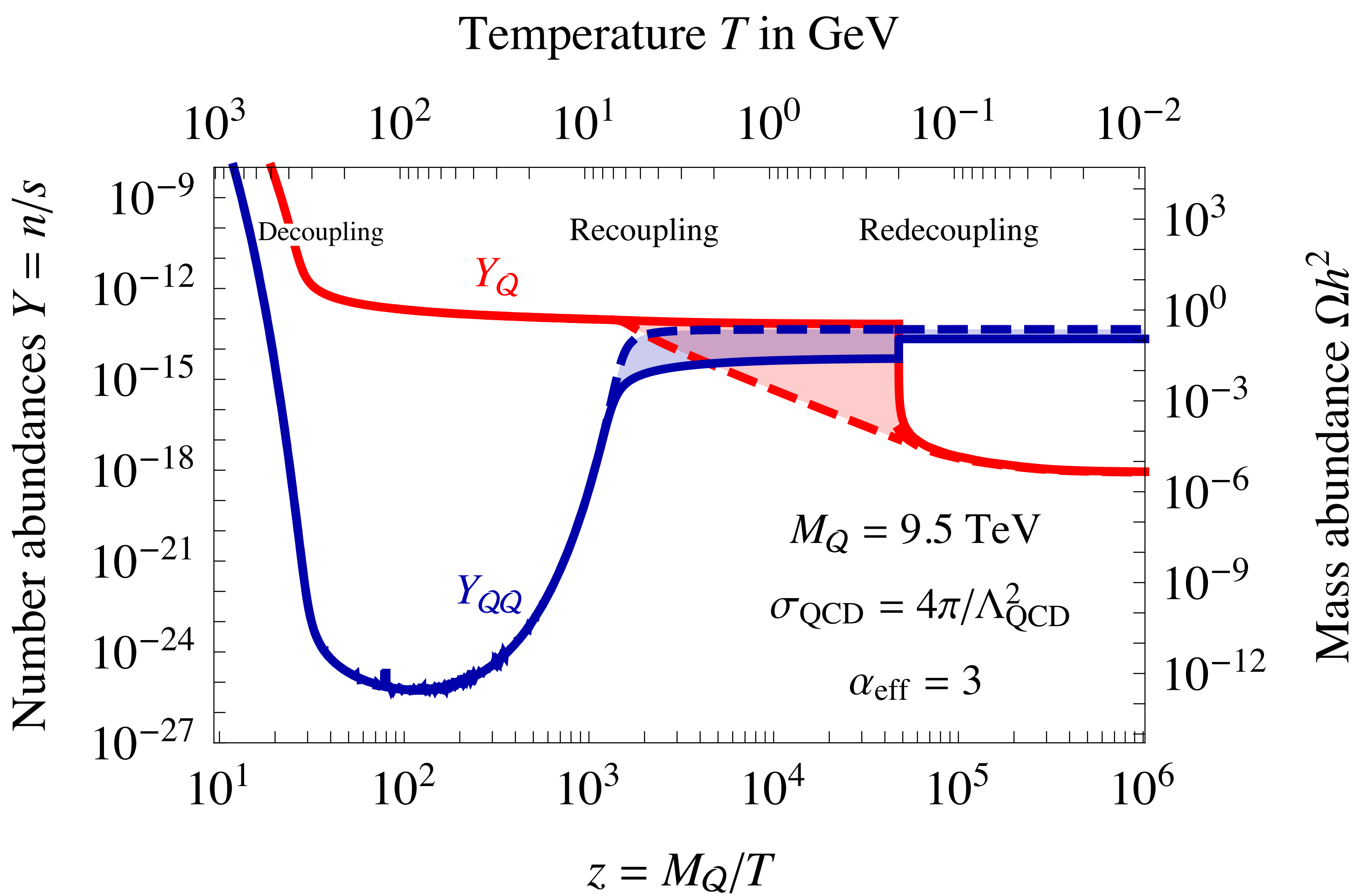
$\mathcal{Q}$ is a new colored particle. We assume a Dirac fermion octet with no weak interactions, no asymmetry. (Alternatives: a color triplet, a $(3,2)$, a scalar...). Could be a Dirac gluino; could be a fermion of natural KSVZ axion models.

$\Omega_{\mathcal{Q}} h^2 \sim 0.1\, M_{\mathcal{Q}}/7\,\text{TeV}$ before confinement. Later hadrons form:

- DM can be the $\mathcal{Q}$-onlyum hadron $\mathcal{Q}\mathcal{Q}$. It is the ground state: big binding $E_B \sim \alpha_3^2 M_{\mathcal{Q}} \sim 200\,\text{GeV}$ and small radius $a \sim 1/\alpha_3 M_{\mathcal{Q}}$, so small interactions.
- Hybrids $\mathcal{Q}g$ and/or $\mathcal{Q}q\bar{q}'$ have small $E_B \sim \Lambda_{\rm QCD}$ and large $\sigma \sim 1/\Lambda^2_{\rm QCD}$. Excluded, unless their relic abundance is small.

Hybrids have zero relic abundance, if cosmology has infinite time to thermalise. A hybrid recombines $M_{\rm Pl}/\Lambda_{\rm QCD} \sim 10^{19}$ times in a Hubble time. Hadronizing with q, g is more likely, $n_{q,g} \sim 10^{14} n_{\mathcal{Q}}$. Result: $n_{\rm hybrid} \sim 10^{-5} n_{\rm DM}$.

Cosmological evolution



1) Usual decoupling at $T \sim M_{\mathcal{Q}}/25$, Sommerfeld and bound states included.

2) Recoupling at $T \gtrsim \Lambda_{\rm QCD}$ because $\sigma_{\rm bound} \sim 1/T^2$.

3) Hadronization at $T \sim \Lambda_{\rm QCD}$ and 'fall': half $\mathcal{Q}\mathcal{Q}$, half $\mathcal{Q}\bar{\mathcal{Q}} \to gg, q\bar{q}$.

4) Redecoupling at $T \sim \Lambda_{\rm QCD}/40$ determines $\Omega_{\mathcal{Q}\mathcal{Q}} \approx \Omega_{\mathcal{Q}}/2$, $\Omega_{\rm hybrid} \sim 10^{-5}\Omega_{\mathcal{Q}\mathcal{Q}}$.

Fall cross section

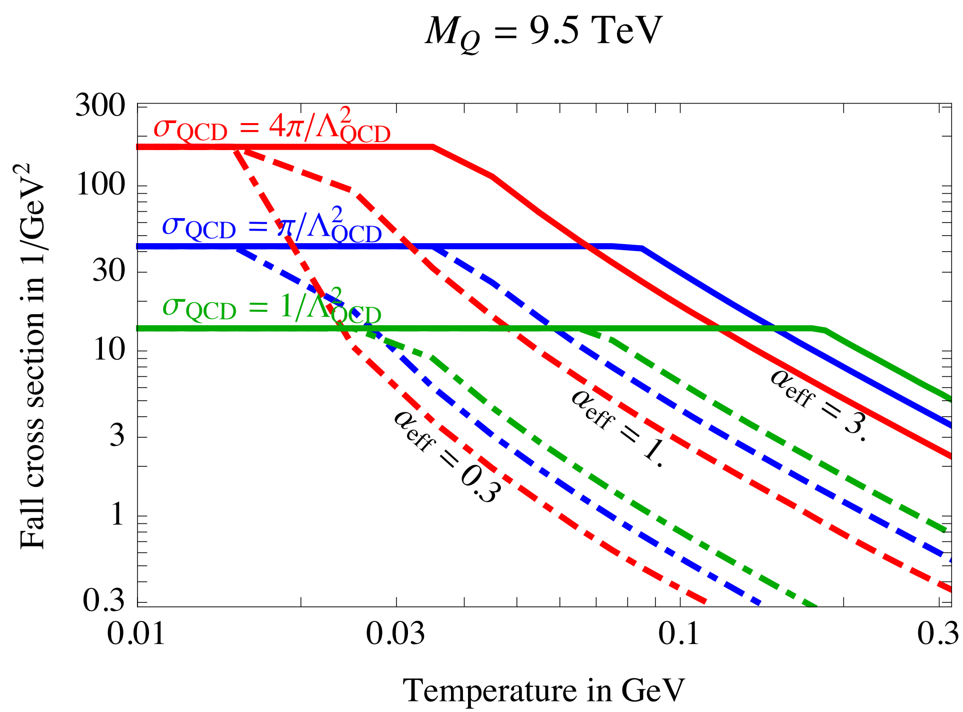
After formation, a $\mathcal{Q}\mathcal{Q}$ can break or fall to an unbreakable (deep enough) level.

$\sigma_{\rm QCD} \sim 1/\Lambda^2_{\rm QCD} \gg \sigma_{\rm pert} \sim \alpha_3^2/M_{\mathcal{Q}}^2$ because constituents have large $\ell = M_{\mathcal{Q}} v b$ where b is the classical impact parameter

$$\sigma \sim b^2 \sim \frac{\ell^2}{K M_{\mathcal{Q}}}.$$

$\mathcal{Q}\mathcal{Q}$ becomes unbreakable when it radiates $\Delta E \gtrsim T$ before the next collision after

$$\Delta t \sim \frac{1}{n_\pi v_\pi \sigma_{\rm QCD}} \sim \left\{ \begin{array}{ll} \Lambda^2_{\rm QCD}/T^3 & T > M_\pi \\ e^{M_\pi/T}/\Lambda_{\rm QCD} & T < M_\pi \end{array} \right.$$

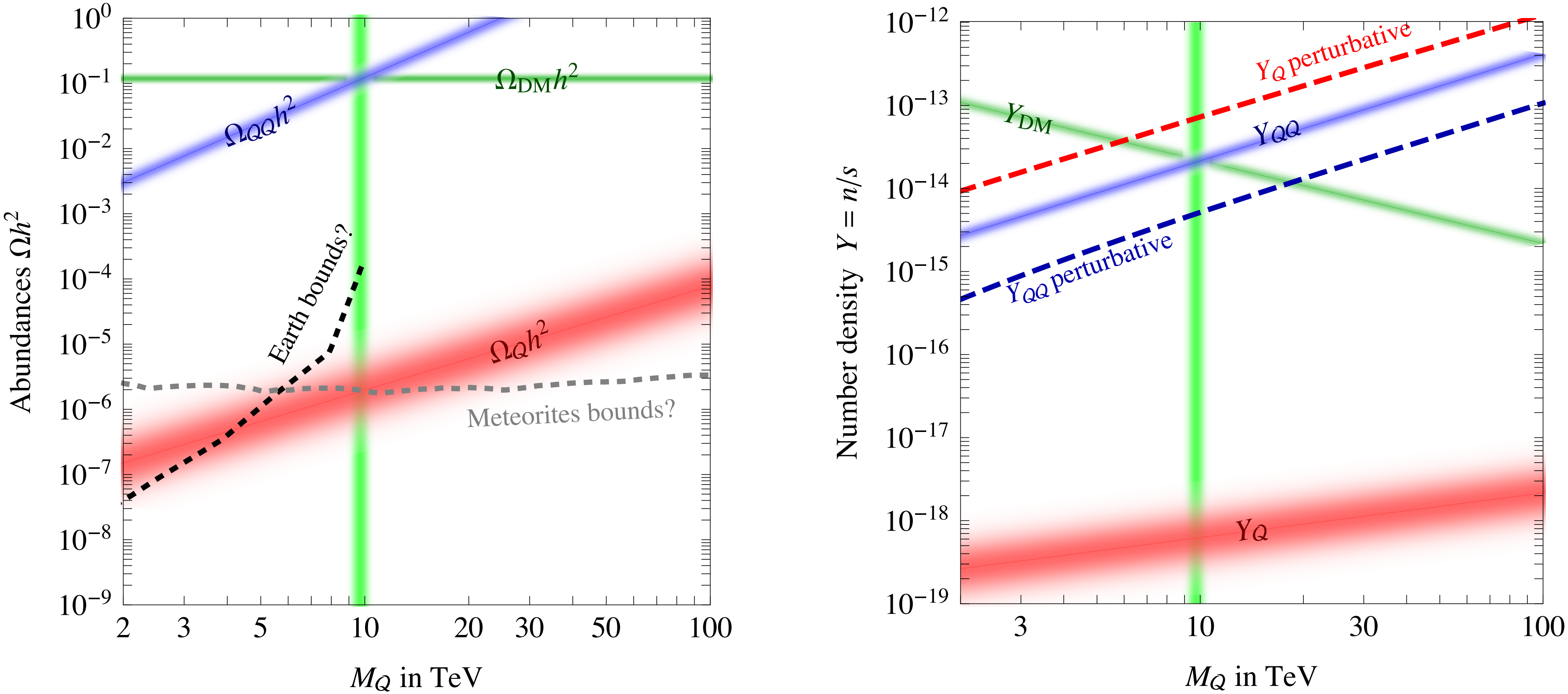


The radiated energy is classical for $n, \ell \gg 1$ and minimal for circular orbits:

$$\frac{\Delta E}{\Delta t} = \langle W_{\rm Larmor} \rangle \simeq \underbrace{\frac{2\alpha^7 \mu^2}{3n^8}}_{\text{circular}} \times \underbrace{\frac{3-(\ell/n)^2}{2(\ell/n)^5}}_{\text{elliptic enhancement}} \qquad \text{for abelian hydrogen.}$$

Non perturbative α_3: could emit $100g$ with $E \sim$ GeV in one shot.

Relic abundances



Direct detection of DM

Interaction $\mathcal{Q}\mathcal{Q}$/gluon analogous to Rayleigh interaction hydrogen/light:

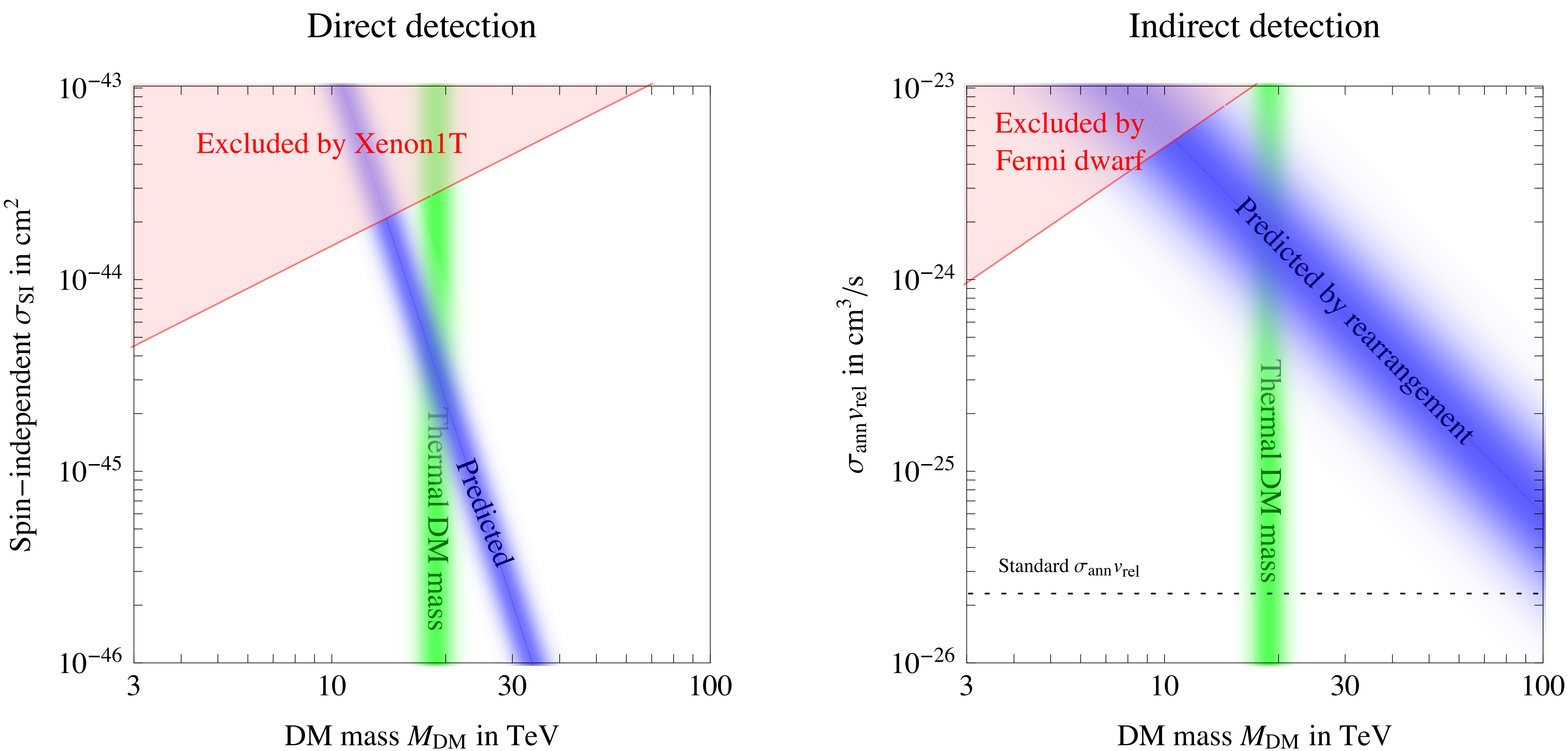
$$\mathscr{L}_{\rm eff} = c_E M_{\rm DM} \bar{B} B \vec{E}^{a2}.$$

Polarizability coefficient estimated as $c_E \sim 4\pi a^3$ in terms of the Bohr-like radius $a = 2/(3\alpha_3 M_{\mathcal{Q}})$. Actual computation gives a bit smaller

$$c_E = \pi\alpha_3 \langle B|\vec{r}\frac{1}{H_8 - E_{10}}\vec{r}|B\rangle = (0.36_{\rm bound} + 1.17_{\rm free})\pi a^3$$

so that the spin-independent cross section is below bounds

$$\sigma_{\rm SI} \approx 2.3\ 10^{-45}\,{\rm cm}^2 \times \left(\frac{20\,{\rm TeV}}{M_{\rm DM}}\right)^6 \left(\frac{0.1}{\alpha_3}\right)^8 \left(\frac{c_E}{1.5\pi a^3}\right)^2.$$

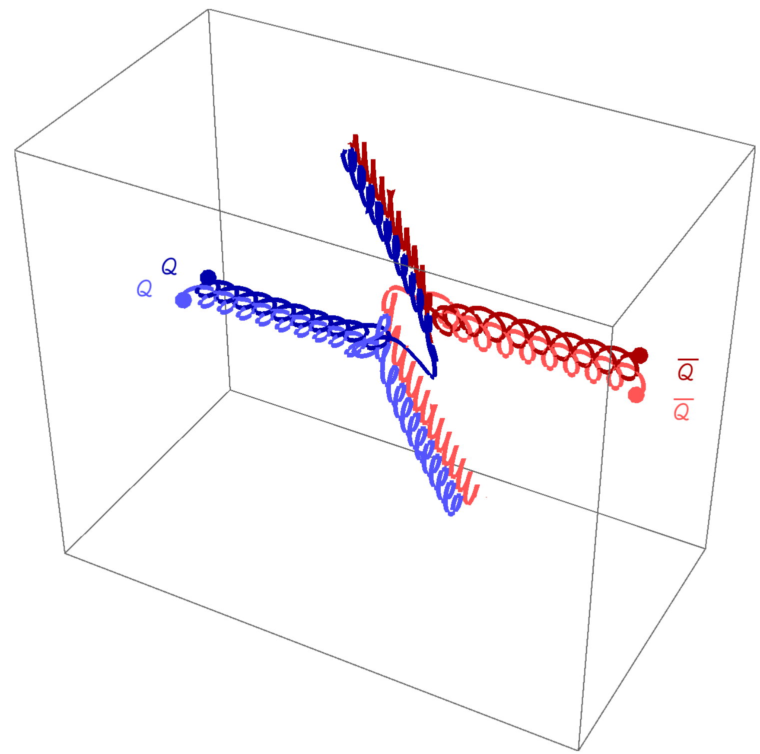

Direct detection
Excluded by Xenon1T
Predicted
Thermal DM mass
Spin−independent $\sigma_{\rm SI}$ in cm^2
10^{-43}
10^{-44}
10^{-45}
10^{-46}
3
10
30
100
DM mass $M_{\rm DM}$ in TeV
Indirect detection
Excluded by
Fermi dwarf
Predicted by rearrangement
Thermal DM mass
Standard $\sigma_{\rm ann} v_{\rm rel}$
$\sigma_{\rm ann} v_{\rm rel}$ in cm^3/s
10^{-23}
10^{-24}
10^{-25}
10^{-26}
3
10
30
100
DM mass $M_{\rm DM}$ in TeV

Indirect detection of DM

Analogous to hydrogen: $\sigma(H\bar{H}) \gg \alpha^2/m_e^2$ has atomic size, because enhanced and dominated by recombination $(ep)+(\bar{e}\bar{p}) \to (e\bar{e})+(p\bar{p}) \to \cdots$. DM annihilation dominated by

$$(\mathcal{Q}\mathcal{Q}) + (\bar{\mathcal{Q}}\bar{\mathcal{Q}}) \to (\mathcal{Q}\bar{\mathcal{Q}}) + (\mathcal{Q}\bar{\mathcal{Q}}).$$

Classical result: $\sigma_{\rm ann} \sim \pi a^2$, enhanced by dipole Sommerfeld. Quantum estimate



$$\sigma_{\rm ann} v_{\rm rel} \sim \frac{\pi a^2 v_{\rm rel}/2}{\sqrt{E_{\rm kin}/E_B}} = \frac{\sqrt{2}\pi}{3M_{\mathcal{Q}}^2\alpha_3} = 1.5\ 10^{-24}\frac{\rm cm^3}{\rm sec} \times \left(\frac{20\ \rm TeV}{M_{\rm DM}}\right)^2 \left(\frac{0.1}{\alpha_3}\right).$$

Collider detection of $\mathcal{Q}$

QCD pair production, $pp \to \mathcal{Q}\bar{\mathcal{Q}}$, two stable hadron tracks, possibly charged.

LHC: $M_{\mathcal{Q}} > 2\,\text{TeV}$. pp collider at $\sqrt{s} \gtrsim 65\,\text{TeV}$ needed to discover $M_{\mathcal{Q}} \sim 9.5\,\text{TeV}$.

Low σ at a muon collider.

Hybrids $\mathcal{Q}g$, $\mathcal{Q}q\bar{q}'$

Strongly Interacting Massive Particles with big $\sigma \sim \sigma_{\rm QCD}$ don't reach underground detectors. Excluded by balloons and over-heating if $\Omega_{\rm SIMP} = \Omega_{\rm DM}$.

$\Omega_{\rm SIMP} \sim 10^{-5}\Omega_{\rm DM}$ **is allowed**

SIMP searches in nuclei: best bounds:

$$\frac{N_{\rm SIMP}}{N_n} < \begin{cases} 3\ 10^{-14} & \text{Oxygen in Earth} \\ 10^{-16} & \text{Enriched C in Earth} \\ 10^{-12} & \text{Iron in Earth} \\ 4\ 10^{-14} & \text{Meteorites} \end{cases} \qquad \text{for } M_{\rm SIMP} \sim 10\,\text{TeV}$$

The predicted **primordial** cosmological average is $N_{\rm SIMP}/N_n \sim 5\ 10^{-9}$.
Difficult to predict abundance in Earth nuclei. Rough result:

Our SIMPs allowed if don't bind to nuclei, borderline otherwise

$\mathcal{Q}g$ presumably lighter than $\mathcal{Q}q\bar{q}'$, that thereby decay. Similarly for $\mathcal{Q}\mathcal{Q}g$, $\mathcal{Q}qq$.
$\mathcal{Q}g$ is iso-spin singlet: π^a cannot mediate long-range nuclear forces.
Heavier mesons mediate short-range forces, not computable from 1st principles.
If attractive $\mathcal{Q}g$ can bind to big nuclei, $A \gg 1$. If repulsive $\mathcal{Q}g$ remains free.

In any case, **SIMPs sank in the primordial (fluid) Earth and stars**.

Secondary hybrids

SIMPs that hit the **Earth** get captured and thermalise in the upper atmosphere.

Accumulated mass $= M = \rho_{\rm SIMP} v_{\rm rel} \pi R_E^2 \Delta t \sim 25\,{\rm Mton} \sim 10^4 \times$ (fossile energy).

Average density $= \left\langle \frac{N_{\rm SIMP}}{N_n} \right\rangle_{\rm Earth} = \frac{M}{M_{\mathcal{Q}}} \frac{m_N}{M_{\rm Earth}} \approx 4\ 10^{-19}$, where are SIMPs now?

- If SIMPs do not bind to nuclei:
  SIMPs sink with $v_{\rm thermal} \approx 40\,{\rm m/s}$, $v_{\rm drift} \approx 0.2\,{\rm km/yr}$ and $\delta h \sim 25\,{\rm m}$.
  Density in the crust: $N_{\rm SIMP}/N_n \sim 10^{-23}$. Rutherford back-scattering?
- If SIMPs bind to nuclei:
  BBN could make hybrid He; collisions in the Earth atmosphere could make hybrid N, O, He kept in the crust kept by electromagnetic binding.

Meteorites are byproducts of stellar explosions: do not contain primordial SIMPs; accumulate secondary SIMPs only if captured by nuclei

$$\left.\frac{N_{\rm SIMP}}{N_n}\right|_{\rm meteorite} = \frac{\rho_{\rm SIMP}}{M_{\mathcal{Q}}} \sigma_{\rm capture} v_{\rm rel} \Delta t \approx 7\ 10^{-15} \frac{\sigma_{\rm capture}}{0.01/\Lambda_{\rm QCD}^2}.$$

3) DM composite under a new force

Theory

Vector-like 'dark quarks' $\mathcal{Q}$ in the fundamental of 'dark color'

$$G_{\rm DC} = {\rm SU}(N_{\rm DC}) \text{ or } {\rm SO}(N_{\rm DC}), \qquad \mathcal{Q} \equiv (N_{\rm DC}, R_{\rm SM}) \oplus (\bar{N}_{\rm DC}, \overline{R}_{\rm SM})$$

possibly with Yukawas:

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{\mathcal{G}^{A2}_{\mu\nu}}{4g^2_{\rm DC}} + \frac{\theta_{\rm DC}}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^A_{\mu\nu} + \bar{\mathcal{Q}}_i(i\not{D} - m_{\mathcal{Q}_i})\mathcal{Q}_i + (y_{ij}H\mathcal{Q}_i\mathcal{Q}_j + \tilde{y}_{ij}H^*\mathcal{Q}_i\mathcal{Q}_j + \text{h.c.})$$

Main possibilities

Higgs H: fundamental or ~~composite~~?

Dark constituents $\mathcal{Q}$: fermions or ~~scalars~~? Real or complex?

Heavier or lighter than the confinement scale $\Lambda_{\rm DC}$? Massless?

DM as dark baryon or dark pion?

Cosmological abundance: thermal or ~~dark baryon asymmetry~~?

DM stability from accidental symmetries

1. **Dark-color number** implies the stability of the lightest **dark baryon** $\mathcal{B}$. Dimension-6 operators give slow enough $\tau_{\rm DM} \sim \Lambda^4/M_{\rm DM}^5$: golden class.

$$M_{\rm DM\mathcal{B}} \sim \left\{ \begin{array}{ll} 100\,\text{TeV} & \text{if DM is a thermal relic,} \\ 5\,\text{GeV}, 3\,\text{TeV} & \text{if DM has a dark asymmetry.} \end{array} \right.$$

2. **Species Number**: if no allowed Yukawas, **dark-pions** π made of different species $\bar{\mathcal{Q}}_i \mathcal{Q}_j$ are stable. Silver class: broken by dim-4,5. EW annihilations:

$$M_{\rm DM\pi} \sim (1\text{–}3)\ \text{TeV like in Minimal Dark Matter.}$$

3. G**-parity**: the $\mathscr{L}$ of real SU(2) rep.s (e.g. 3_0) is symmetric under $\mathcal{Q} \stackrel{G}{\to} \exp(i\pi T^2)\mathcal{Q}^c$. A DC$\pi$ in the 3_0 can have vanishing anomaly under SU(2)$_L$.

4. More: $m_{\mathcal{Q}} \sim \Lambda_{\rm DC}$ can lead to extra stable states. E.g. in QCD $\Lambda = uds$ does not decay into KN.

Bonus: why DM is neutral under γ, g and Z? If many bound states are present, the less charged state tends to be the lightest. And DM mass scale natural.

Assumptions

- $\beta_{\text{DC}} < 0$ confines. No sub-Planckian Landau poles for g_Y, g_2, g_3.
- Dark quarks in $\text{SU}(5)_{\text{GUT}}$ fragments:

SU(5)	$\text{SU}(3)_c$	$\text{SU}(2)_L$	$\text{U}(1)_Y$	charge	name
1	1	1	0	0	N
$\bar{5}$	$\bar{3}$	1	$1/3$	$1/3$	D
	1	2	$-1/2$	$0, -1$	L
10	$\bar{3}$	1	$-2/3$	$-2/3$	U
	1	1	1	1	E
	3	2	$1/6$	$2/3, -1/3$	Q
24	1	3	0	$-1, 0, 1$	V
	8	1	0	0	G
	$\bar{3}$	2	$5/6$	$4/3, 1/3$	X

SU(N_{DC}) and $m_{\mathcal{Q}} \ll \Lambda_{\text{DC}}$

Dynamics: the condensate $\langle \bar{\mathcal{Q}}\mathcal{Q} \rangle$ breaks the flavour symmetry

$$\text{SU}(N_{\text{DF}})_L \otimes \text{SU}(N_{\text{DF}})_R \to \text{SU}(N_{\text{DF}}).$$

So DCπ are $\bar{\mathcal{Q}}\mathcal{Q}$. Dark-baryons are dark-color anti-symmetric, the lighter ones have $\ell = 0$, so must be symmetric under spin $\otimes$ flavor:

$$\text{lighter DC}\mathcal{B} = \begin{cases} \ydiagram{2,1} \\ \ydiagram{2,2} \\ \ydiagram{3,2} \end{cases} \qquad \text{heavier DC}\mathcal{B} = \begin{cases} \ydiagram{3} & \text{for } N_{\text{DC}} = 3 \\ \ydiagram{3,1} \oplus \ydiagram{4} & \text{for } N_{\text{DC}} = 4 \\ \ydiagram{4,1} \oplus \ydiagram{5} & \text{for } N_{\text{DC}} = 5 \end{cases}$$

SU($N_{\rm DC}$) and $m_Q \ll \Lambda_{\rm DC}$: golden models

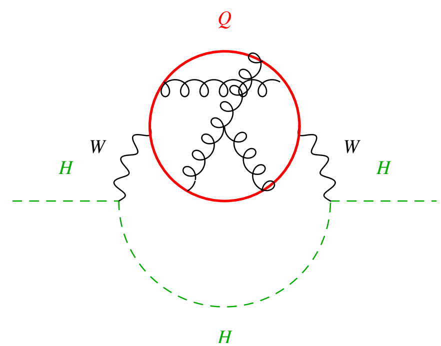
SU($N_{\rm DC}$) dark-color. Dark-quarks	Yukawa couplings	Allowed $N_{\rm DC}$	Dark-pions	Dark-baryons	under
$N_{\rm DF}=3$			8	$8, \bar{6}, \ldots$ for $N_{\rm DC}=3,4,\ldots$	SU(3)$_{\rm DF}$
$\mathcal{Q}=V$	0	3	3	$VVV=3$	SU(2)$_L$
$\mathcal{Q}=N\oplus L$	1	3, .., 14	unstable	$N^{N*}=1$	SU(2)$_L$
$N_{\rm DF}=4$			15	$\overline{20}, 20', \ldots$	SU(4)$_{\rm DF}$
$\mathcal{Q}=V\oplus N$	0	3	3×3	$VVV, VNN=3,\ VVN=1$	SU(2)$_L$
$\mathcal{Q}=N\oplus L\oplus \tilde{E}$	2	3, 4, 5	unstable	$N^{N*}=1$	SU(2)$_L$
$N_{\rm DF}=5$			24	$\overline{40}, \overline{50}$	SU(5)$_{\rm DF}$
$\mathcal{Q}=V\oplus L$	1	3	unstable	$VVV=3$	SU(2)$_L$
$\mathcal{Q}=N\oplus L\oplus \tilde{L}$	2	3	unstable	$NL\tilde{L}=1$	SU(2)$_L$
$=$	2	4	unstable	$NNL\tilde{L}, L\tilde{L}L\tilde{L}=1$	SU(2)$_L$
$N_{\rm DF}=6$			35	$70, \overline{105'}$	SU(6)$_{\rm DF}$
$\mathcal{Q}=V\oplus L\oplus N$	2	3	unstable	$VVV, VNN=3, VVN=1$	SU(2)$_L$
$\mathcal{Q}=V\oplus L\oplus \tilde{E}$	2	3	unstable	$VVV=3$	SU(2)$_L$
$\mathcal{Q}=N\oplus L\oplus \tilde{L}\oplus \tilde{E}$	3	3	unstable	$NL\tilde{L}, \tilde{L}\tilde{L}\tilde{E}=1$	SU(2)$_L$
$=$	3	4	unstable	$NNL\tilde{L}, L\tilde{L}L\tilde{L}, N\tilde{E}\tilde{L}\tilde{L}=1$	SU(2)$_L$
$N_{\rm DF}=7$			48	112	SU(7)$_{\rm DF}$
$\mathcal{Q}=L\oplus \tilde{L}\oplus E\oplus \tilde{E}\oplus N$	4	3	unstable	$LLE, \tilde{L}\tilde{L}\tilde{E}, L\tilde{L}N, E\tilde{E}N=1$	SU(2)$_L$
$\mathcal{Q}=N\oplus L\oplus \tilde{E}\oplus V$	3	3	unstable	$VVV, VNN=3,\ VVN=1$	SU(2)$_L$
$N_{\rm DF}=9$			80	240	SU(9)$_{\rm DF}$
$\mathcal{Q}=Q\oplus \tilde{D}$	1	3	unstable	$QQ\tilde{D}=1$	SU(2)$_L$

Notation: $R \equiv (R, N_{\rm DC}) \oplus (\bar{R}, \bar{N}_{\rm DC})$ $\qquad \tilde{R} \equiv (\bar{R}, N_{\rm DC}) \oplus (R, \bar{N}_{\rm DC})$

Simplest model: massless dark quark

$G_{\rm SM} \otimes {\rm SU}(N_{\rm DC})$ with one extra fermion $\mathcal{Q} = V = (0_Y, 3_L, 1_c, N_{\rm DC} \oplus \bar{N}_{\rm DC})$.

Select a sample point in parameter space: no masses, $m_h = m_{\mathcal{Q}} = 0$ (motivation not discussed here). As many parameters as in the SM: all new physics is univocally predicted. Dark-color strong at $\Lambda_{\rm DC}$ induces the weak scale

$m_h^2 =$ 

$$\sim -\frac{g_2^4 m_{{\rm D}\rho}^2}{(4\pi)^2 g_\rho^2}$$

So $m_{{\rm D}\rho} \sim 20\,{\rm TeV}$, dark-baryons at $m_{\rm DB} \sim 50\,{\rm TeV}$; dark-pions in the $3 \otimes 3 - 1 = 3 \oplus 5$ of ${\rm SU}(2)_L$ at $m_{{\rm D}\pi_n} \approx \frac{g_2 m_\rho}{4\pi}\sqrt{\frac{3}{4}(n^2-1)} \sim 2\,{\rm TeV}$. $\pi_5 \to WW$ via anomalies.

Dark Matter

The model has **two** accidentally stable composite DM candidates:

- **The dark pion** π_3. Thermal relic abundance predicted, ok for

$$m_{\pi_3} = 2.5\ \text{TeV}$$

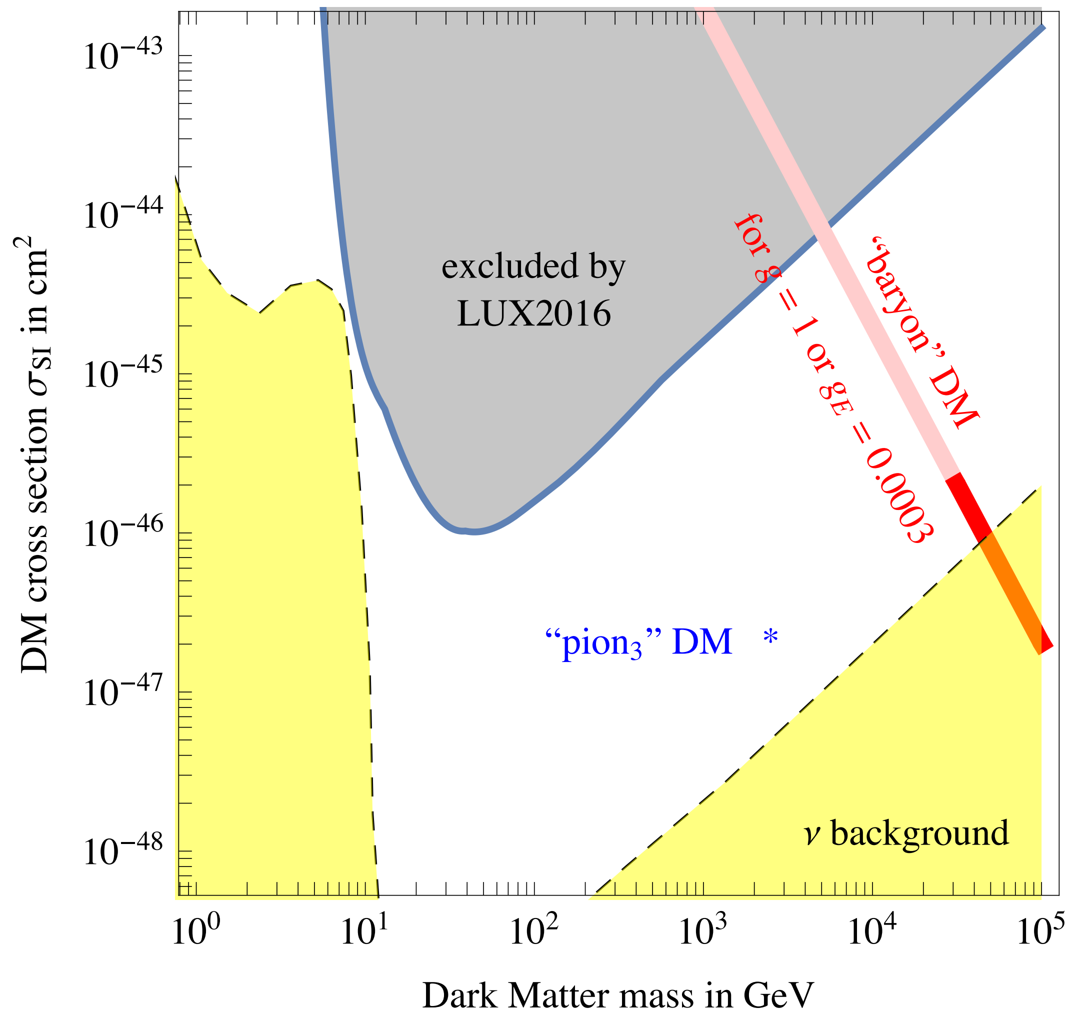
Direct detection:

$$\sigma_{\text{SI}} \approx 0.2\ 10^{-46}\,\text{cm}^2.$$

- **The lightest dark baryon**, presumably subdominant:

$$\Omega_{\text{thermal}} \approx 0.1 \left(\frac{m_B}{200\ \text{TeV}}\right)^2$$

Characteristic magnetic dipole direct detection interaction.



DM with electric and magnetic dipoles

For odd SU(N_{DC}) dark baryons are fermions and have

$$\mu_{\text{mag}} \sim \frac{e}{M_{\text{DM}}}, \qquad d_{\text{el}} \sim \frac{e\,\theta_{\text{DC}}\,\text{min}[m_{\mathcal{Q}}]}{M_{\text{DM}}^2}$$

Direct detection enhanced at low recoil energy E_R:

$$\frac{d\sigma}{dE_R} \approx \frac{e^2 Z^2}{4\pi E_R}\left(\mu_{\text{mag}}^2 + \frac{d_{\text{el}}^2}{v^2}\right) \neq \sigma_{\text{SI}} \frac{A^2}{2M_{\mathcal{N}} v^2}.$$

Some models have higher-spin DM that could give rise e.g. to $B_\mu B_\nu^* F^{\mu\nu}$?

Furthermore, Yukawa couplings give Higgs-mediated direct-detection

$$\sigma_{\text{SI}} = \frac{g_{\text{DM}}^2 m_N^4 f_N^2}{2\pi v^2 M_h^4}, \qquad g_{\text{DM}} = \frac{\partial M_{\text{DM}}}{\partial h}$$

SO(N_{DC}) and $m_{\mathcal{Q}} \ll \Lambda_{\text{DC}}$

Dark quarks in real R (complex C) SM representations are Majorana (Dirac).

Condensate $\langle C\bar{C}\rangle = 2\langle RR\rangle \sim 4\pi\Lambda^3_{\text{DC}}$ breaks flavor symmetry as SU(N_{DF}) $\to$ SO(N_{DF}). So dark-pions are $\mathcal{Q}\mathcal{Q}$. CC have bad quantum numbers for DM: Majorana dark quarks are needed to let them decay.

There is no conserved U(1)$_{\text{DB}}$; lightest baryon kept stable by $\text{Z}_2 = \text{O}(N)/\text{SO}(N)$. Baryons are those of SU(N) because $\epsilon_{ijk\cdots}$ is the same, but decompose under flavor SO(N_{DF}) $\subset$ SU(N_{DF})

$$
\begin{aligned}
N_{\text{DC}} = 3 &: \quad \left(\ydiagram{2,1}\right)_{\text{SU}(N_{\text{DF}})} = \left(\ydiagram{2,1} \oplus \ydiagram{1}\right)_{\text{SO}(N_{\text{DF}})} \\
N_{\text{DC}} = 4 &: \quad \left(\ydiagram{2,2}\right)_{\text{SU}(N_{\text{DF}})} = \left(\ydiagram{2,2} \oplus \ydiagram{2} \oplus 1\right)_{\text{SO}(N_{\text{DF}})} \\
N_{\text{DC}} = 5 &: \quad \left(\ydiagram{3,2}\right)_{\text{SU}(N_{\text{DF}})} = \left(\ydiagram{3,2} \oplus \ydiagram{2,1} \oplus \ydiagram{3} \oplus \ydiagram{1}\right)_{\text{SO}(N_{\text{DF}})}.
\end{aligned}
$$

'8-fold' way would be 5-fold way plus 3-fold way. Presumably smaller is lighter.

SO($N_{\rm DC}$) and $m_{\mathcal{Q}} \ll \Lambda_{\rm DC}$: golden models

SO($N_{\rm DC}$) dark-color. Dark-quarks	Yukawa couplings	Allowed $N_{\rm DC}$	Dark-pions	Dark-baryons
$N_{\rm DF} = 3$			5	$3, 1, \ldots$ for $N_{\rm DC} = 3, 4, \ldots$
$\mathcal{Q} = V$	0	$3, 4, .., 7$	unstable	$V^N = 3, 1, \ldots$
$N_{\rm DF} = 4$			9	$4, 1, \ldots$
$\mathcal{Q} = N \oplus V$	0	$3, 4, .., 7$	3	$VVN = 1, V(VV + NN) = 3,$ $VV(VV + NN) = 1, \ldots$
$N_{\rm DF} = 5$			14	$5, 1\ldots$
$\mathcal{Q} = L \oplus N$	1	$3, 4, .., 14$	unstable	$L\bar{L}N = 1,$ $L\bar{L}(L\bar{L} + NN) = 1, \ldots$
$N_{\rm DF} = 7$			27	$1, \ldots$
$\mathcal{Q} = L \oplus V$	1	4	unstable	$(L\bar{L} + VV)^2 = 1$
$\mathcal{Q} = L \oplus E \oplus N$	2	$4, 5$	unstable	$(E\bar{E} + L\bar{L})^2 + NN(L\bar{L} + E\bar{E}) = 1$
$N_{\rm DF} = 8$			35	1
$\mathcal{Q} = G$	0	4	unstable	$GGGG = 1$
$\mathcal{Q} = L \oplus N \oplus V$	2	4	unstable	$(L\bar{L} + VV)^2 + NN(L\bar{L} + VV) = 1$
$N_{\rm DF} = 9$			44	1
$\mathcal{Q} = L \oplus E \oplus V$	2	4	unstable	$(E\bar{E} + L\bar{L} + VV)^2 = 1$
$N_{\rm DF} = 10$			54	1
$\mathcal{Q} = L \oplus E \oplus V \oplus N$	3	4	unstable as	$L \oplus E \oplus V + NN(L\bar{L} + E\bar{E} + VV) = 1$

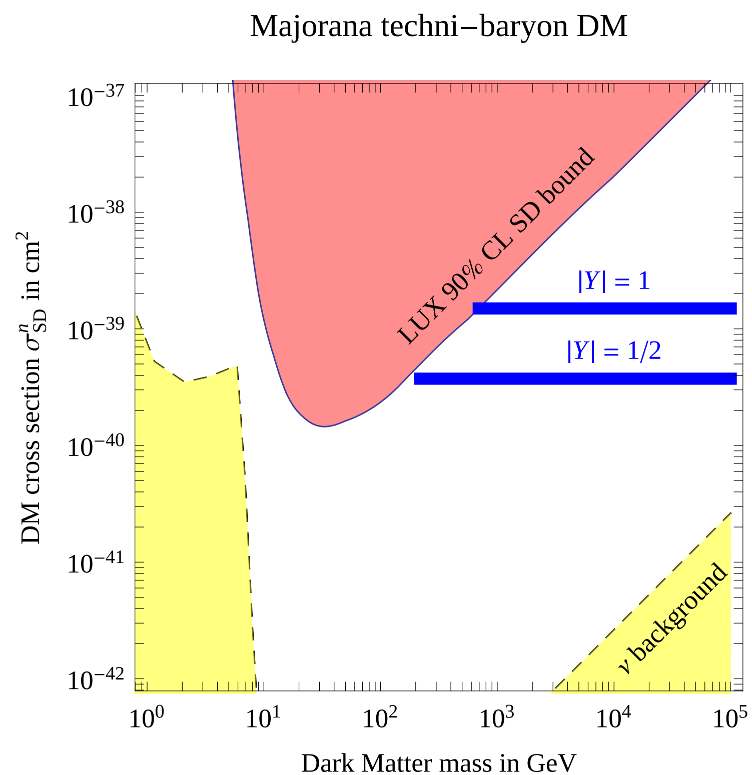
Phenomenology of real dark baryons

No Z vector couplings, no dipoles, no asymmetry. They mix like Wino/Bino/Higgsino giving spin-dependent effects from

$$-g_A Z_\mu \frac{g_2}{\cos\theta_{\rm W}} \frac{\overline{\rm DM}\gamma_\mu\gamma_5{\rm DM}}{2}$$

with

$$g_A \sim \frac{y^2 v^2}{\Delta m^2}, \qquad \Delta m \gtrsim \frac{\alpha_2}{4\pi} M_{\rm DM}$$



If $\Delta m_{2_{1/2}} \lesssim 100\,{\rm keV}$ one gets inelastic DM.

Complex ineliminable phases in Yukawas can give **electric dipoles**

$$d_e \sim Ne \frac{\alpha\,{\rm Im}[y_L y_R]}{16\pi^3}\frac{m_e}{m_L\, m_V} \sim 10^{-27}\, e\,{\rm cm} \times {\rm Im}[y_L y_R]\frac{{\rm TeV}^2}{m_L m_V} < 0.09\ 10^{-27} e\,{\rm cm}$$

Collider signals: dark pions

gauge group	Dark-quark content	Dark-pion content under $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$								
		1_0	$1_{\pm 1}$	$1_{\pm 2}$	$2_{\pm 1/2}$	$2_{\pm 3/2}$	3_0	$3_{\pm 1}$	$4_{\pm 1/2}$	5_0
$\mathrm{SU}(N)_{\mathrm{DC}}$	V						1_{stable}			1
	$N \oplus V$	1					3_{stable}			1
	$N \oplus L$	1			1		1			
	$N \oplus L \oplus \tilde{E}$	2	1		2		1			
	$V \oplus L$	1			1		2		1	1
	$V \oplus L \oplus \tilde{E}$	2			2		2	1	1	1
	$V \oplus L \oplus N$	2			2		4		1	1
	$N \oplus L \oplus \tilde{L}$	2	1		2		2	1		
	$N \oplus L \oplus \tilde{L} \oplus \tilde{E}$	3	2		3	1	2	1		
	$N \oplus L \oplus \tilde{E} \oplus V$	3	1		3		4	1	1	1
	$N \oplus L \oplus \tilde{L} \oplus E \oplus \tilde{E}$	4	3	1	4	2	2	1		
$\mathrm{SO}(N)_{\mathrm{DC}}$	V									1
	$L \oplus N$	1			1		1	1		
	$N \oplus V$	1					1_{stable}			1
	$L \oplus V$	1			1		1	1	1	1
	$L \oplus N \oplus E$	2	1	1	2	1	1	1		
	$L \oplus E \oplus V$	2		1	2	1	1	2	1	1
	$L \oplus N \oplus V$	2			2		2	1	1	1
	$L \oplus N \oplus V \oplus E$	3	1	1	3	1	2	2	1	1

(Models with coloured $\mathcal{Q}$ give coloured DCπ)

Some darkπ decay and can be singly produced via anomalies: $\pi_{1,3,5_0} \leftrightarrows WW, ZZ, \gamma\gamma$.
Others are pair-produced via $g_{Y,2}$ and decay $\pi_{2_{1/2}} \to H\pi_{1_0}$, $\pi_{1_1} \to HH\pi_{1_0}$.

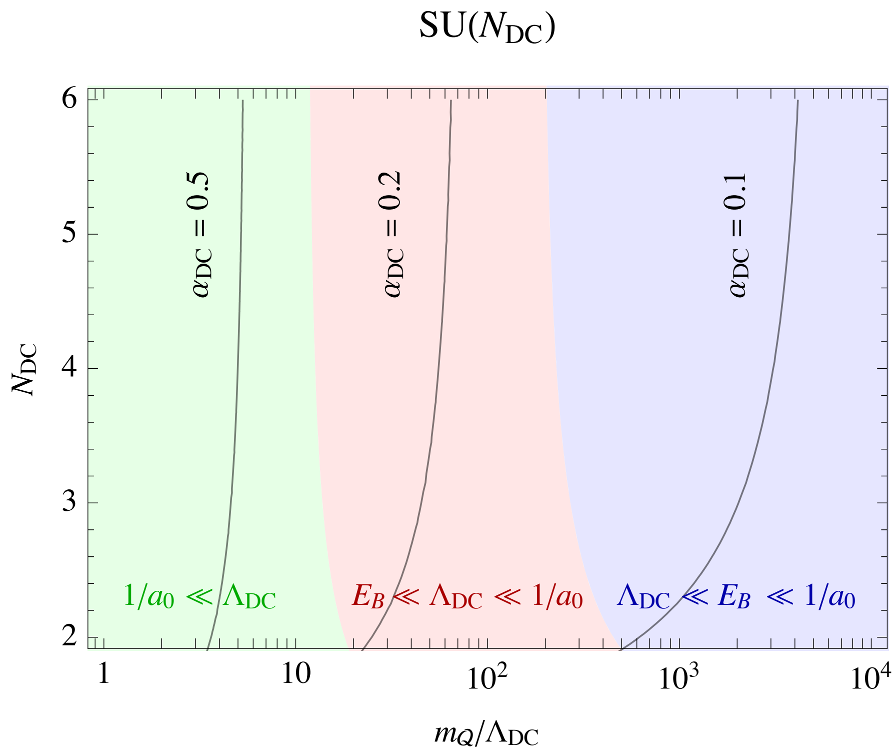
Heavy dark quarks, $m_{\mathcal{Q}} \gg \Lambda_{\rm DC}$

We assume that DM is the lightest $\mathcal{Q}$

SU: $\mathcal{Q} = V$ or N (then $\mathcal{B}$ with spin $N_{\rm DC}/2$).

SO: $\mathcal{Q} = L$ slightly mixed with heavier N or V trough LHN.

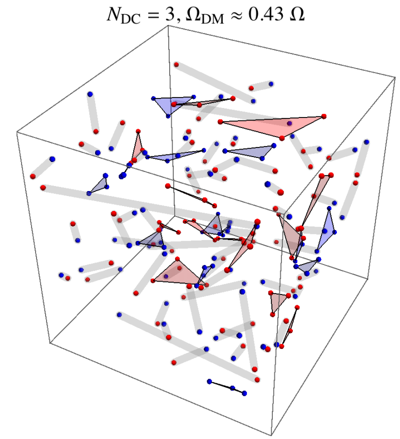
Non-relativistic non-abelian $V \sim -\alpha_{\rm DC}/r + \Lambda^2_{\rm DC} r$ makes bound states $\mathcal{Q}\bar{\mathcal{Q}}$, $\mathcal{Q}\mathcal{Q}$, $\mathcal{Q}\mathcal{Q}\mathcal{Q}$ ... with size $a_0 \sim 1/\alpha_{\rm DC} m_{\mathcal{Q}}$ and binding $E_B \sim \alpha^2_{\rm DC} m_{\mathcal{Q}}$. 3 distinct regions:



Non-standard dark cosmology

1) If $\Lambda_{\rm DC} < T_{\rm fo} \approx m_{\mathcal{Q}}/25$, free $\mathcal{Q}$ freeze-out at $T \sim T_{\rm fo}$.

2) Dark confinement at $T \sim \Lambda_{\rm DC}$ (1st order phase transition: gravity waves). Some $\mathcal{Q}$ form dark baryons $\mathcal{B}$:



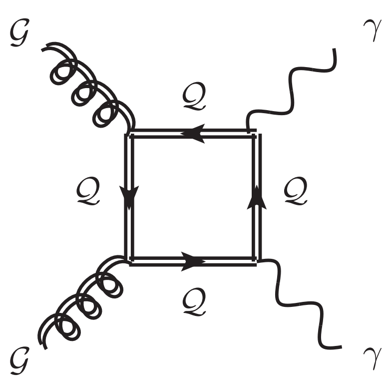
$$\Omega_{{\rm DM}\mathcal{B}} = \frac{\Omega_{\mathcal{Q}+\bar{\mathcal{Q}}}}{1 + 2^{N_{\rm DC}-1}/N_{\rm DC}}$$

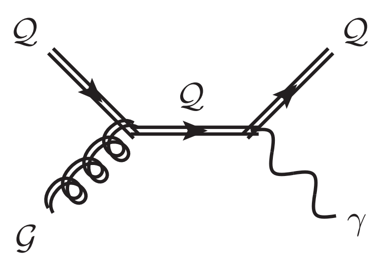
3) $\mathcal{B}\bar{\mathcal{B}}$ annihilations enhanced by (kinematically allowed) recombination

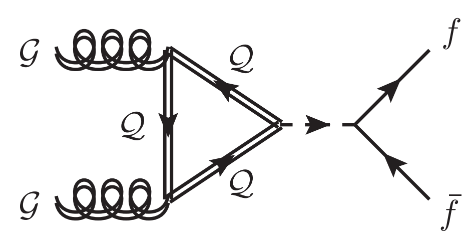
$$(\mathcal{Q}^{N_{\rm DC}}) + (\bar{\mathcal{Q}}^{N_{\rm DC}}) \to (\mathcal{Q}\bar{\mathcal{Q}}) + (\mathcal{Q}^{N_{\rm DC}-1})(\bar{\mathcal{Q}}^{N_{\rm DC}-1}), \qquad \sigma_{\mathcal{B}\bar{\mathcal{B}}} v_{\rm rel} \sim \frac{\pi}{\alpha_{\rm DC} m_{\mathcal{Q}}^2}$$

Cross section could be bigger if bound states $\mathcal{B}^*$ are excited by $T > E_{\mathcal{B}}$.

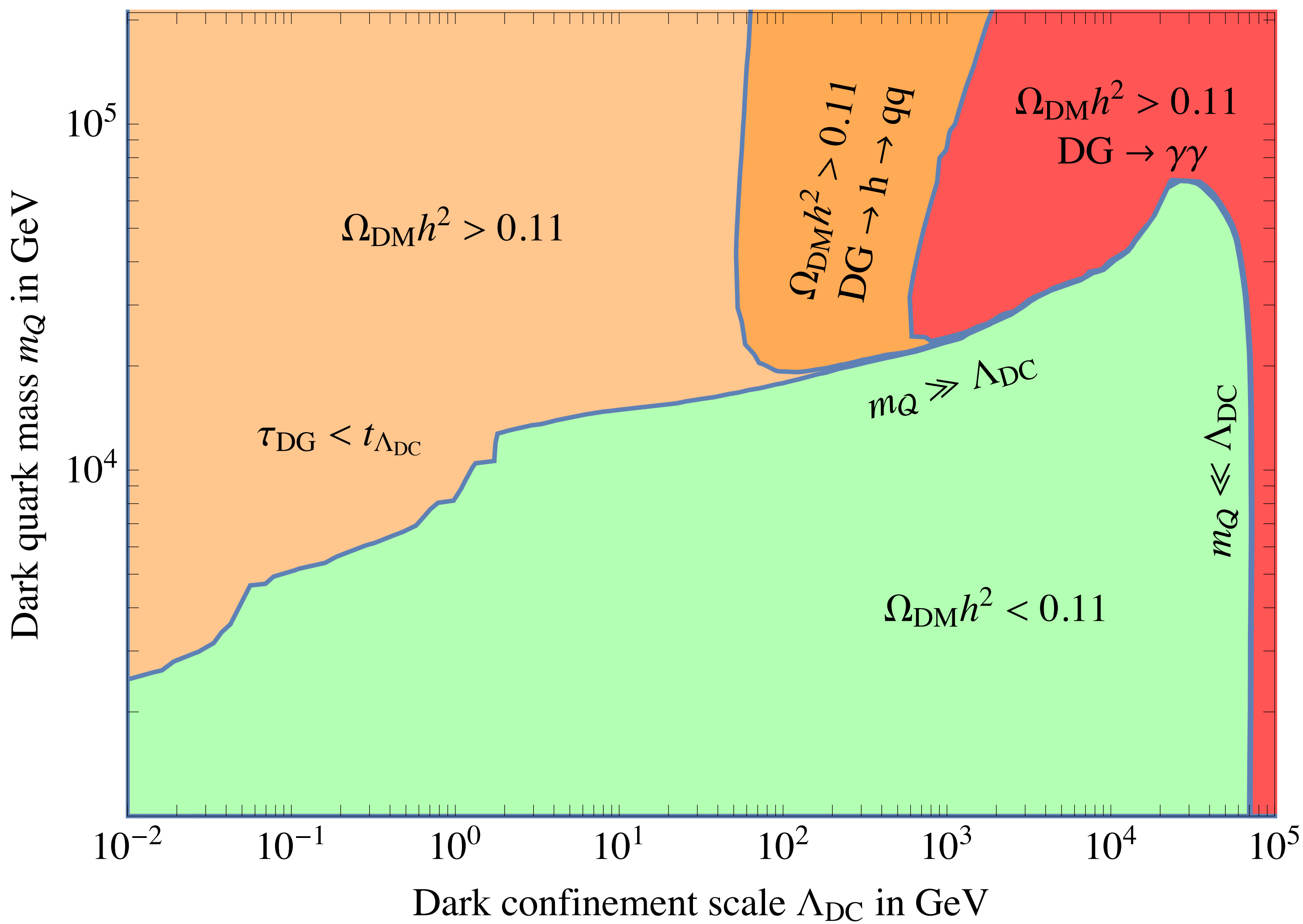
4) Slow decays of dark glue-balls with $M_{\rm DG} \sim 7\Lambda_{\rm DC}$ can dilute DM







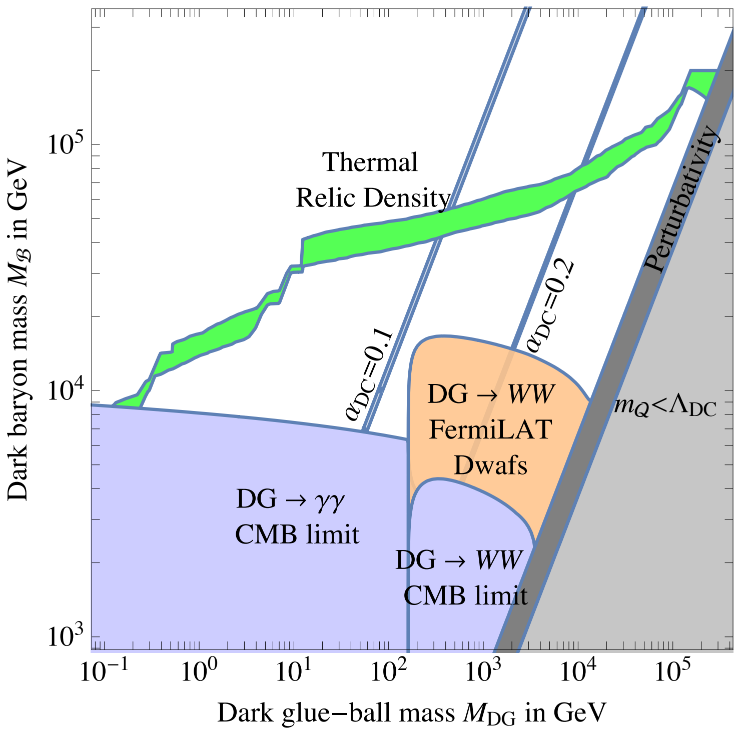
Composite DM cosmological abundance

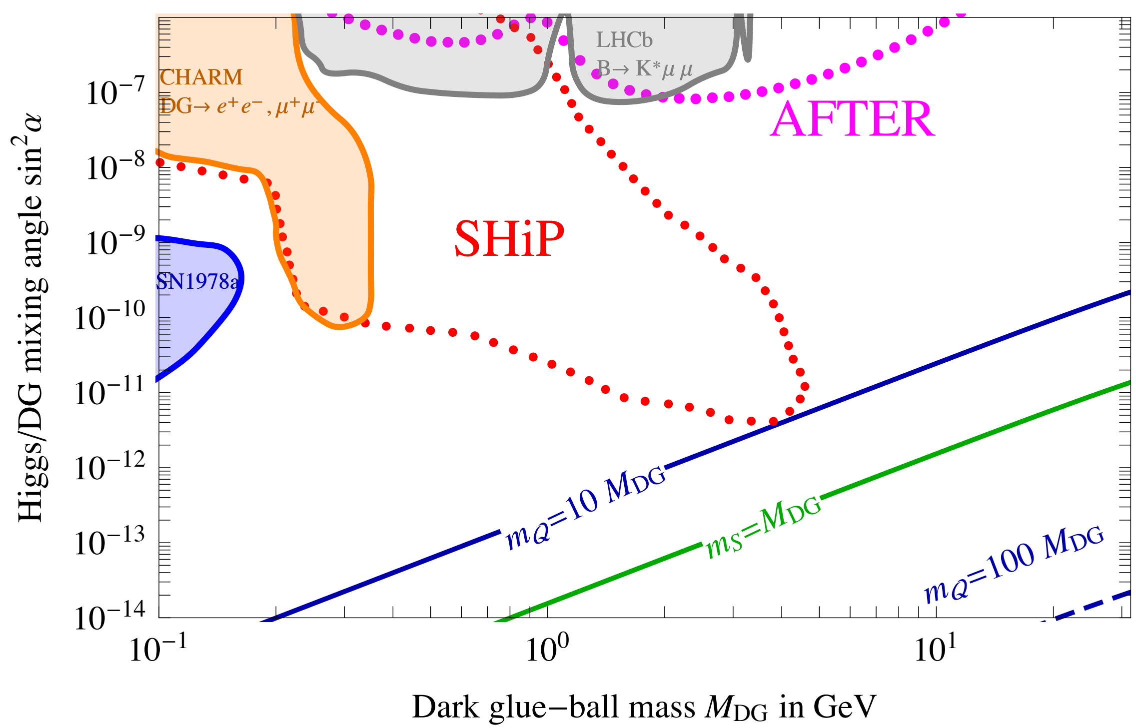


(Enhanced σ in intremediate region? [Harigaya et al.])

Extra unusual DM signals

Indirect detection: enhanced $\sigma_{\mathcal{B}\bar{\mathcal{B}}} > 3\ 10^{-26}\,\text{cm}^3/\,\text{sec}$.





Long-lived glue-balls can be tested at accelerators.

Radioactive DM: excited states $\mathcal{B}^*$ are long-lived if $E_B < M_{\text{DG}}$.

Conclusions

DM as accidentally stable composite under a new force:

- DM abundance reproduced for $\Lambda_{\rm DC} \sim 100\,{\rm TeV}$ if $M_{\mathcal{Q}} \ll \Lambda_{\rm DC}$.
- Magnetic dipoles $\Rightarrow$ peculiar $d\sigma/dE_R$ in direct detection.
- $\sigma_{\mathcal{B}\mathcal{B}^*}$ enhanced by recombination: indirect detection, cosmology.
- β, γ decays of radioactive DM.
- light dark glue-balls at accelerators.

DM as a QCD hadron made of a new heavy $\mathcal{Q}$:

- $\mathcal{Q}$-onlyum can be DM for $M_{\mathcal{Q}} \approx 9.5\,{\rm TeV}$; hybrids suppressed.
- Direct detection predicted just below bounds.
- Stable tracks at colliders, pp at $\sqrt{s} = 65\,{\rm TeV}$ needed.
- Indirect detection enhanced by recombination.
- Search for $\mathcal{Q}g$ hybrids, free or in nuclei.

DM as the QCD di-baryon $uuddss$

- DM abundance reproduced for $M_{\mathcal{S}} \approx 1.5\,{\rm GeV}$. Excluded by SK.