1) SM Dark Matter?
2) Colored Dark Matter
3) Supercool Dark Matter

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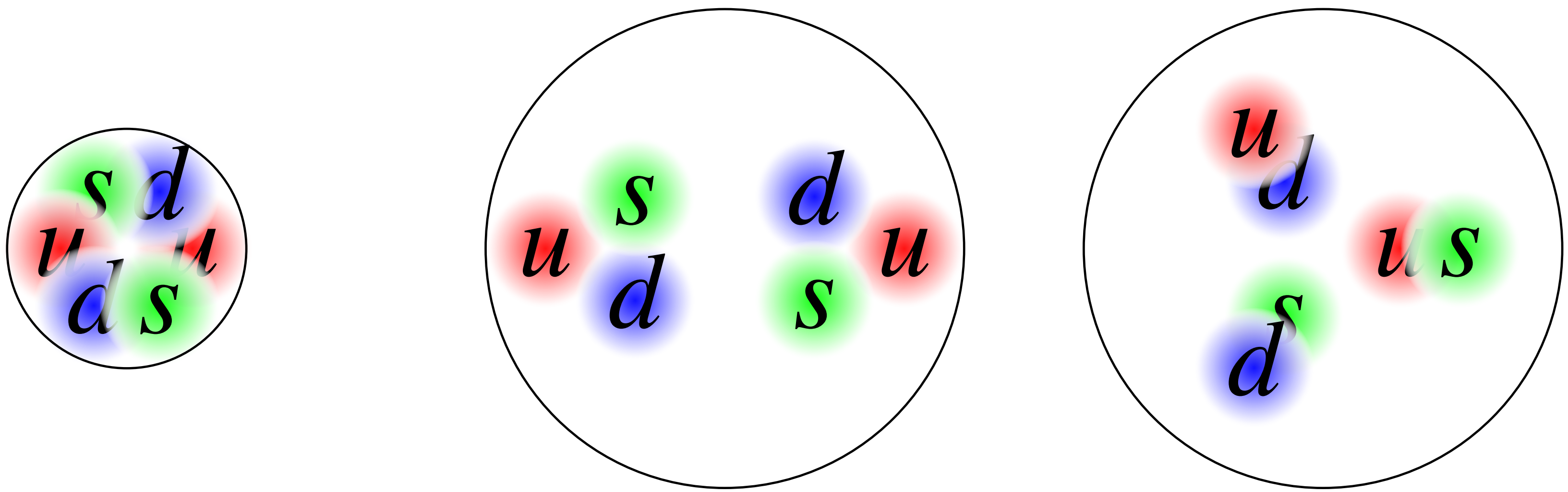
Cargese, 2019

European Commission
Horizon 2020
European Union funding
for Research & Innovation
erc European Research Council

1) DM within the SM?

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



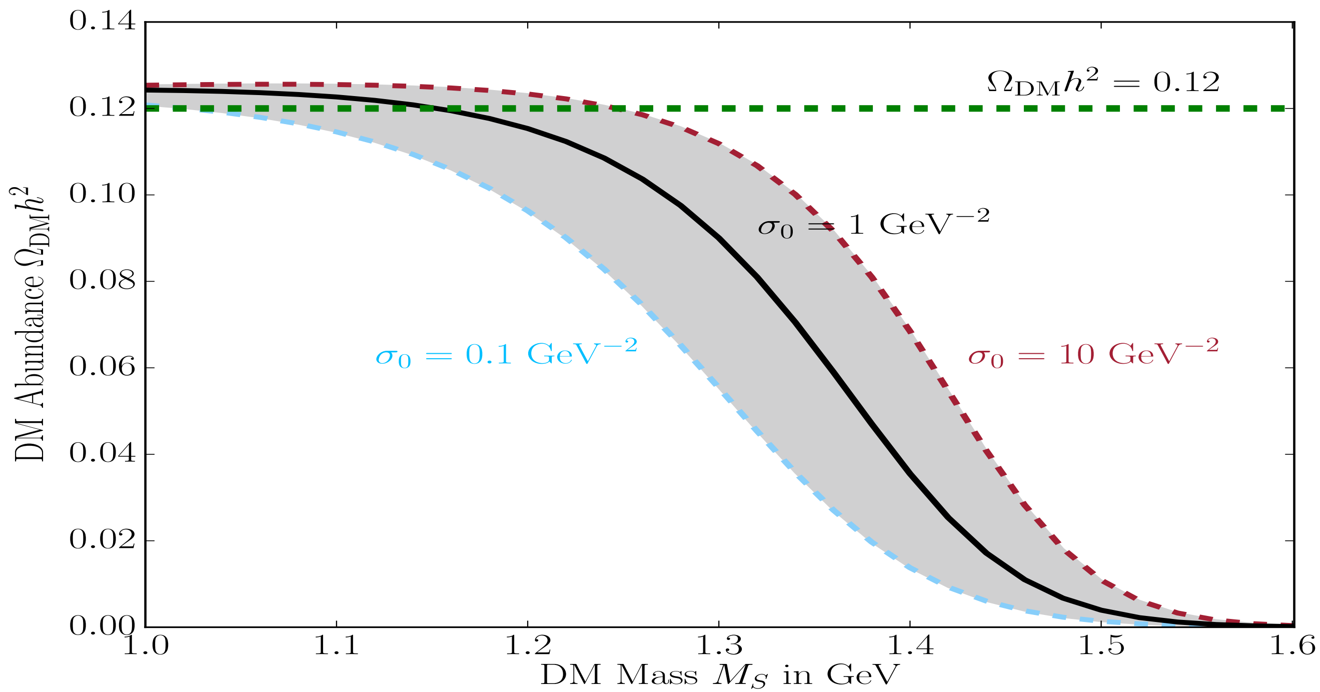
Farrar: if huge binding $E_B \gtrsim 2m_s$ such that $M_{\mathcal{S}} < 2(M_p + M_e)$, $\mathcal{S}$ is (co)stable with p, n due to conservation of baryon number. Maybe $\mathcal{S}$ could be small enough to be a marginally acceptable DM candidate.

Thermal relic abundance

Interactions with strange hadrons (e.g. $\Lambda\Lambda \leftrightarrow \mathcal{S}X$) keep $\mathcal{S}$ in thermal equilibrium until $\Lambda = uds$ get Boltzmann suppressed at $T_{\rm dec} \sim M_\Lambda - M_p$ and $\mathcal{S}$ decouples.

Relic $\mathcal{S}$ abundance $\approx$ thermal $\mathcal{S}$ abundance at decoupling.

DM abundance $\Omega_{\mathcal{S}} \sim 5\Omega_b$ reproduced for $M_{\mathcal{S}} \approx 1.3\,\text{GeV}$ at the observed Y_b



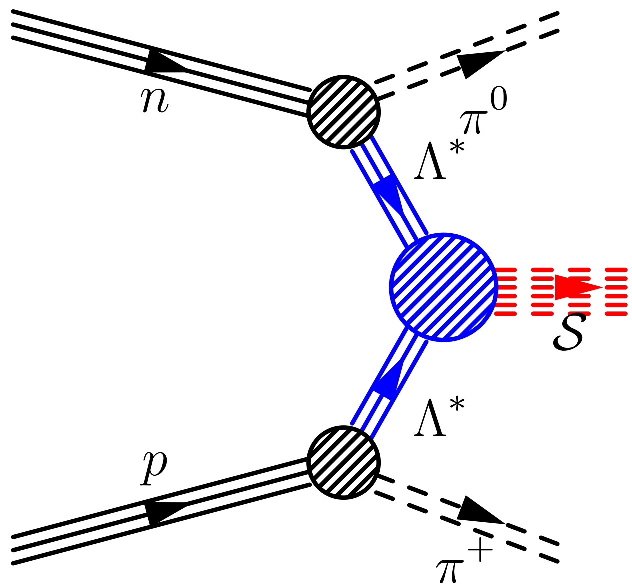
(Possible production at $T \sim \Lambda_{\rm QCD}$ made irrelevant by later thermalisation).

Nuclear decay

A too light $\mathcal{S}$ 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.



$M_{\mathcal{S}} \approx 1.84\,\mathrm{GeV}$ co-stable but QCD interactions keep it thermal: small Ω_{DM}.

Conclusion: lattice indicates that $\mathcal{S}$ is a loosely bound state similar to deuteron.

2) Colored DM??

Theory

As everybody knows DM must be WIMP, colored DM is obviously excluded. Writing a DM review I failed to proof the obvious: colored DM is allowed.

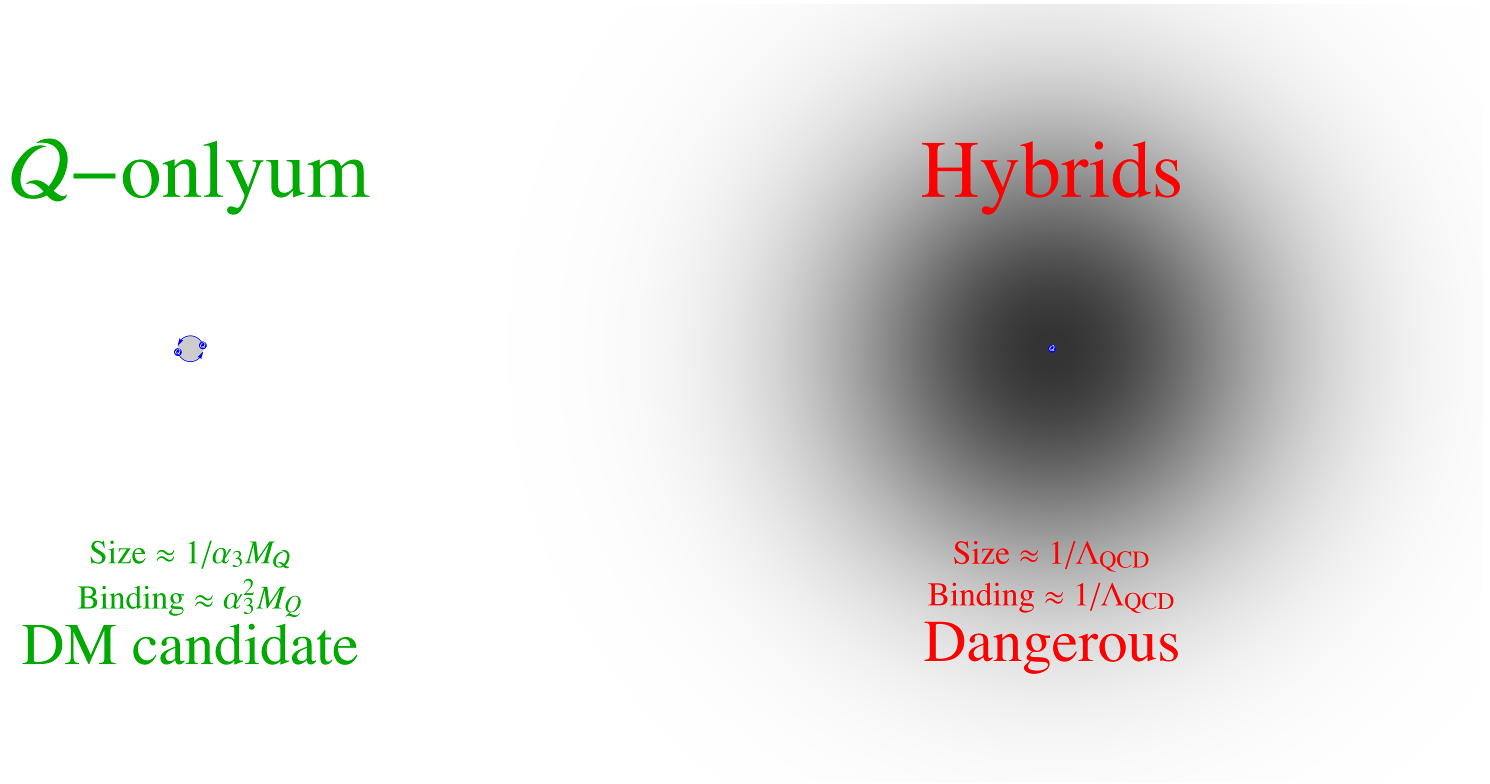
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\mathcal{Q}}(i\not{D} - M_{\mathcal{Q}})\mathcal{Q}.$$

$\mathcal{Q}$ is a new colored particle. We assume a Dirac fermion octet with no weak interactions, no asymmetry: 'quorn'. (Alternatives: a $(3,1)_0$, a $(3,2)$, a scalar...). Could be a Dirac gluino; could be a fermion of natural KSVZ axion models.

Relic density: $\Omega_{\mathcal{Q}}h^2 \sim 0.1\, M_{\mathcal{Q}}/8$ TeV before confinement. Later hadrons form...

The DM candidate

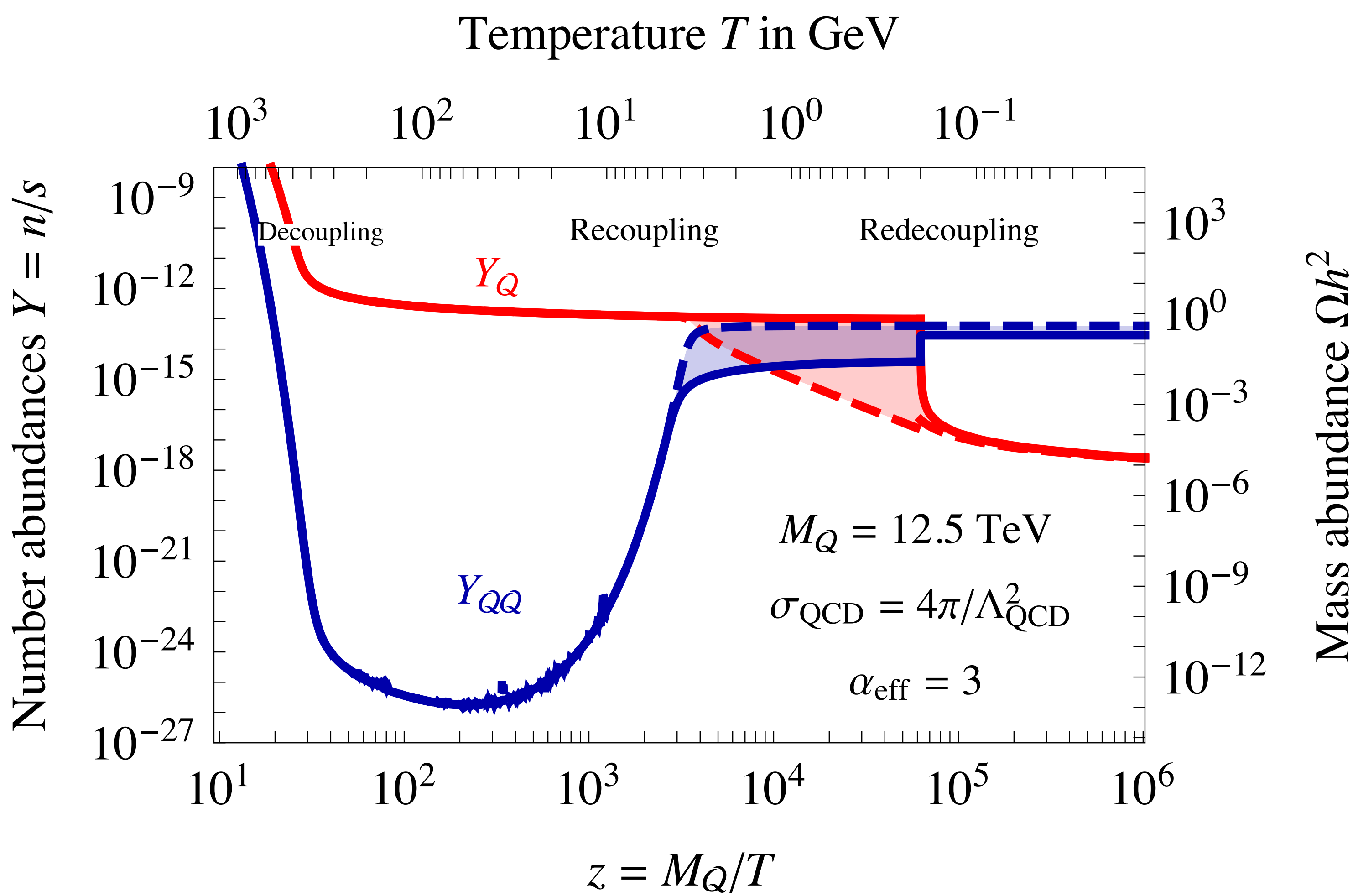
- DM can be the $\mathcal{Q}$-onlyum hadron $\mathcal{Q}\mathcal{Q}$ in its ground state: big binding $E_B \sim \alpha_3^2 M_\mathcal{Q} \sim 200\,\text{GeV}$ and small radius $a \sim 1/\alpha_3 M_\mathcal{Q}$, so small interactions.



- Hybrids $\mathcal{Q}g$ and/or $\mathcal{Q}q\bar{q}'$ have large $\sigma \sim 1/\Lambda^2_{\rm QCD}$ and small $E_B \sim \Lambda_{\rm QCD}$. Excluded by DM bounds, unless their relic abundance is small enough.

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.
Meeting 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 $T \sim M_Q/25$, Sommerfeld and bound states included.

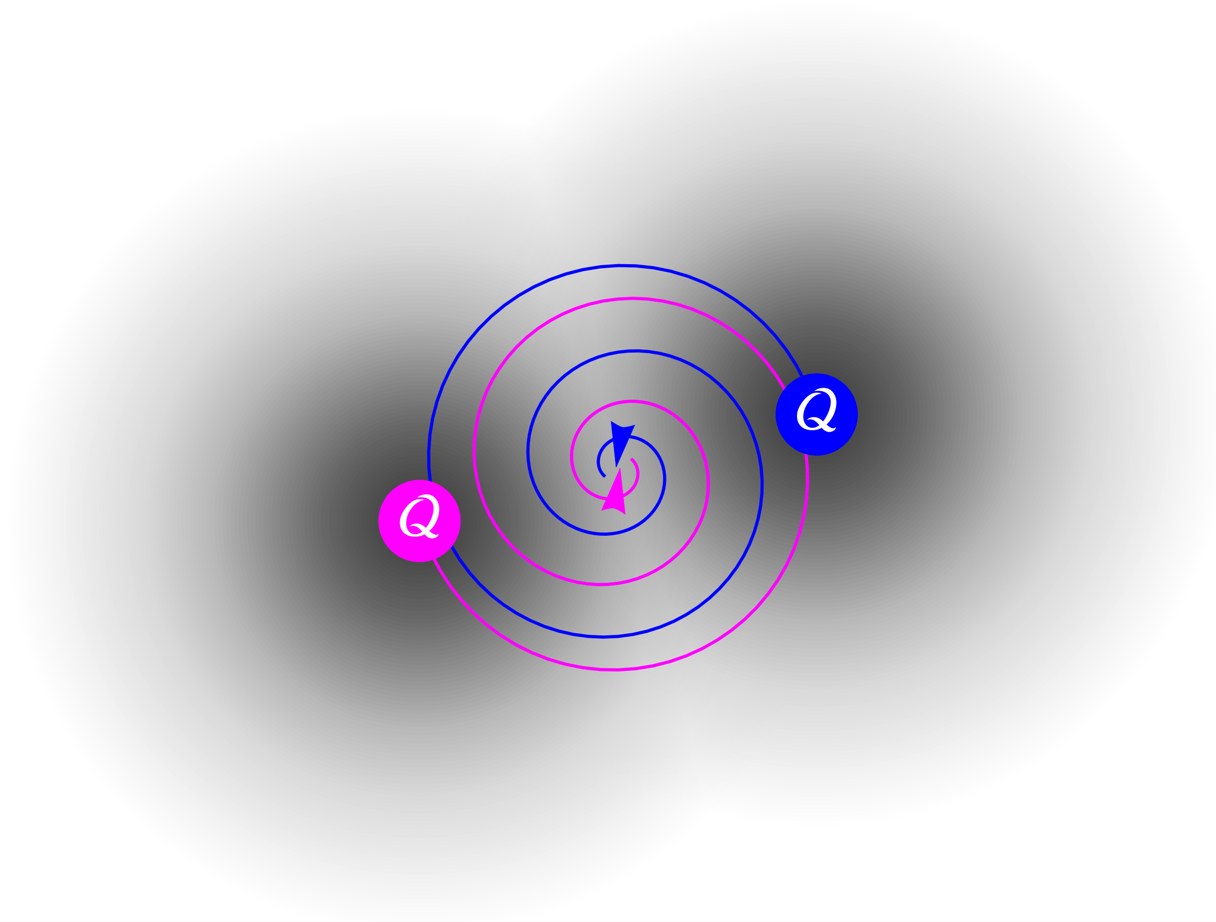
2) Recoupling at $T \gtrsim \Lambda_{\rm QCD}$ because $\sigma_{\rm bound} \sim 1/T^2$.

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

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

Fall

$\mathcal{Q}\mathcal{Q}$ form and break with initial distance $b \sim 1/\Lambda_{\rm QCD}$, initial $E_B \sim \Lambda_{\rm QCD}$, big $\sigma \sim 1/\Lambda^2_{\rm QCD}$ thanks to big $\ell \sim M_{\mathcal{Q}} b v$.



$\sigma_{\rm fall}$: formation of $\mathcal{Q}\mathcal{Q}$ and falling to an unbreakable (deep enough) level.

Fall cross section: abelian approx

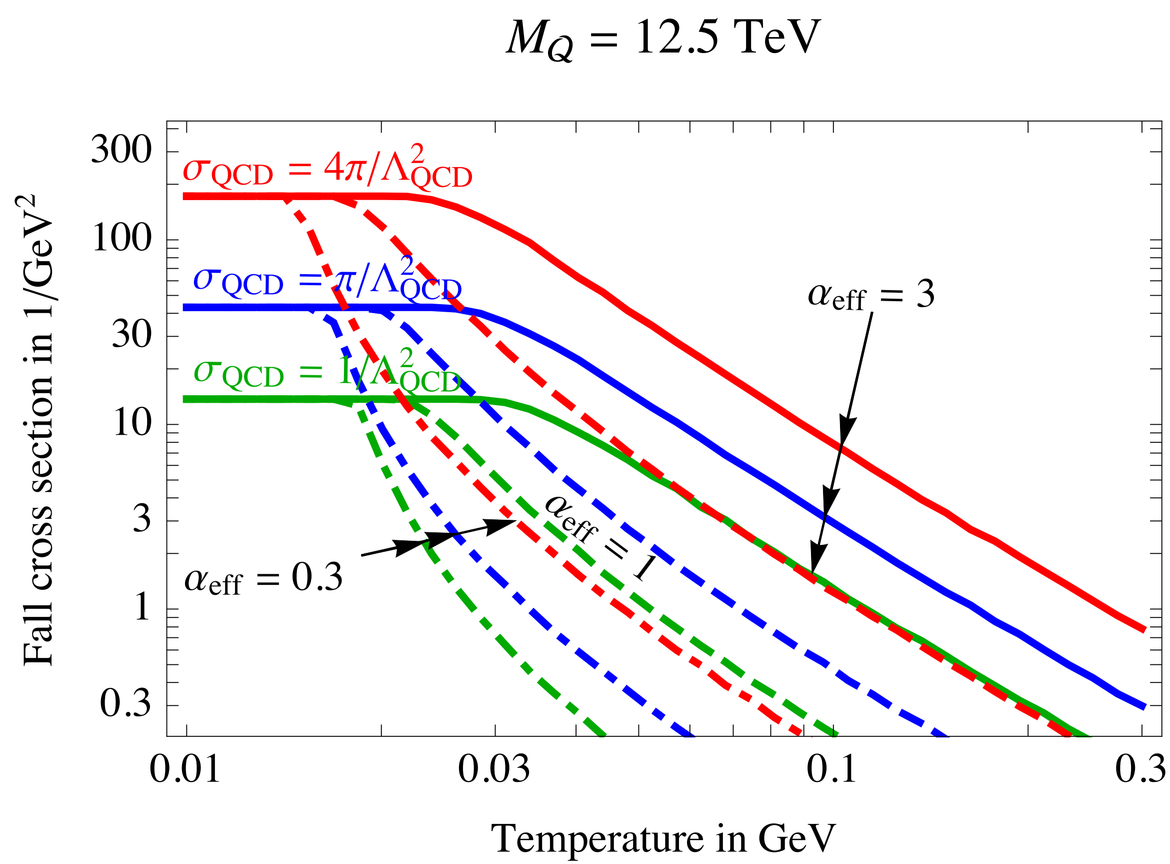
$\mathcal{QQ}$ unbreakable if it radiates

$$\Delta E \gtrsim T$$

before the next collision after

$$\Delta t \sim \frac{1}{n_\pi v_\pi \sigma_{\rm QCD}}$$

Guaranteed at $T \ll M_\pi$. The radiated energy is classical for $n, \ell \gg 1$ and minimal for circular orbits. Abelian computation:



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

Fall cross section: non abelian

By radiatiating a colored gluon the bound state changes $1 \leftrightarrow 8_{A,S}$. Classical limit for large n, ℓ: unknown. We did a brute-force quantum computation

$$\sigma_\ell = 4\pi \frac{2\ell+1}{M_Q^2 v_{\rm rel}^2} \underbrace{\sin^2 \delta_\ell}_{1/2} \qquad \text{up to large} \qquad \ell_{\max} \sim \frac{M_Q v_{\rm rel}}{\Lambda_{\rm QCD}}$$

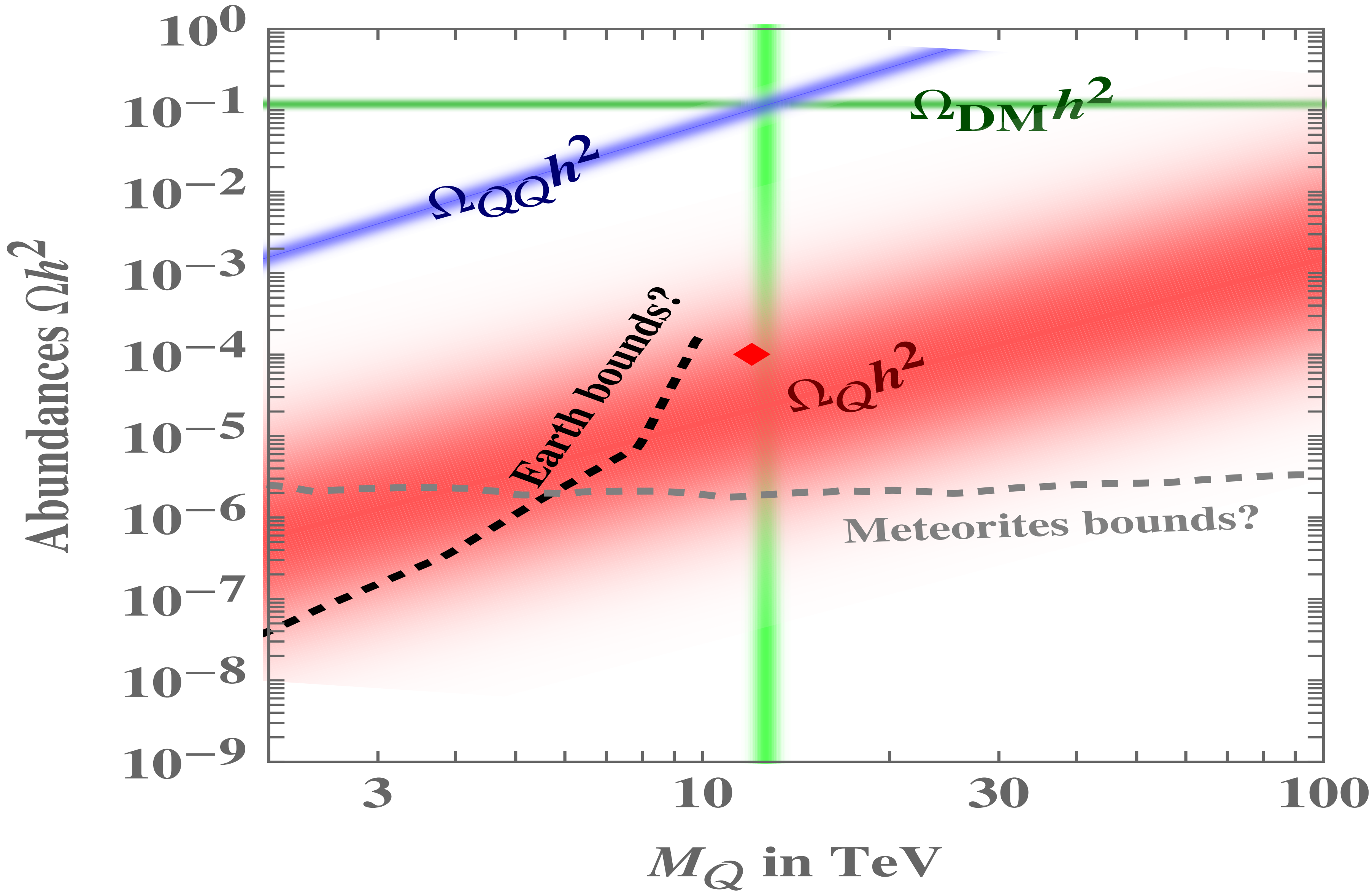
$$\sigma_{\rm QCD} = \sum_{\ell=0}^{\ell_{\max}} \sigma_\ell \sim \frac{1}{\Lambda_{\rm QCD}^2}, \qquad \sigma_{\rm fall} = \sum_{\ell=0}^{\ell_{\max}} \sigma_\ell \wp_\ell.$$

Compute $\wp_\ell$: brute-force sum over all quantum partial widths. We are in the worst QCD region: unclear if octet bound states exist down to $E_B \sim \Lambda_{\rm QCD}$:

- If yes, $8_A \to 1g$ decays are fast: $\wp_\ell$ cut by kinematics, simple analytic result.
- If not, $1 \to 1gg$ decays are slower: computed numerically.

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

Relic abundances



DM abundance for $M_{\mathcal{Q}} \approx 12.5\,\text{TeV}$. Hybrids suppressed by 10^{3-5}.

Direct detection of DM

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

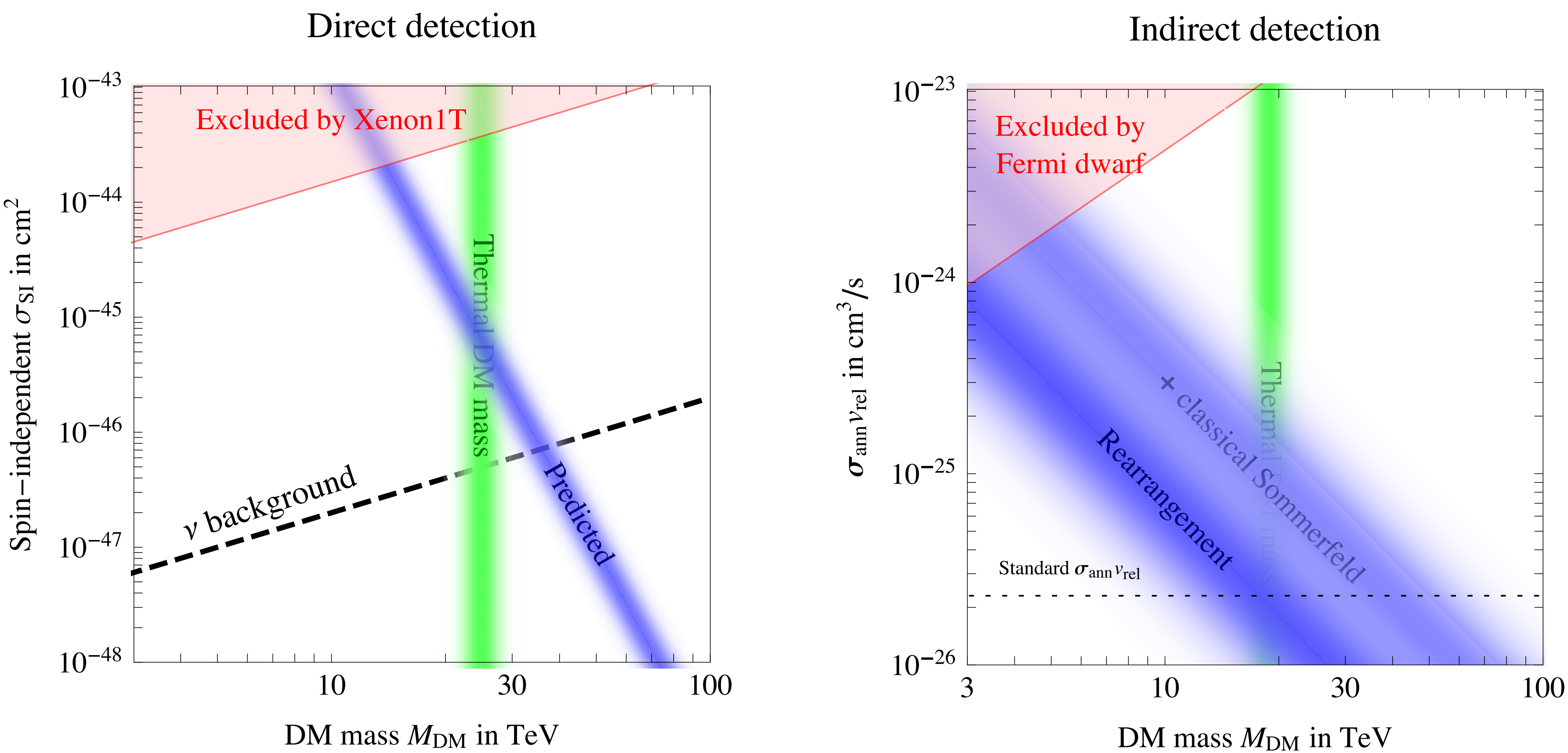
$$\mathscr{L}_{\rm eff} = c_E M_{\rm DM} \bar{B} B \vec{E}^{a2}.$$

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
Thermal DM mass
Predicted
ν background
Spin-independent σ_{SI} in cm^2
DM mass M_{DM} in TeV
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10
30
100
Indirect detection
Excluded by
Fermi dwarf
classical Sommerfeld
Rearrangement
Thermal DM mass
Standard $\sigma_{ann} v_{rel}$
$\sigma_{ann} v_{rel}$ in cm^3/s
10^{-23}
10^{-24}
10^{-25}
10^{-26}
3
10
30
100
DM mass M_{DM} in TeV

Indirect detection of DM

Analogous to hydrogen:

$$\sigma_{H\bar{H}} v_{\rm rel} \sim \frac{1}{\alpha m_e^2} \gg \frac{\alpha^2}{m_e^2}$$

Atomic size, because enhanced and dominated by recombination

$$(ep) + (\bar{e}\bar{p}) \to (e\bar{e}) + (p\bar{p}) \to \cdots$$

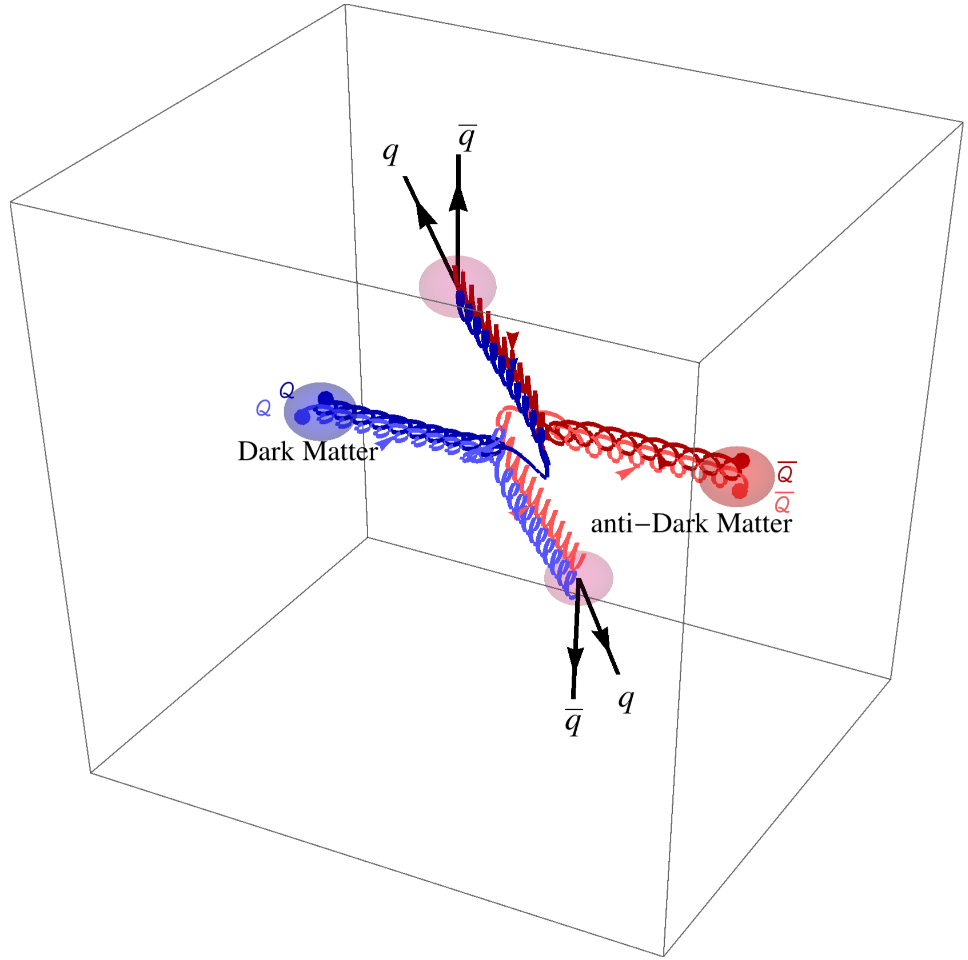
$m_p \gg m_e$: simple and exothermic. DM annihilation dominated by

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

Not exothermic, no $v_{\rm rel}$:

$$\sigma_{\rm ann} \sim \frac{1}{\alpha_3 M_{\mathcal{Q}}^2}$$

Enhanced by dipole Sommerfeld:



$$\sigma_{\rm ann} v_{\rm rel} \sim \frac{v_{\rm rel}^{3/7}}{M_{\mathcal{Q}}^2 \alpha_3^{12/7}} \sim 3\ 10^{-25} \frac{\rm cm^3}{\rm sec} \times \left(\frac{20\ {\rm TeV}}{M_{\rm DM}}\right)^2.$$

Collider detection of $\mathcal{Q}$

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

Discovering $M_{\mathcal{Q}} \sim 12.5\,\mathrm{TeV}$ needs a pp collider at $\sqrt{s} \gtrsim 85\,\mathrm{TeV}$.

LHC: $M_{\mathcal{Q}} \gtrsim 2\,\mathrm{TeV}$. ($\mathcal{Q}$ below 10 TeV excluded by direct detection).

Please don't build a μ 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 $\Omega_{\rm SIMP} = \Omega_{\rm DM}$.

$\Omega_{\rm SIMP} \sim 10^{-4}\Omega_{\rm DM}$ **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 $N_{\rm SIMP}/N_n \sim 10^{-8}$.
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 $= \left\langle \frac{N_{\rm SIMP}}{N_n} \right\rangle_{\rm Earth} = \frac{M}{M_{\mathcal{Q}}} \frac{m_N}{M_{\rm Earth}} \approx 10^{-18}$, 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

$$\left.\frac{N_{\rm SIMP}}{N_n}\right|_{\rm meteorite} = \frac{\rho_{\rm SIMP}}{M_{\mathcal{Q}}} \sigma_{\rm capture} v_{\rm rel} \Delta t \approx 10^{-14} \frac{\sigma_{\rm capture}}{0.01/\Lambda_{\rm QCD}^2}.$$

3) Super-Cool DM

Usual "WIMP miracle": observed DM density reproduced with TeV-scale particle, that freeze-out at $T \approx M_{\text{DM}}/\ln\lambda$ with $\lambda = M_{\text{Pl}} M_{\text{DM}} \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle \sqrt{\pi g_{\text{SM}}/45}$.

A new mechanism achieves the same in theories where the weak scale is dynamically generated trough dimensional transmutation. Coleman-Weinberg used the Higgs, but predicted $M_h \ll 125\,\text{GeV}$. New physics needed, many recent proposals: new strong interactions, warped extra dimensions... a new scalar:

A sample model: weakly coupled SU(2)$_X$

$G_{\text{SM}} \otimes \text{SU}(2)_X$ with one extra scalar S, doublet under SU(2)$_X$ and potential

$$V = \lambda_H |H|^4 - \lambda_{HS} |HS|^2 + \lambda_S |S|^4.$$

Weakly coupled SU(2)$_X$ model

1) **Dynamically generates** the weak scale and weak scale DM
2) **Preserves** the successful automatic features of the SM: B, L...
3) **Gets DM stability** as one extra automatic feature.

1) λ_S runs negative at low energy:

$$\lambda_S \simeq \beta_{\lambda_S} \ln \frac{s}{s_*} \qquad \text{with} \qquad \beta_{\lambda_S} \simeq \frac{9 g_X^4}{8(4\pi)^2}$$

$$S(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ w + s(x) \end{pmatrix} \qquad w \simeq s_* e^{-1/4}$$

$$H(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \qquad v \simeq w \sqrt{\frac{\lambda_{HS}}{2\lambda_H}}$$

2) No new Yukawas.

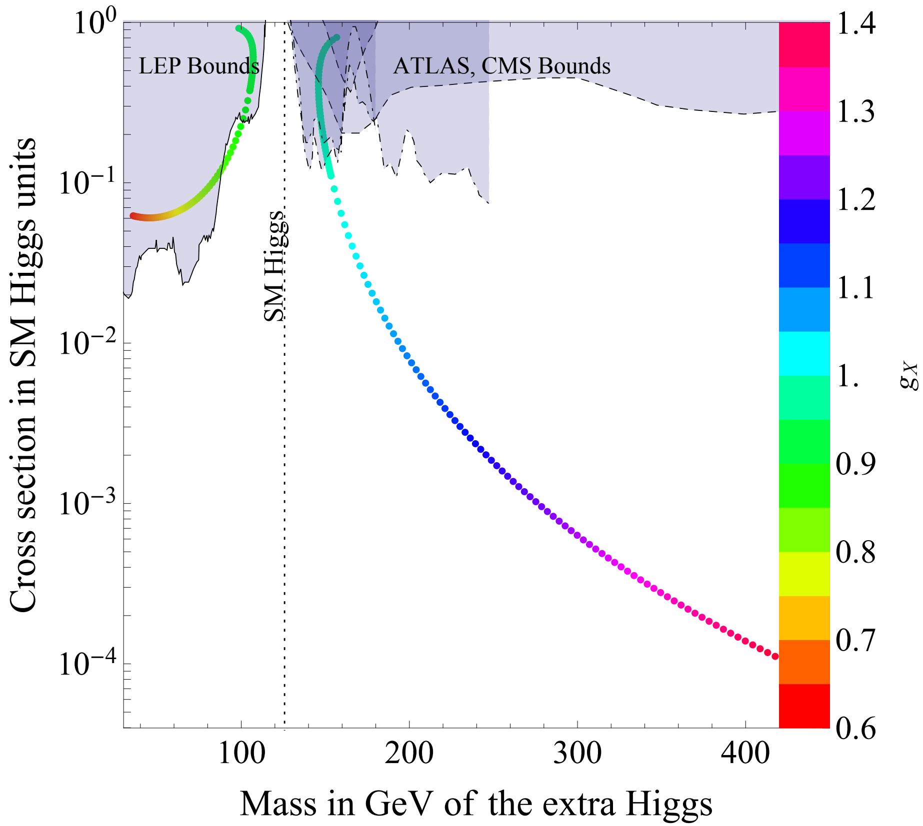
3) SU(2)$_X$ vectors get mass $M_X = \frac{1}{2} g_X w$ and are automatically stable.

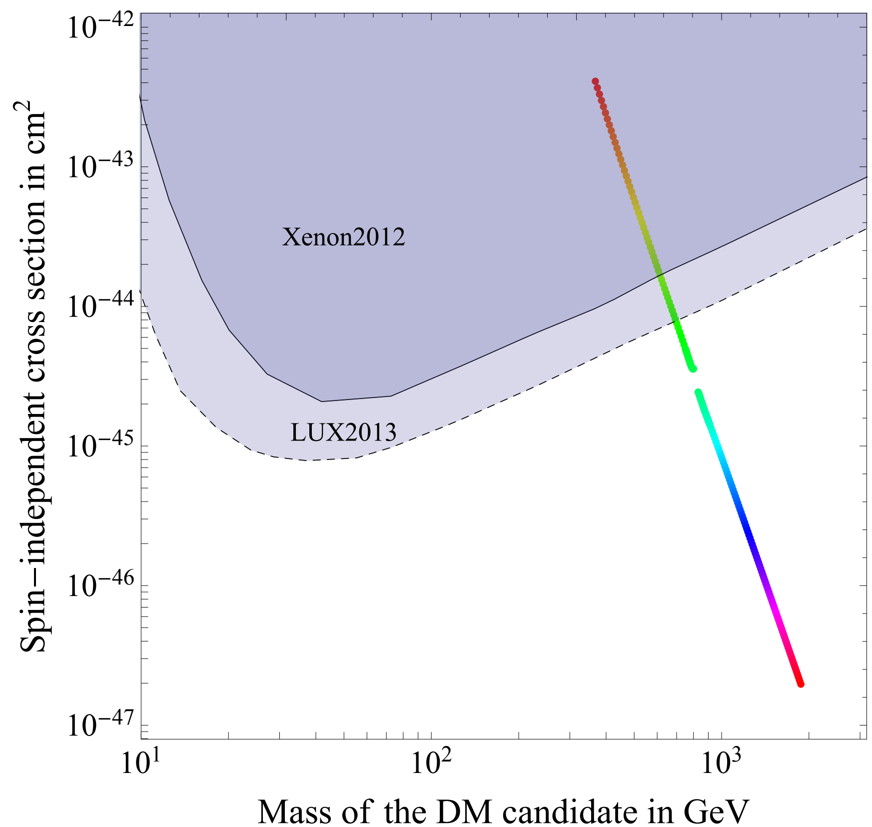
DM is usual relic if $g_X \gtrsim 1$

DM abundance reproduced for

$$\sigma v_{\rm ann} + \frac{1}{2}\sigma v_{\rm semi-ann} = \frac{11 g_X^2}{1728\pi w^2} + \frac{g_X^2}{64\pi w^2} \approx 2.2\times 10^{26}\,\frac{\rm cm^3}{\rm s}$$

fixes $g_X = w/2\,{\rm TeV}$, so all is predicted in terms of one parameter e.g. g_X:





Smaller g_X gives super-cooling

At large temperature thermal masses $m^2 + g^2T^2$ restore symmetry: $s, h = 0$. Any T is large in theories with $m = 0$: the universe remains trapped at $s, h = 0$.

- For large $g_X \sim 1$ quantum tunnelling is fast enough that the Universe exits to $h, s \neq 0$ trough a first order SM/dark phase transition. Gravity waves:

$$f_{\rm peak} \approx 0.3\,{\rm mHz} \qquad \Omega_{\rm peak} h^2 \approx 2\ 10^{-11}.$$

- For small g_X the universe remains trapped in a thermal inflationary phase.

Super-cool DM

If all masses come from the vev of a 'dilaton' scalar s, it remains trapped at $s = 0$ because $V \sim g^2 T^2 s^2 + \lambda_S(s) s^4$. Thermal inflation starts at $T_{\rm infl}$:

$$\frac{g_* \pi^2 T_{\rm infl}^4}{30} = V_\Lambda = \frac{3H^2 M_{\rm Pl}^2}{8\pi}.$$

DM and everybody is massless so **super-cools** down to some $T_{\rm end}$ at which vevs develop: the universe reheats up to $T_{\rm RH} \approx T_{\rm infl} \min(1, \Gamma/H)^{1/2}$. DM abundance:

$$\begin{aligned} Y_{\rm DM} &\approx Y_{\rm DM}|_{\rm super-cool} + Y_{\rm DM}|_{\rm sub-thermal} \\ &= Y_{\rm DM}^{\rm eq} \frac{T_{\rm RH}}{T_{\rm infl}} \left(\frac{T_{\rm end}}{T_{\rm infl}}\right)^3 + \lambda \frac{2025 g_{\rm DM}^2}{128\pi^7 g_{\rm SM}^2} e^{-2z_{\rm RH}}(1 + 2z_{\rm RH}) \end{aligned}$$

Super-cool DM is colder than cold: this has minor implications.

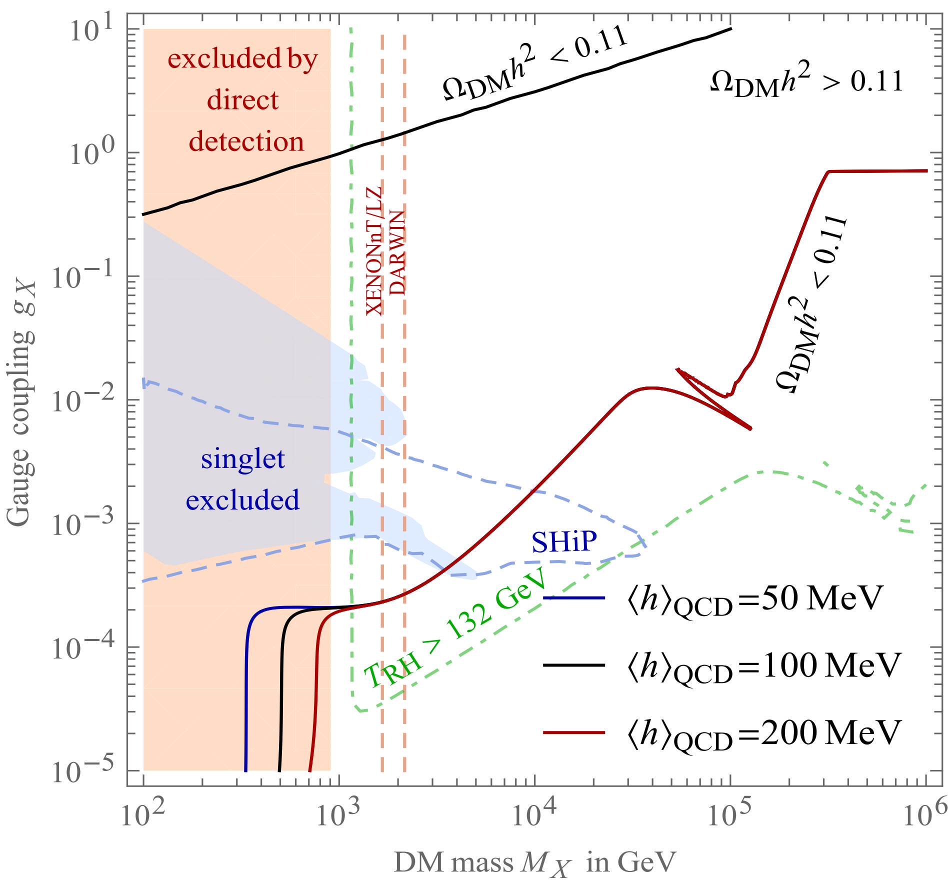
QCD ends super-cooling: $y_t h \langle \bar{t}t \rangle$ induces $\langle h \rangle_{\rm QCD} \sim \Lambda_{\rm QCD}$ so $M_s^2|_{\rm QCD} = -\lambda_{HS} \langle h \rangle_{\rm QCD}^2 / 2$ so s, h roll down when $M_s^2|_{\rm total} < 0$: at $T_{\rm end} \sim \Lambda_{\rm QCD}$ or below.

If $T_{\rm end} \sim \Lambda_{\rm QCD}$ the DM abundance is reproduced for $M_{\rm DM} \lesssim$ TeV.

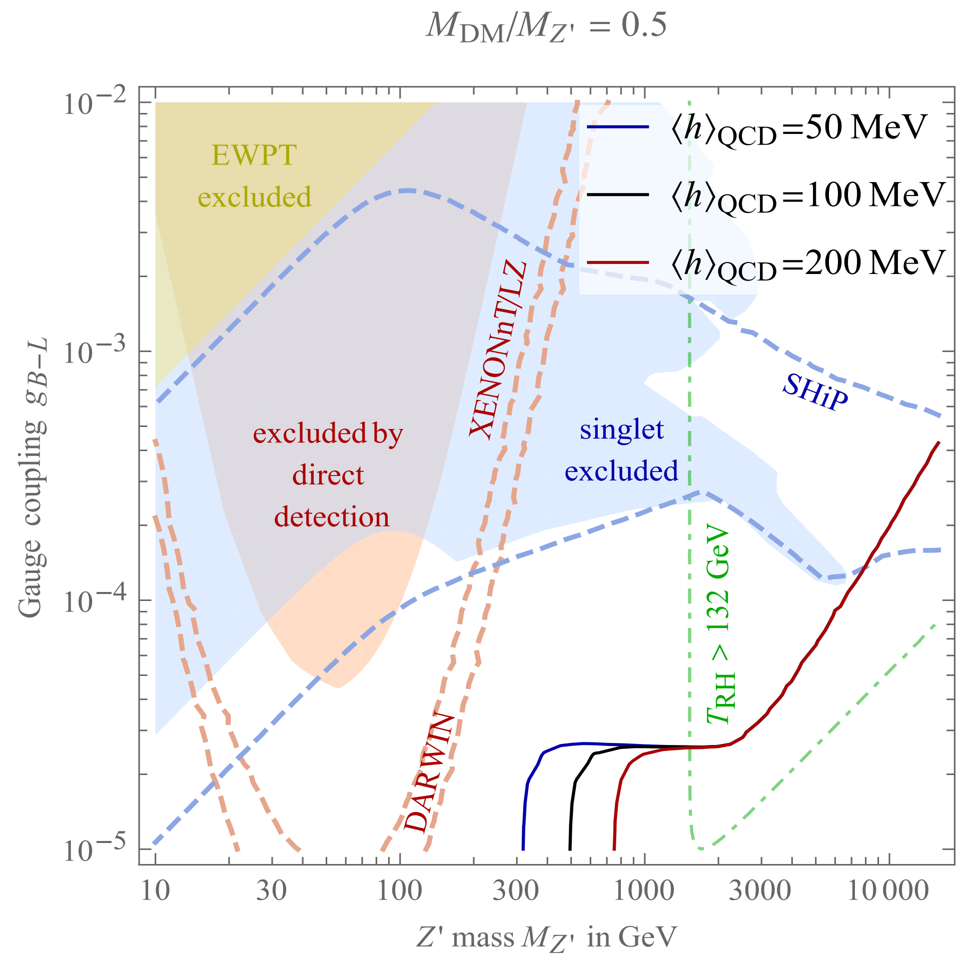
Like WIMP 'miracle'; but super-cool $Y_{\rm DM}$ does not depend on DM couplings.

Computations in specific models

$SU(2)_X$ model



$U(1)_{B-L}$ model



GeV-scale s enhances direct detection, is bounded by LEP, tested by SHiP

Baryogenesis

Super-cooling erases pre-existing Y_B.

- If $T_{\rm RH} < T_{\rm sph} \approx 132\,{\rm GeV}$ one needs **low scale 'cold' baryogenesis**. Model gives out-of-equilibrium, extra CP violation needed: axions? extra H'?...

- If $T_{\rm RH} > T_{\rm sph}$ one needs **low-scale leptogenesis**. Model with U(1)$_{B-L}$ and $(B-L)_S = 2$ such that right-handed neutrinos N get weak-scale mass from $y_S\, SNN$. Quasi-degenerate N can give Y_L.

Conclusions

1) The di-baryon $uuddss$ is not an acceptable DM candidate.

2) A new 12.5 TeV quark $\mathcal{Q}$ gives acceptable DM, with unusual signals.

3) Supercooling can generate the DM abundance for TeV-scale particles.