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Dark Matter from ’t Hooft anomaly matching

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Based on: arxiv 2008.12291
see also 1503.08749 + 1811.06975

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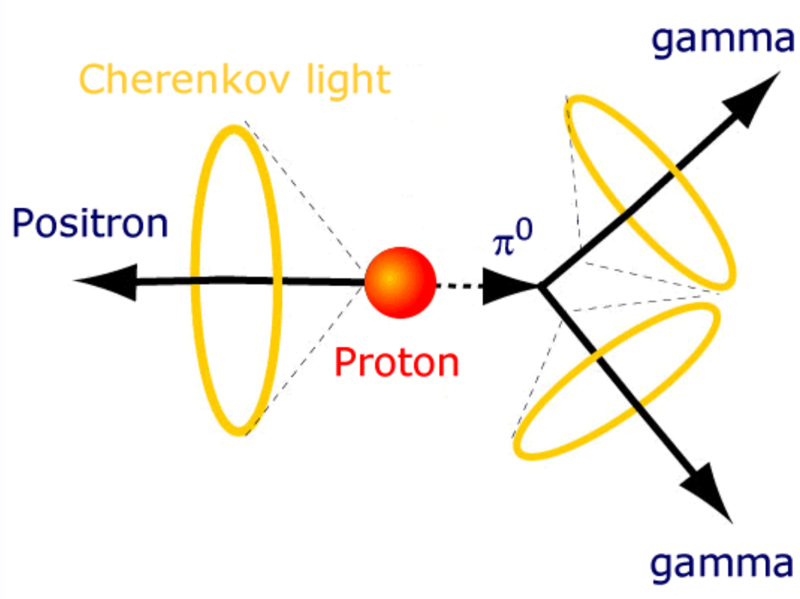
DARK MATTER STABILITY:

The proton lifetime is long:



$$\tau_p > 10^{34}\,\mathrm{y}$$

This follows from accidental baryon number conservation of the SM lagrangian:

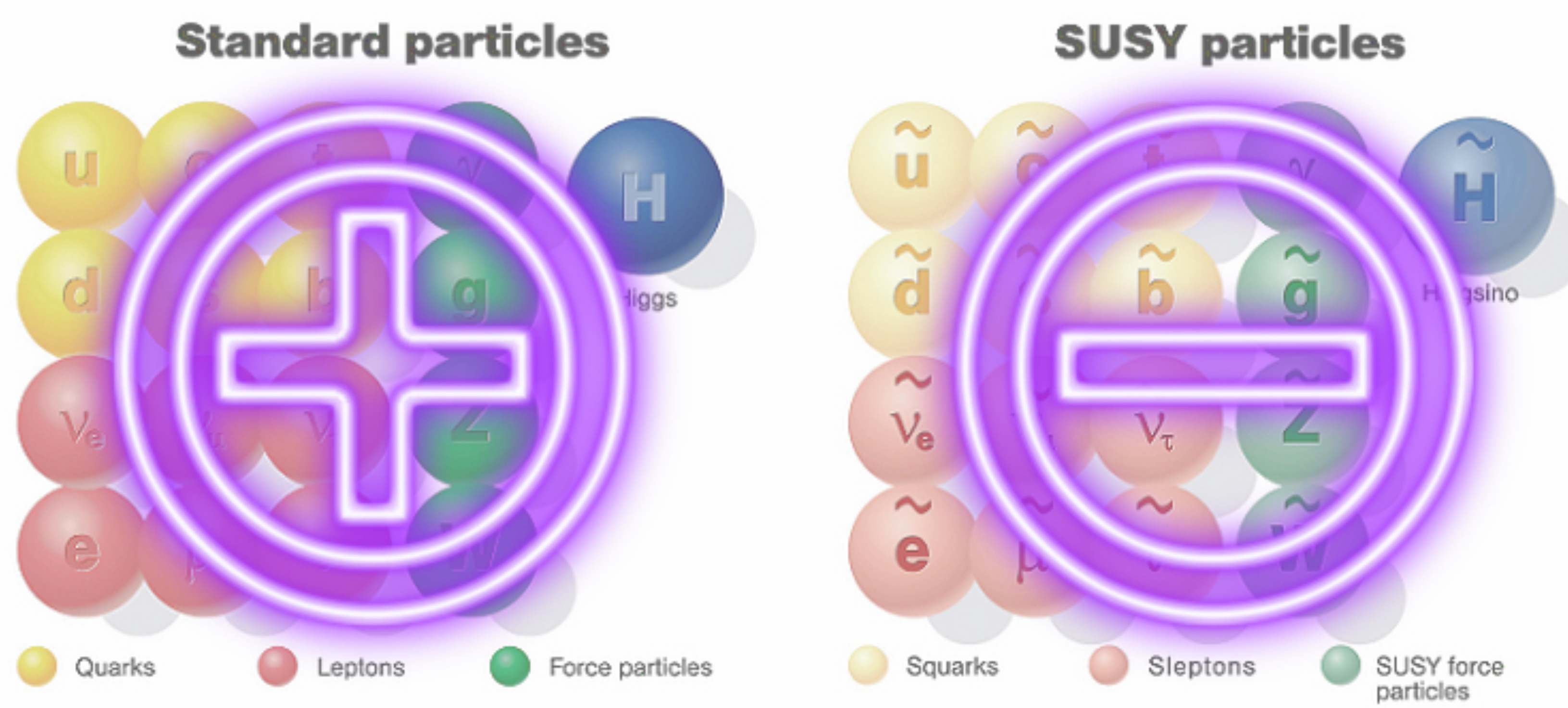
$$U(1)_B \qquad\qquad q \to e^{i\alpha} q$$

Violation:

$$\frac{qqql}{\Lambda^2} \longrightarrow \tau_p \sim \frac{8\pi\Lambda^4}{m_p^5} = 3\times 10^{34}\,\mathrm{y}\left(\frac{\Lambda}{10^{16}\,\mathrm{GeV}}\right)^4$$

Cosmological stability of DM is often obtained imposing ad hoc global symmetries. In supersymmetry:

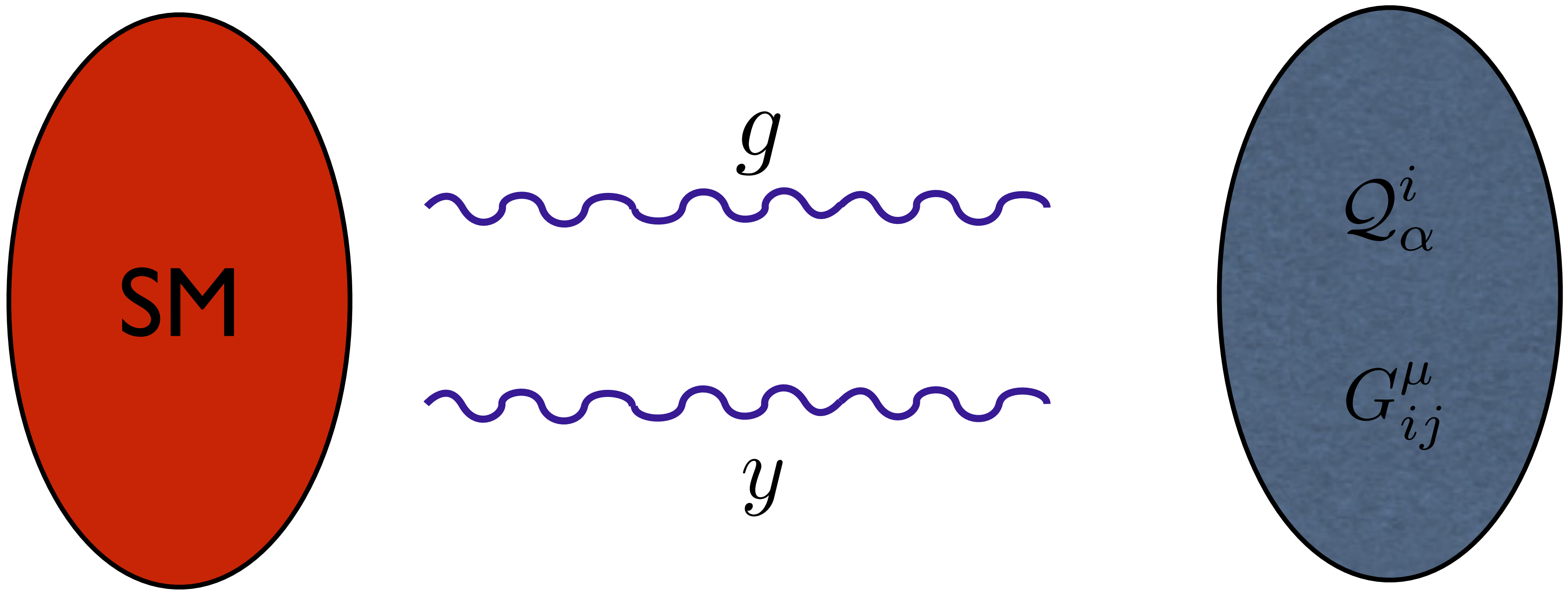
R-parity:



Can DM be accidentally stable as the proton?

New "dark" forces:
DM is an accidentally stable dark-hadron

Confining gauge theory with vector-like fermions



The visible sector couples minimally to the dark sector through gauge and Yukawa interactions:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{Q}_i(i\gamma^\mu D_\mu - m_i)Q_i - \frac{\mathcal{G}^{A2}_{\mu\nu}}{4g^2_{\rm DC}} + \frac{\theta_{\rm DC}}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^A_{\mu\nu} + [H\bar{Q}_i(y^L_{ij}P_L + y^R_{ij}P_R)Q_j + \text{h.c.}]$$

$$Q = ({\rm R_{DC}}\,, {\rm R_{SM}})$$

Accidental symmetries:

- Dark-Baryon number

$$\mathcal{Q}^i \to e^{i\alpha}\mathcal{Q}^i \longrightarrow B = \epsilon^{i_1 i_1 \ldots i_n} Q_{i_1}^{\{\alpha_1} Q_{i_2}^{\alpha_2} \ldots Q_{i_n}^{\alpha_n\}}$$

- Dark-Species number

$$\mathcal{Q}^i \to e^{i\alpha_i}\mathcal{Q}^i \longrightarrow M = \bar{\mathcal{Q}}^i \mathcal{Q}^j$$

Dark baryons robustly cosmologically stable:

$$\tau_p \sim \frac{8\pi\Lambda_{\rm UV}^4}{M_{\rm DM}^5} = 10^{26}\,{\rm s}\left(\frac{\Lambda_{\rm UV}}{M_p}\right)^4 \left(\frac{100\,{\rm TeV}}{M_{\rm DM}}\right)^5$$

Models

- Q-complex (SU(N) fundamental)

Baryons and anti-baryons are different particles that can be produced thermally or through an asymmetry.

[Antipin, MR, Strumia Vigiani, 2015]
[Mitridate, MR, Smirnov, Strumia, 2017]

- Q-real (SO(N) fundamental)

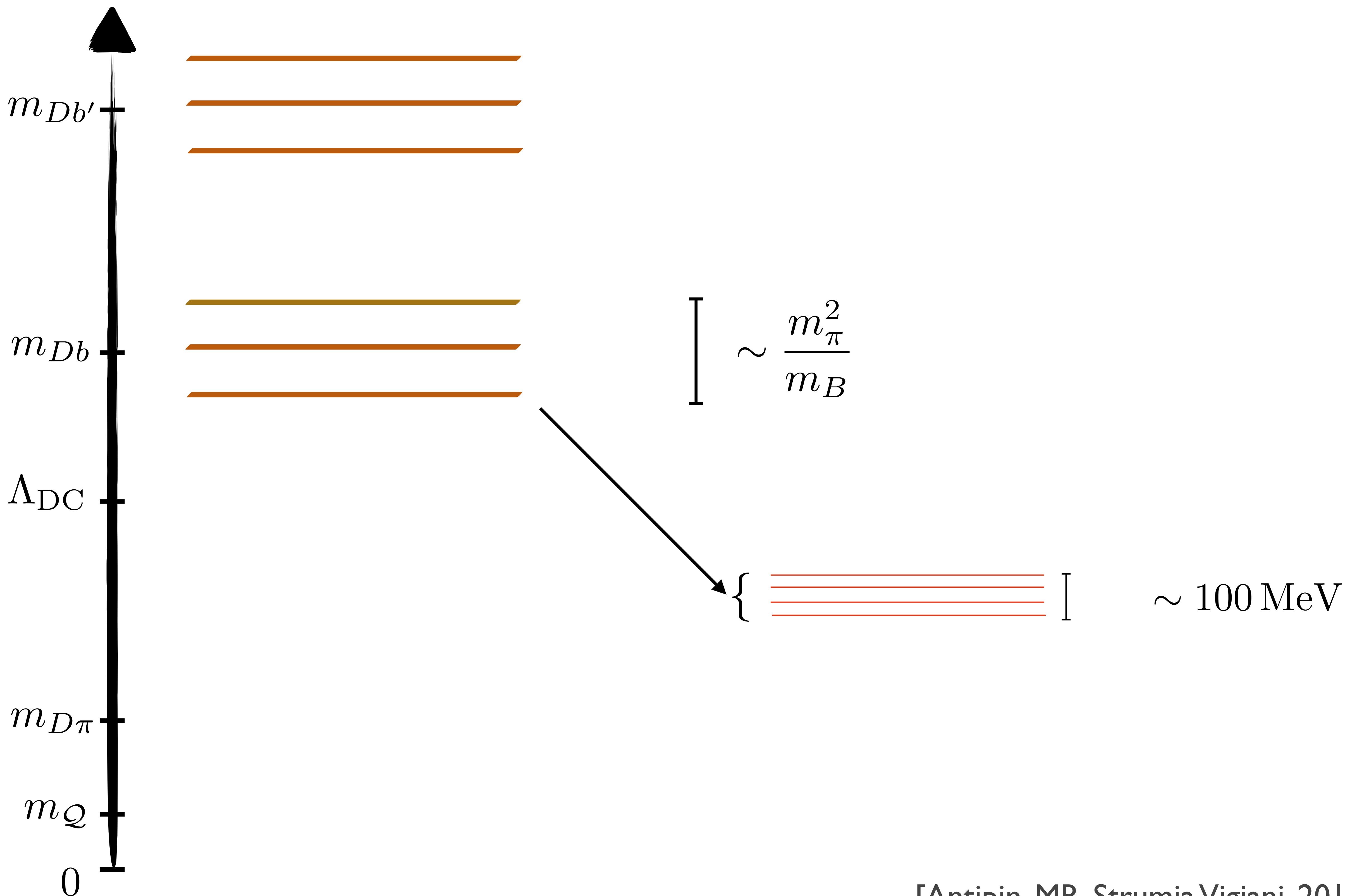
Baryon and anti-baryons are the same particle so 2 DM particles can annihilate. DM cannot be asymmetric.

- Q-adjoint

DM is a bound state of dark quarks and dark gluons.

[Contino, Mitridate, Podo, MR, 2018]

- Light Dark Quarks: $(m_Q < \Lambda_{DC})$



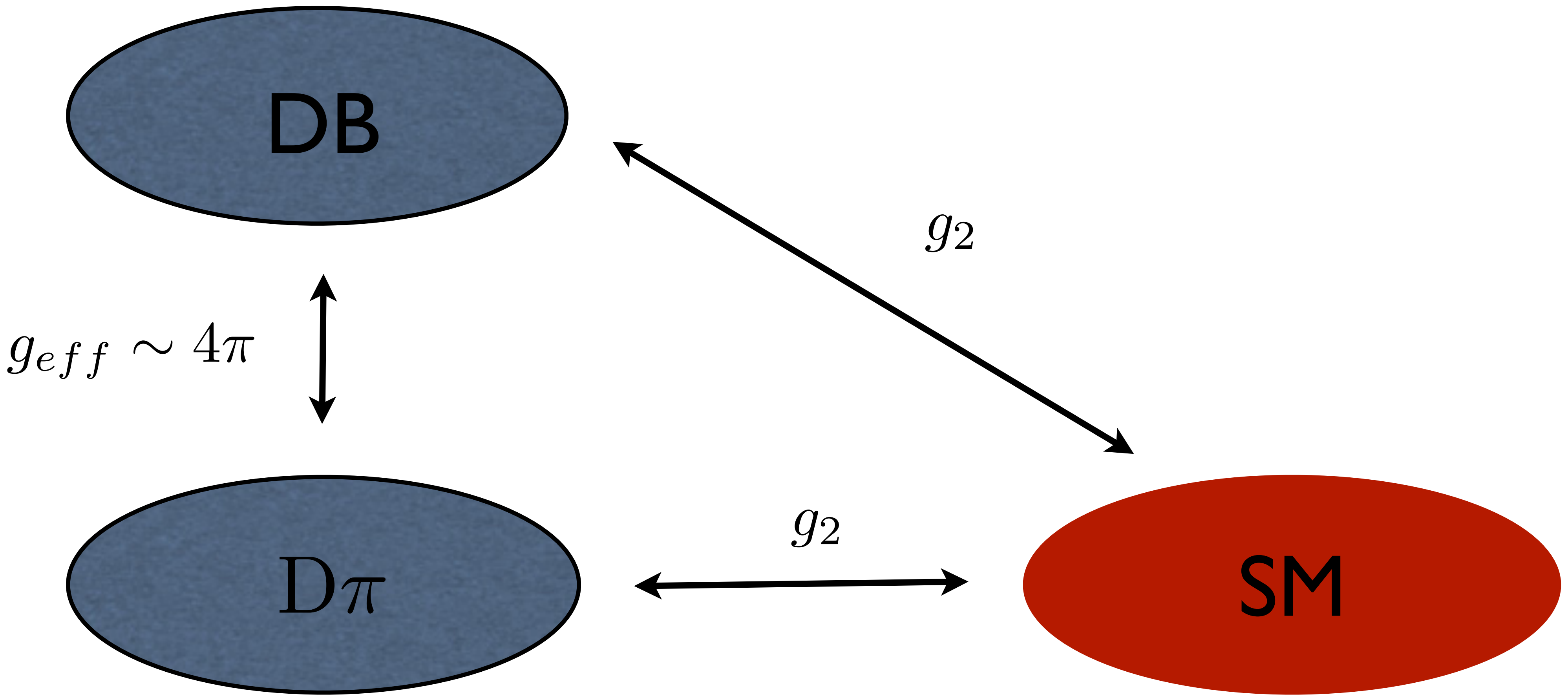
[Antipin, MR, Strumia Vigiani, 2015]

SU(N) classification:

SU(N) techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{\rm TF}=3$			8	$8, \bar{6}, \dots$ for $N=3,4,\dots$	$\mathrm{SU}(3)_{\rm TF}$
$\Psi=V$	0	3	3	$VVV=3$	$\mathrm{SU}(2)_L$
$\Psi=N\oplus L$	1	3, .., 14	unstable	$N^{N*}=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=4$			15	$\overline{20}, 20', \dots$	$\mathrm{SU}(4)_{\rm TF}$
$\Psi=V\oplus N$	0	3	3×3	$VVV, VNN=3,\ VVN=1$	$\mathrm{SU}(2)_L$
$\Psi=N\oplus L\oplus\tilde{E}$	2	3, 4, 5	unstable	$N^{N*}=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=5$			24	$\overline{40}, \overline{50}$	$\mathrm{SU}(5)_{\rm TF}$
$\Psi=V\oplus L$	1	3	unstable	$VVV=3$	$\mathrm{SU}(2)_L$
$\Psi=N\oplus L\oplus\tilde{L}$	2	3	unstable	$NL\tilde{L}=1$	$\mathrm{SU}(2)_L$
=	2	4	unstable	$NNL\tilde{L}, L\tilde{L}L\tilde{L}=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=6$			35	$70, \overline{105'}$	$\mathrm{SU}(6)_{\rm TF}$
$\Psi=V\oplus L\oplus N$	2	3	unstable	$VVV, VNN=3, VVN=1$	$\mathrm{SU}(2)_L$
$\Psi=V\oplus L\oplus\tilde{E}$	2	3	unstable	$VVV=3$	$\mathrm{SU}(2)_L$
$\Psi=N\oplus L\oplus\tilde{L}\oplus\tilde{E}$	3	3	unstable	$NL\tilde{L}, \tilde{L}\tilde{L}\tilde{E}=1$	$\mathrm{SU}(2)_L$
=	3	4	unstable	$NNL\tilde{L}, L\tilde{L}L\tilde{L}, N\tilde{E}\tilde{L}\tilde{L}=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=7$			48	112	$\mathrm{SU}(7)_{\rm TF}$
$\Psi=L\oplus\tilde{L}\oplus E\oplus\tilde{E}\oplus N$	4	3	unstable	$LLE, \tilde{L}\tilde{L}\tilde{E}, L\tilde{L}N, E\tilde{E}N=1$	$\mathrm{SU}(2)_L$
$\Psi=N\oplus L\oplus\tilde{E}\oplus V$	3	3	unstable	$VVV, VNN=3,\ VVN=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=9$			80	240	$\mathrm{SU}(9)_{\rm TF}$
$\Psi=Q\oplus\tilde{D}$	1	3	unstable	$QQ\tilde{D}=1$	$\mathrm{SU}(2)_L$
$N_{\rm TF}=12$			143	572	$\mathrm{SU}(12)_{\rm TF}$
$\Psi=Q\oplus\tilde{D}\oplus\tilde{U}$	2	3	unstable	$QQ\tilde{D}, \tilde{D}\tilde{D}\tilde{U}=1$	$\mathrm{SU}(2)_L$

- SU(N) asymptotically free
- No Landau poles below the Planck scale.
- Lightest dark-baryon with Q=Y=0
- No unwanted stable particles

Thermal abundance:



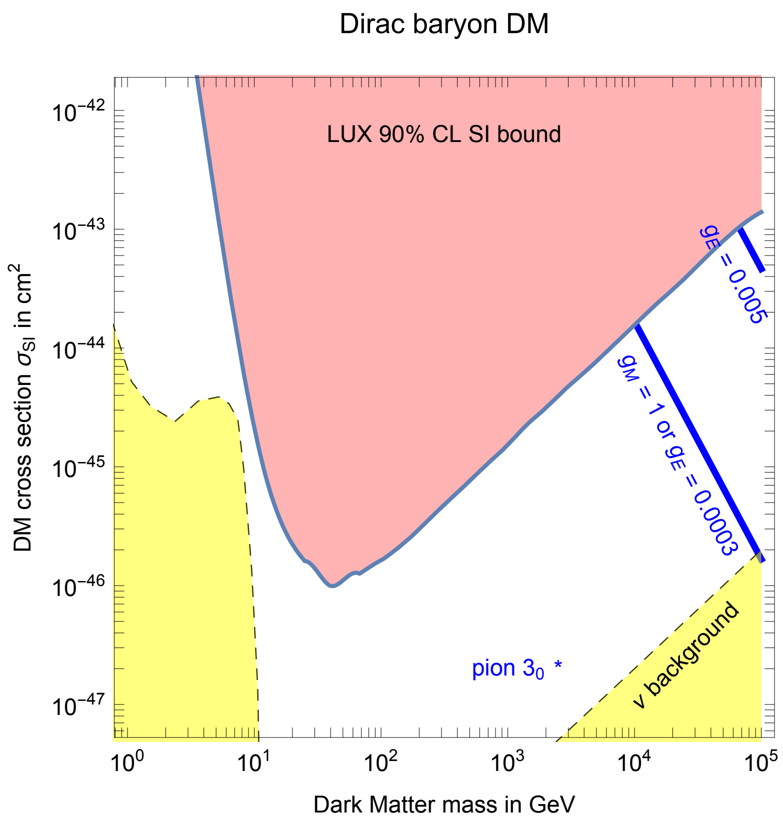
$$\langle \sigma v_{\rm rel} \rangle_{\rm ann} \sim \frac{4\pi}{M_B^2} \longrightarrow m_B \sim 100\,\mathrm{TeV}$$

If DM is asymmetric its mass could be up to 1 TeV.

Detailed predictions depend on the strongly coupled dynamics of SU(N) or SO(N) gauge theories:

- Spectrum of lightest hadrons

- Electric and magnetic dipole moments



- Annihilation cross-section

Determines DM thermal abundance and indirect detection.
Possible non-standard cosmologies.

Light Composite Fermions

[MR, 2008.12291]

Confinement w/out χSB

Previous works assumed QCD-like dynamics where confinement is accompained by chiral symmetry breaking.

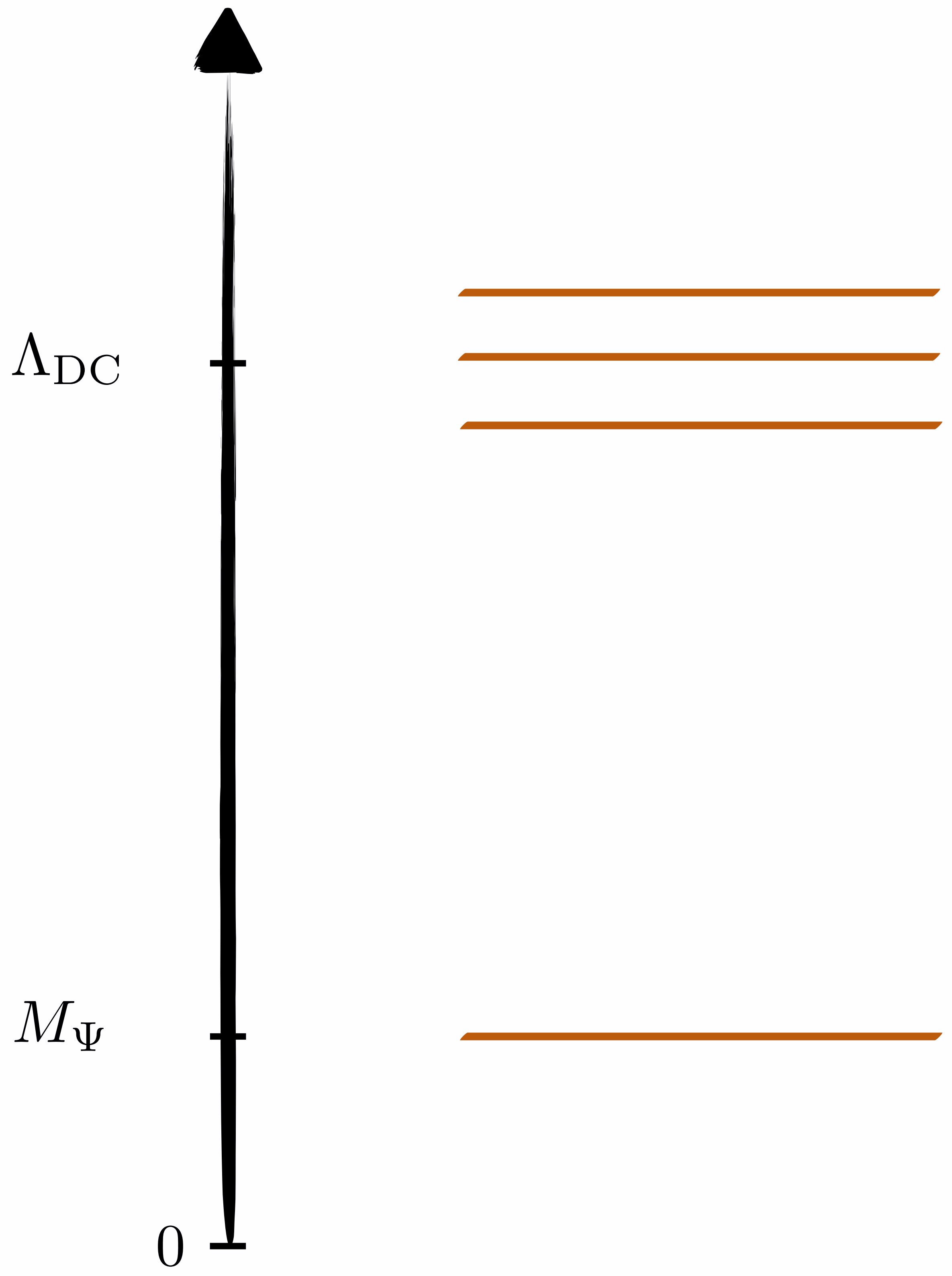
't Hooft argued that theories may confine without chiral symmetry breaking. In this case matching global anomalies requires the existence of massless composite fermions in the chiral limit.

['t Hooft '80]

The lightest composite fermion would be accidentally stable as a consequence of fermion parity.

$$\frac{1}{\tau_{\rm DM}} \sim \frac{M_{\rm DM}\Lambda^4}{8\pi\Lambda_{\rm UV}^4} \sim \frac{10^{-28}}{\rm s}\left(\frac{M_{\rm Pl}}{\Lambda_{\rm UV}}\right)^4\left(\frac{\Lambda}{100\,{\rm TeV}}\right)^4\left(\frac{M_{\rm DM}}{\rm TeV}\right)$$

- Light composite fermions:



Light composite fermions can be excellent DM candidates. As pions they behave as mostly as elementary particles at energies below Λ.
The annihilation x-sec of a composite fermion is the same as in the SM to leading order:

$$\Omega(M_i, \Lambda) = \Omega_{SM}(M_i) + \mathcal{O}\left(\frac{M_i^2}{\Lambda^2}\right)$$

Thermal abundance reproduced in the TeV range.

Compositeness effects are however crucial:

- Singlets interactions depend entirely on compositeness effects.

- Higher dimensional operators control decays of accidentally stable heavier states.

SU(N) + 3 adj

Standard pattern of symmetry breaking:

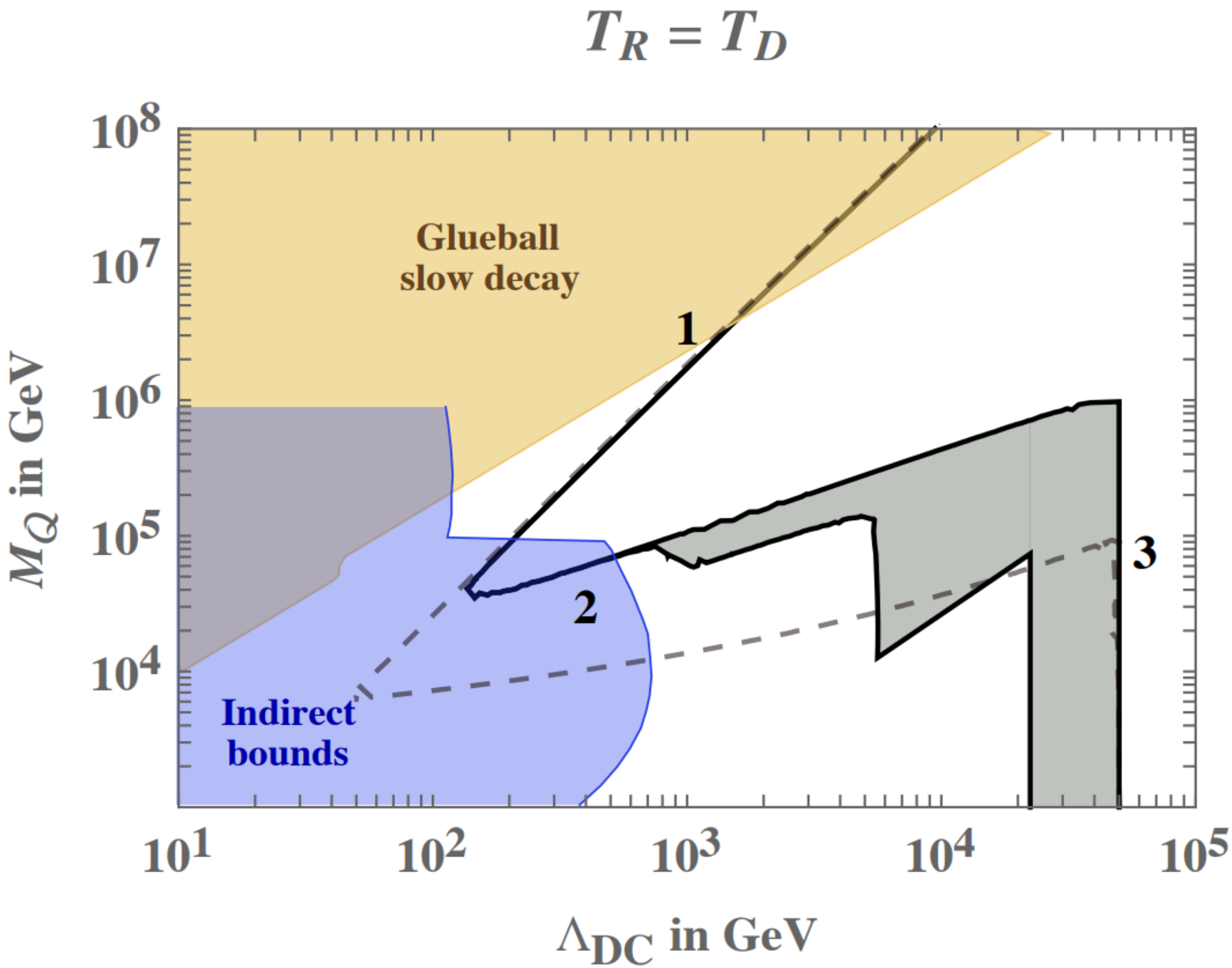
$$\langle V_i^a V_j^a \rangle \propto \delta_{ij} \longrightarrow \frac{SU(3)}{SO(3)} \longrightarrow \text{5 NGB}$$

The lightest fermion is the "gluequark":

$$\Psi_i = V_i^a \sigma^{\mu\nu} G_{\mu\nu}^a \qquad\qquad M_\Psi \sim \Lambda$$

If V is a triplet of SU(2) this realizes a composite "Wino".

[Contino, Mitridate, Podo, MR, 2018]



Complicated strong dynamics: non-perturbative annihilation, re-annihilation after confinement, entropy injection…

DM is typically heavy.

Poppitz and Ryttov (1904.11640) argued that this theory might confine without χSB. Anomalies can be matched by (N^2-1) composite fermions triplets of SU(3).

$$(\lambda_n)_i = \mathrm{Tr}[G_{\mu\alpha_1}\dots G_\nu^{\alpha_n}(\sigma^{\mu\nu})V_i]$$

$$M_n = c_n M_V \qquad\qquad c_n = \mathcal{O}(1)$$

Phenomenology radically different. For SU(3) with 3 adjoints triplets of SU(2) this leads to 8 Wino-like fermions. Compositeness effects allow the heavier states to decay:

$$\frac{\alpha_2\alpha_*}{\Lambda^3}\lambda_3^a\lambda_{3'}^a W_{\mu\nu}^b W^{b\,\mu\nu}$$

$$\frac{1}{\tau_{3'}} \sim \frac{\alpha_2^2\alpha_*^2}{192\pi^3}\frac{M_{3'}^7}{\Lambda^6} \sim \frac{10^{-28}}{\mathrm{s}}\left(\frac{M_{3'}}{\mathrm{TeV}}\right)^7\left(\frac{10^{11}\,\mathrm{GeV}}{\Lambda}\right)^6$$

Diverse and rich pheno:

- $\Lambda > 10^{11}\,\mathrm{GeV}$

All triplets are stable: $$\sum_{i=1}^{8} M_i^2 \approx (3\,\mathrm{TeV})^2 \quad \longrightarrow M_i \sim 1\,\mathrm{TeV}$$

- $10^9\,\mathrm{GeV} \lesssim \Lambda \lesssim 10^{11}\,\mathrm{GeV}$

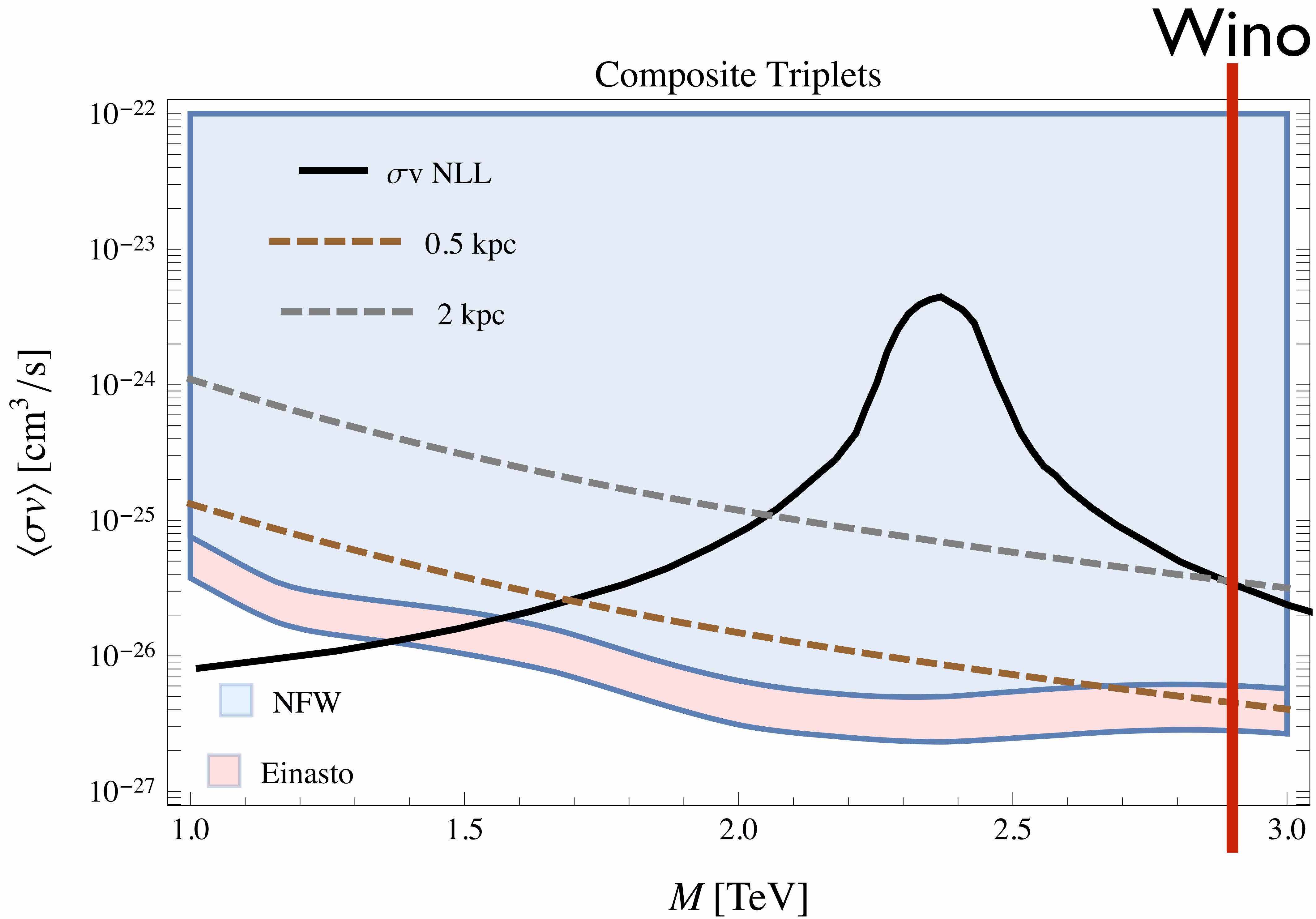
Lifetime longer than age of universe but fraction decays.

- $10^5\,\mathrm{GeV} \lesssim \Lambda \lesssim 10^9\,\mathrm{GeV}$

Heavier states decay after freeze-out modifying abundance. Possible effects for CMB and BBN.

- $\Lambda \lesssim 10^5\,\mathrm{GeV}$

For small splittings heavier states co-annihilate.



For large compositeness scale multiple photon lines.
Triplets around **1 TeV** will be seen at FCC or even HL-LHC.

SO(N) + (N-4) x F + adj

Name	$SO(N)$	$SU(N-4)$	U(1)
F	$\square$	$\square$	$-\frac{N-2}{N-4}$
A	$\substack{\square \\ \square}$	1	1
Ψ	1	$\square\square$	$-\frac{N}{N-4}$

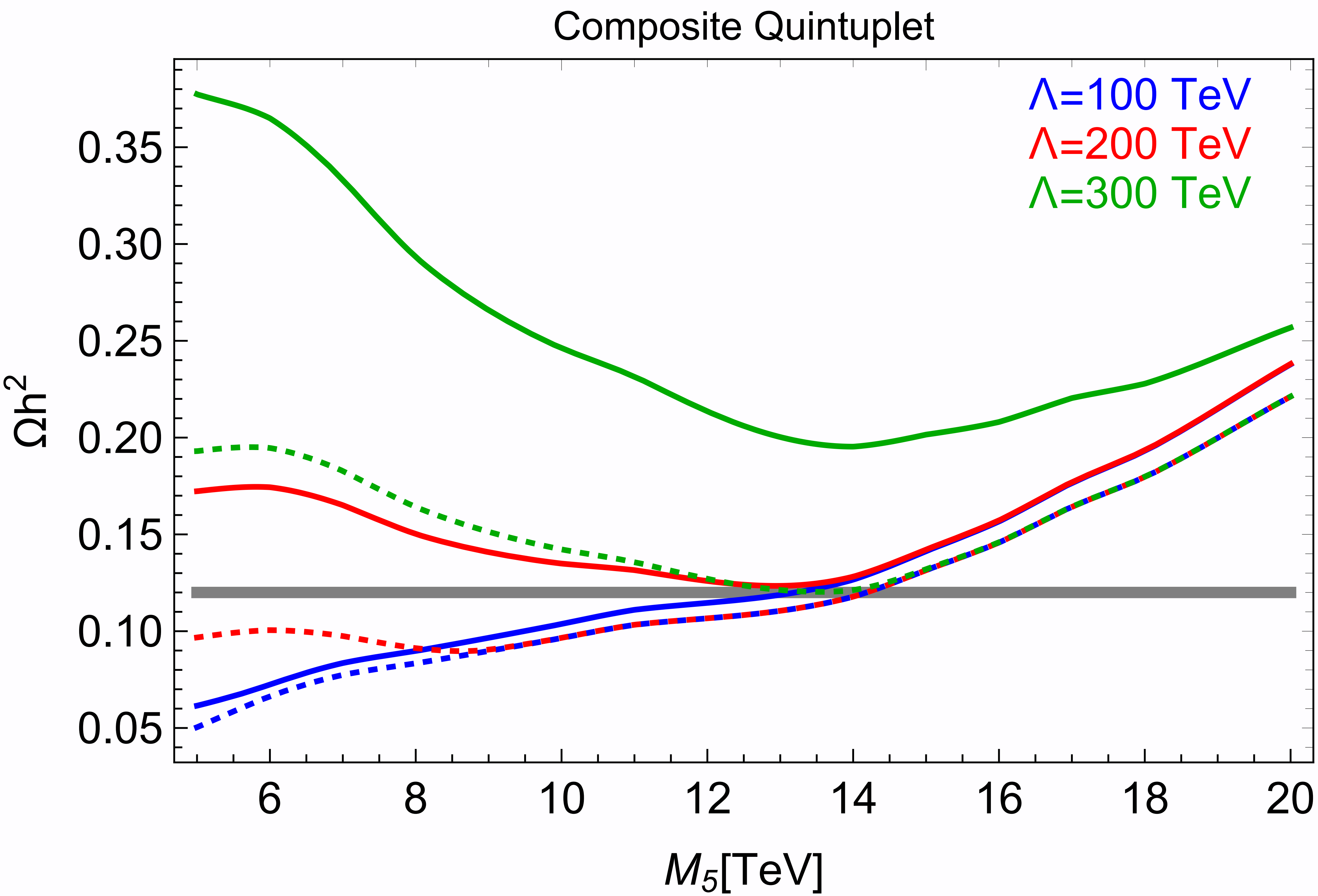
Anomaly free global symmetry SU(N-4) x U(1).
Anomalies can be matched by:

$$\Psi^{ij} = F^i_\alpha A_{\alpha\beta} F^j_\beta$$

$$\mathcal{L}_M = a_1 M_A \mathrm{Tr}[M_F \Psi]^2 + a_2 M_A |\mathrm{Tr} M_F \Psi M_F \Psi| + h.c.$$

• $N_F = 3 \, : V$

$\Psi = 6 = 1 \oplus 5$ $\qquad$ $M_1 - M_5 = a_1 M_A M_V^2$



- $N_F = 5:\ L + \bar{L} + N$

$$-\mathcal{L}_M = M_L L\bar{L} + M_N N^2 + yLHN + \tilde{y}\bar{L}\tilde{H}N$$

$$\Psi = 15 = 2 \times 1_0 \oplus 3_{\pm 1} + 3_0 + 2_{\pm\frac{1}{2}}$$

Composite neutralino system + triplets with hypercharge.
DM is the lightest neutral Majorana fermion.
Phenomenological predictions for direct detection, CP violating effects etc., calculable in terms of $a_{1,2}$,

For $M_N \gg M_L$ the system reduces to $N_F = 4$:

$$\Psi = 10 = 1_0 + 3_0 + 3_{\pm 1}$$

Triplets are almost degenerate with lifetime controlled by the singlet.

SUMMARY

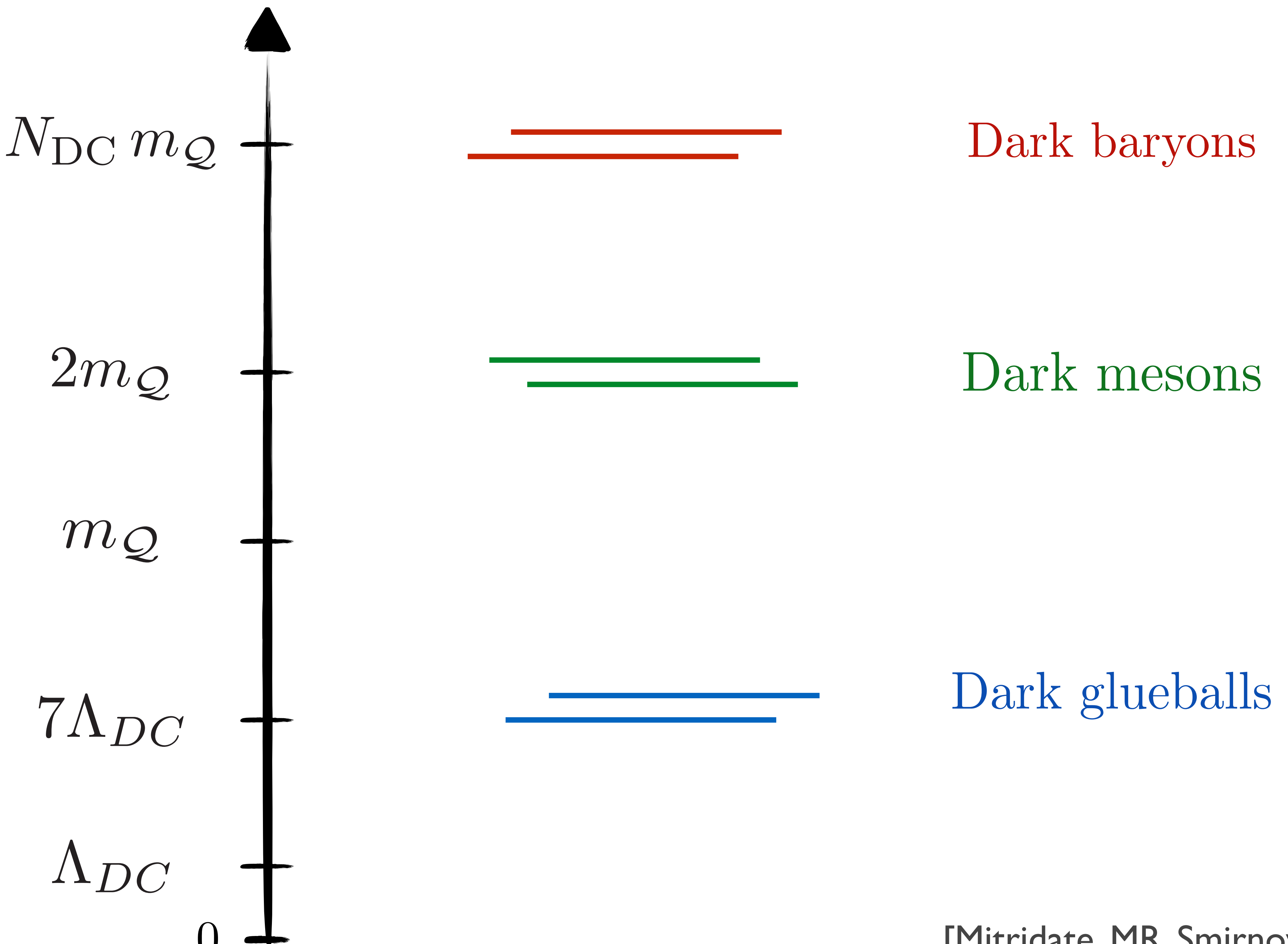
- Stable DM candidates automatically arise if DM is charged under a dark gauge group. Dark baryons are simplest DM candidates. Many models are possible with different phenomenology from WIMPs.

- If confinement takes place w/out χSB the lightest composite fermion is the DM candidate. Phenomenology radically different interpolating between elementary and composite DM. Experimentally accessible.

- Better understanding of strong dynamics is necessary to determine when confinement w/out χSB takes place. Explicit examples can be constructed in SUSY theories. Adding scalars is expected to lead to new classes of theories.

- Heavy Dark Quarks:

$(m_Q > \Lambda_{DC})$



[Mitridate, MR, Smirnov, Strumia, 2017]

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