Istituto Nazionale di Fisica Nucleare

Accidental Dark Matter in Confining Gauge Theories

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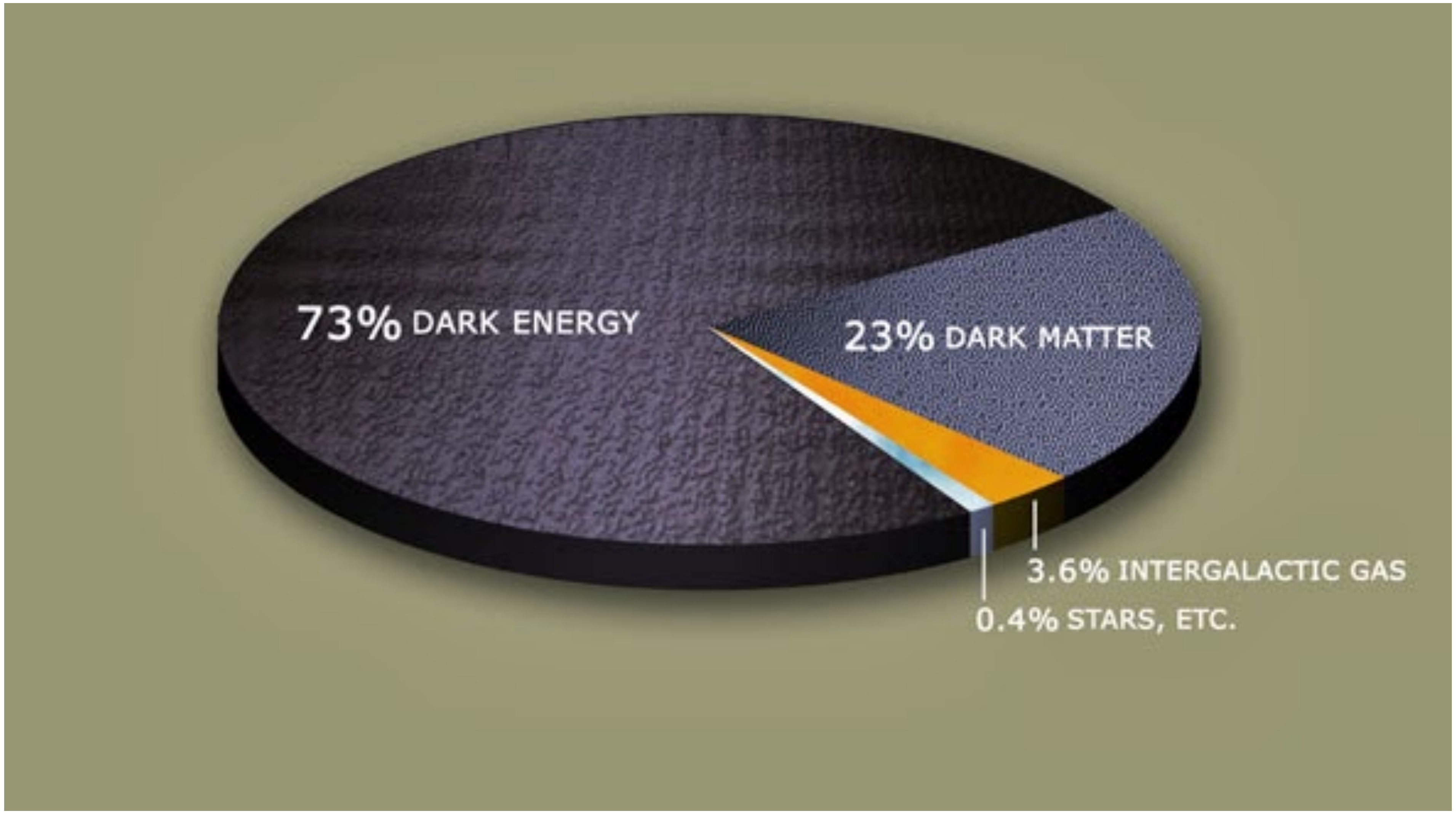
Based on: arxiv 2008.12291

see also 1503.08749 + 1811.06975

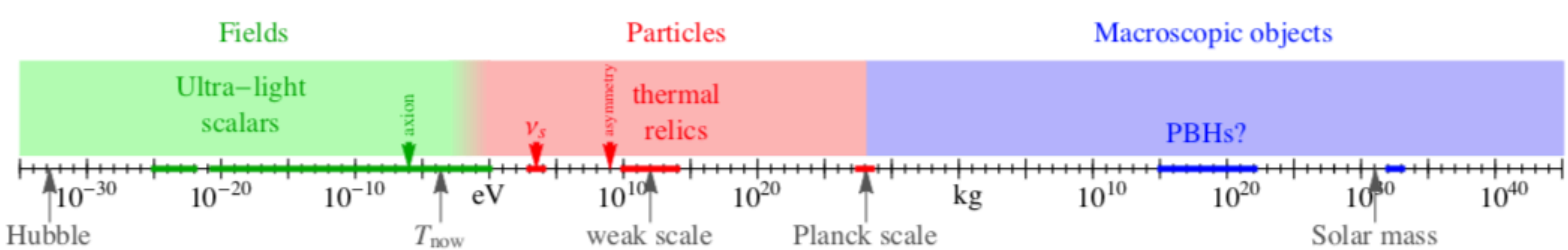
Toronto - November 16, 2020



Rotation curves, structure formation, weak lensing, BBN and CMB measurements agree on the existence of a non-relativistic, non-baryonic and collision-less component of matter.

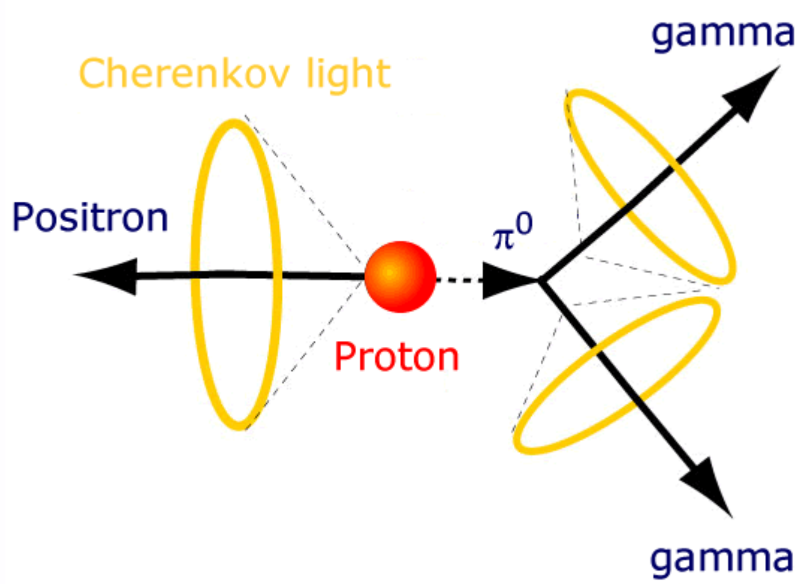
$$\Omega_{\rm DM} = \frac{\rho_{\rm DM}}{\rho_c} \approx 0.25$$

Observations don't give many hints on what DM is:



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:

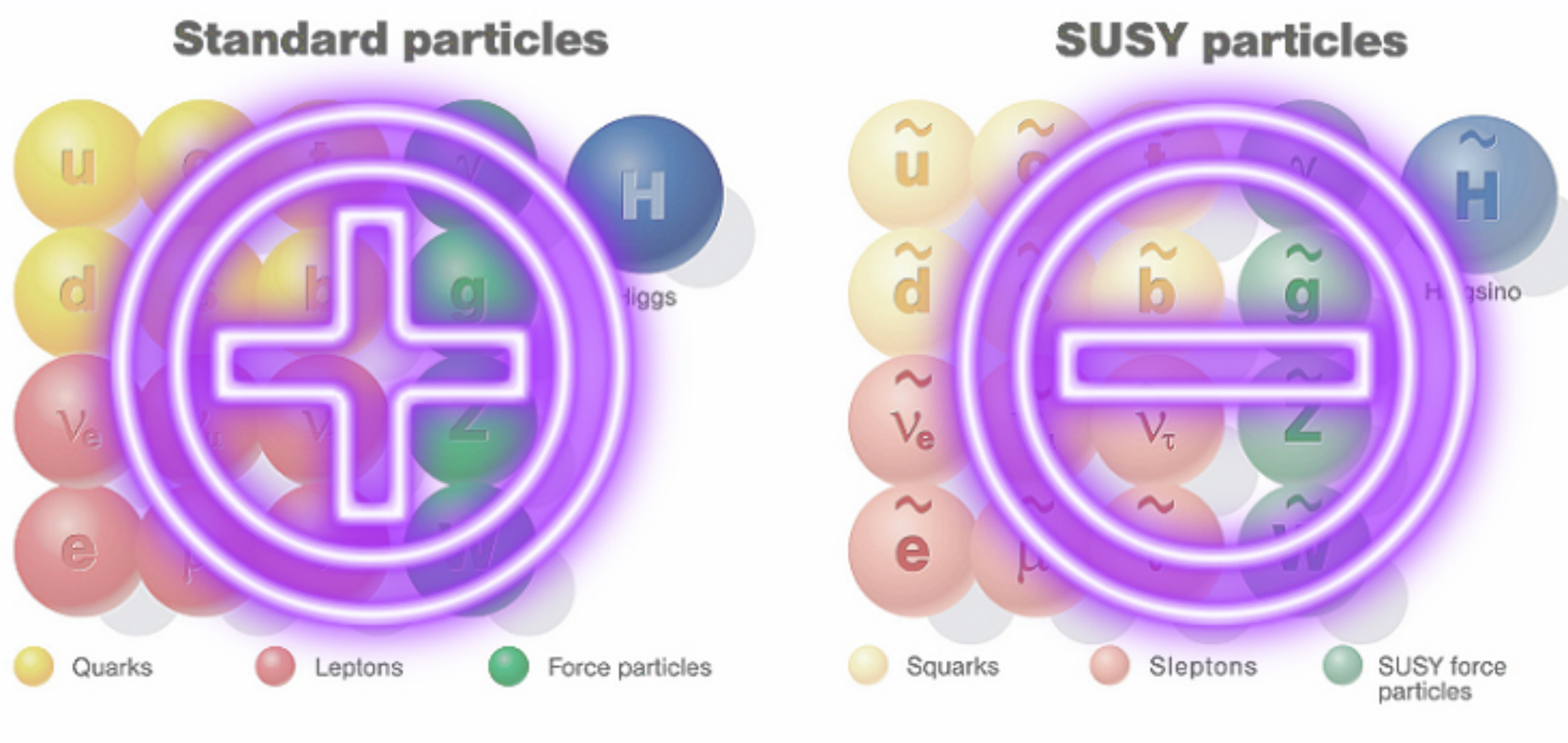
$$U(1)_B \qquad\qquad q \to e^{i\alpha} q$$

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:

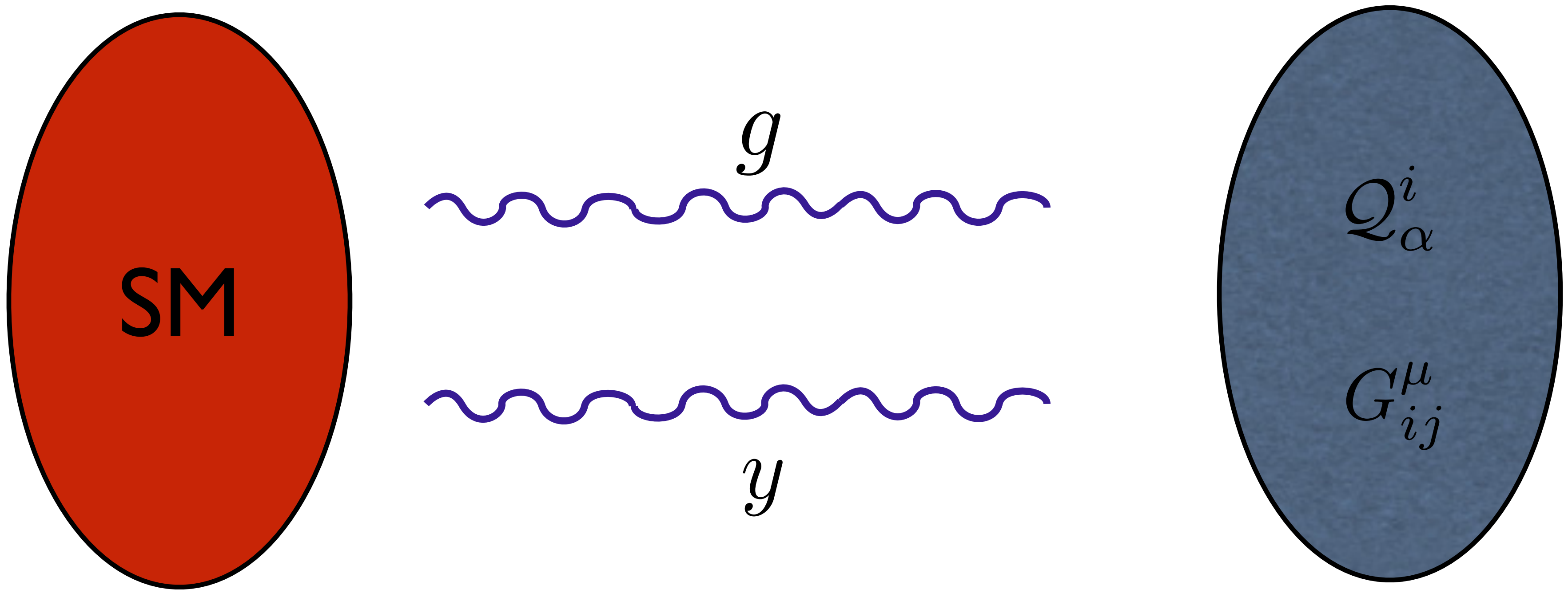
R-parity:



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:

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

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

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.
No asymmetry and weak direct detection constraints.

- Q-adjoint

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

[Contino, Mitridate, Podo, MR, 2018]

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

Strongly coupled dynamics, DM simple.

- Heavy Dark Quarks: $(m_Q > \Lambda_{DC})$

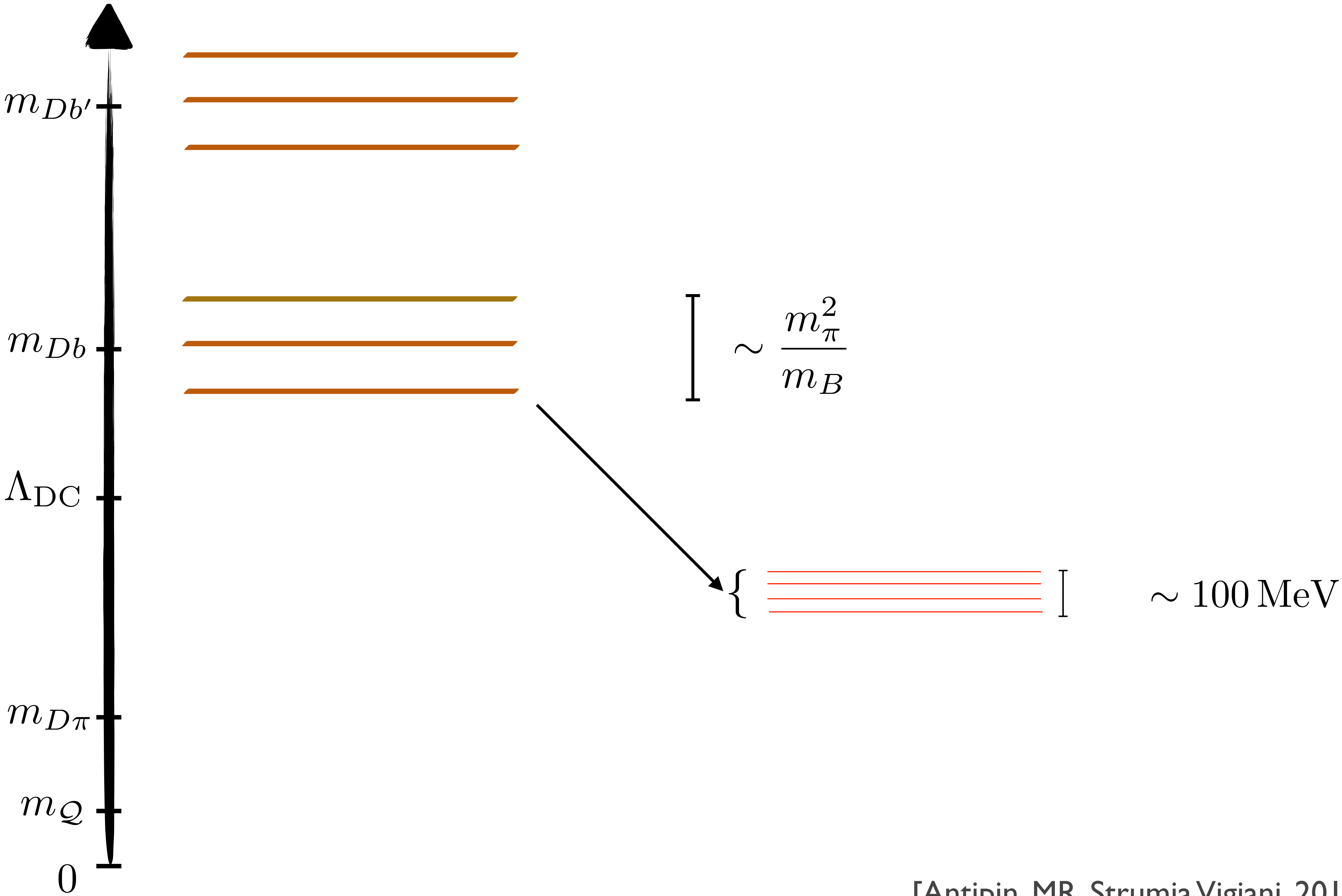
$$\Lambda_{DC} \sim m_Q \exp\left[-\frac{6\pi}{11 C_2(G)\alpha_{DC}(m_Q)}\right] \qquad r_{DC} \sim (\alpha_{DC} m_Q)^{-1}$$

Effective DM coupling is perturbative.
Cosmology non-standard and model dependent:

- $r_{DC} < \Lambda_{DC}^{-1}$ "Coulomb"
- $r_{DC} > \Lambda_{DC}^{-1}$ "Quarkonium"

- Light Dark Quarks:

$$(m_Q < \Lambda_{DC})$$



[Antipin, MR, Strumia Vigiani, 2015]

SU(N)

SU(N) gauge theory with NF light flavors.
Dark-quarks are vectorial with respect to SM.

Fermions	SM	$SU(n)_{\rm TC}$
Ψ_L	$\sum_i r_i$	n
Ψ_R	$\sum_i \bar{r}_i$	$\bar{n}$

$$\sum_i d[r_i] = N_F$$

$$\langle \bar{\Psi}^i \Psi^j \rangle \sim 4\pi f^3 \delta^{ij}$$

Vacuum does not break electro-weak symmetry.

Nambu-Goldstone bosons:

$$\frac{SU(N_F)\times SU(N_F)}{SU(N_F)}$$

$$\mathrm{Adj}_{SU(N_F)} = \sum_{i=1}^{K} r_i \times \sum_{i=1}^{K} \bar{r}_i - 1$$

● Dark-Pions

Stable pions behave as elementary minimal dark matter candidates.

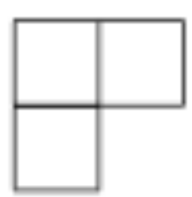
Strumia, Cirelli '05

$$M_{I=1} \approx 3\,\mathrm{TeV} \qquad \sigma_{SI} = 0.12 \pm 0.03 \times 10^{-46}\,\mathrm{cm}^2$$

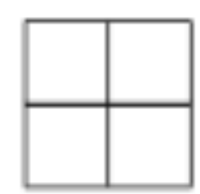
● Dark-Baryons

Lightest multiplet has minimum spin. Flavor rep:

$N_{DC} = 3$



$N_{DC} = 4$



DM candidate:

$$Q_{DB} = T^3_{DB} + Y_{DB} = 0$$

$$Y_{DB} = 0$$

⇒ I=0,1,2,...

(see however 1503.04203)

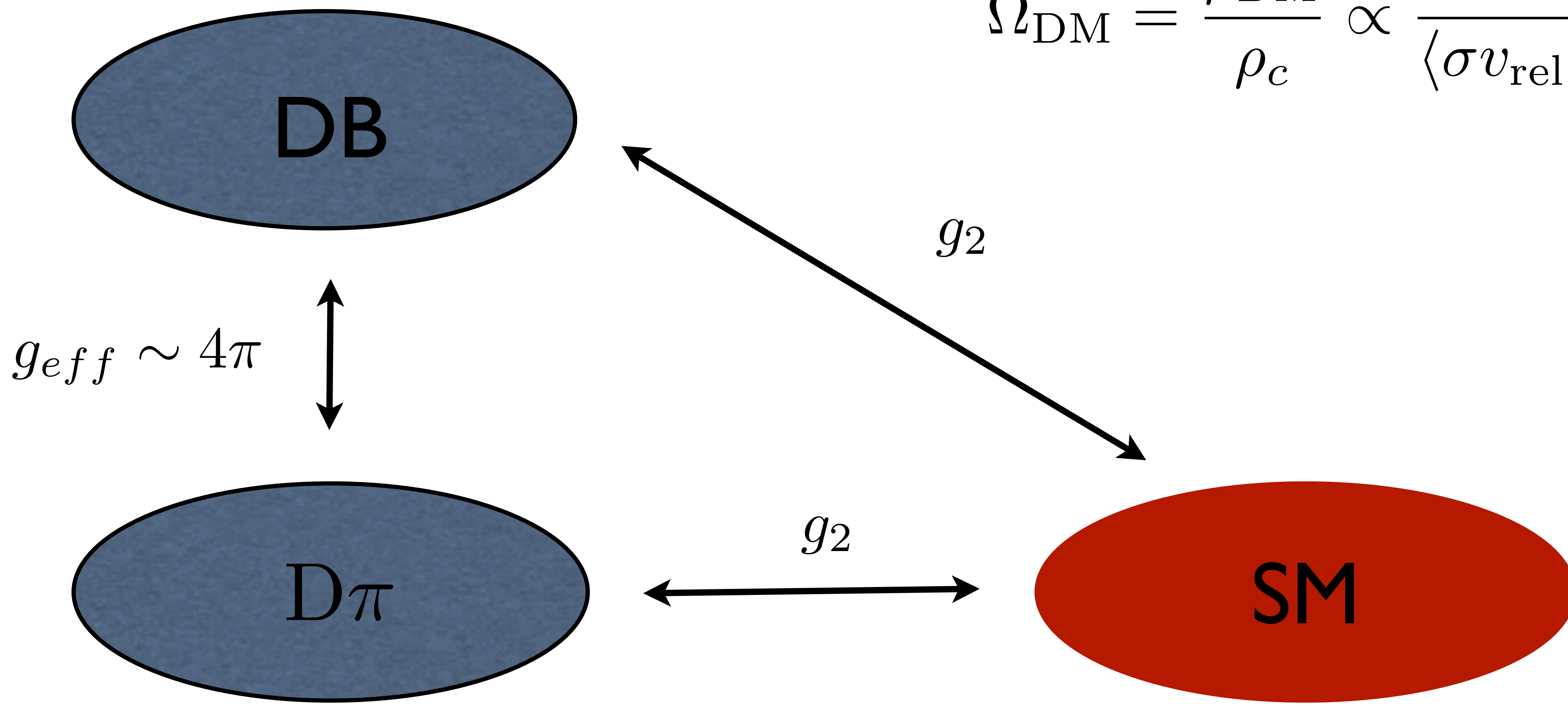
SU(N) classification:

SU(N) techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{\rm TF} = 3$			8	$8, \bar{6}, \ldots$ for $N = 3, 4, \ldots$	$\mathrm{SU}(3)_{\rm TF}$
$\Psi = V$	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	$\overline{20}, 20', \ldots$	$\mathrm{SU}(4)_{\rm TF}$
$\Psi = V \oplus N$	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

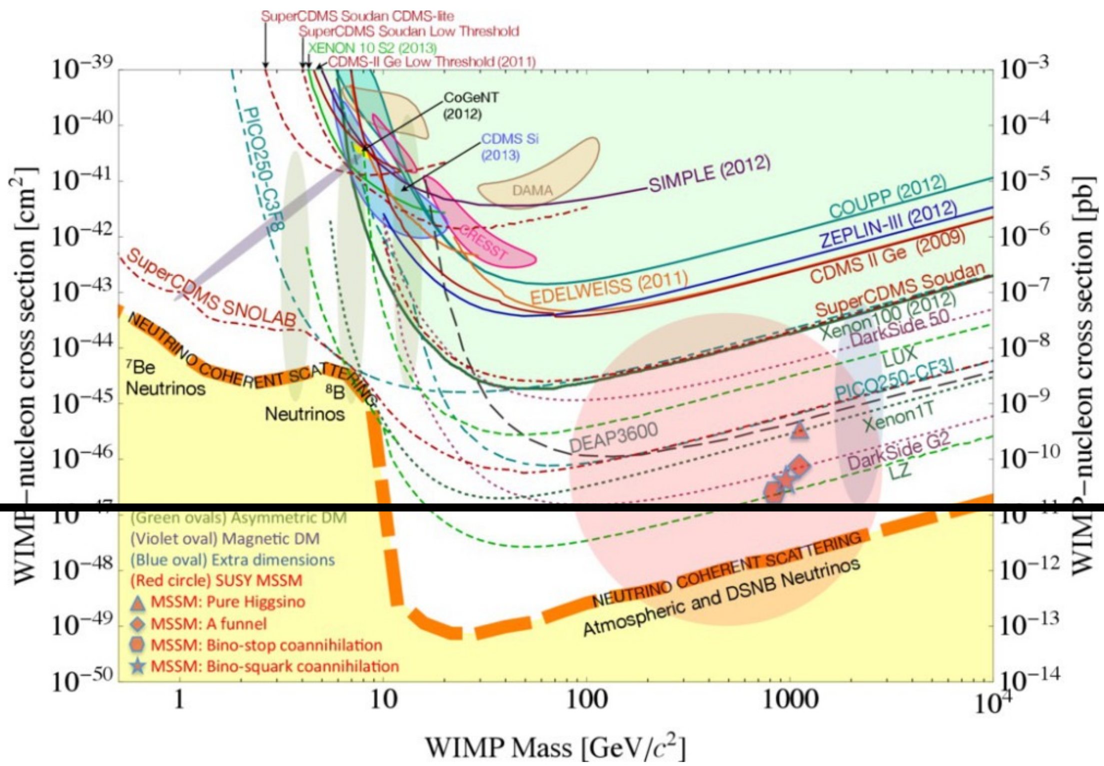
Thermal abundance:

$$\Omega_{\rm DM} = \frac{\rho_{\rm DM}}{\rho_c} \propto \frac{1}{\langle \sigma v_{\rm rel} \rangle_{\rm ann}}$$



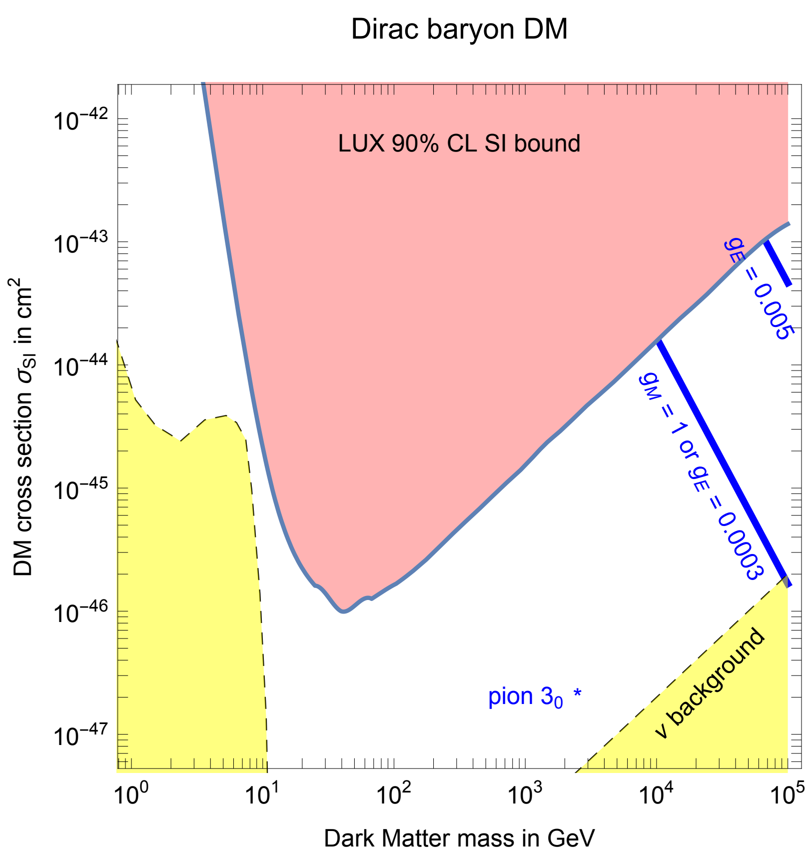
$$\langle \sigma v_{\rm rel} \rangle_{\rm ann} \sim \frac{4\pi}{M_B^2} \longrightarrow M_B \sim 100\,{\rm TeV}$$

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



$$\sigma^3_{SI} = 0.12 \times 10^{-46}\,\mathrm{cm}^2$$

Weak direct detection constraints unless there are Yukawa couplings. Interesting dipoles:

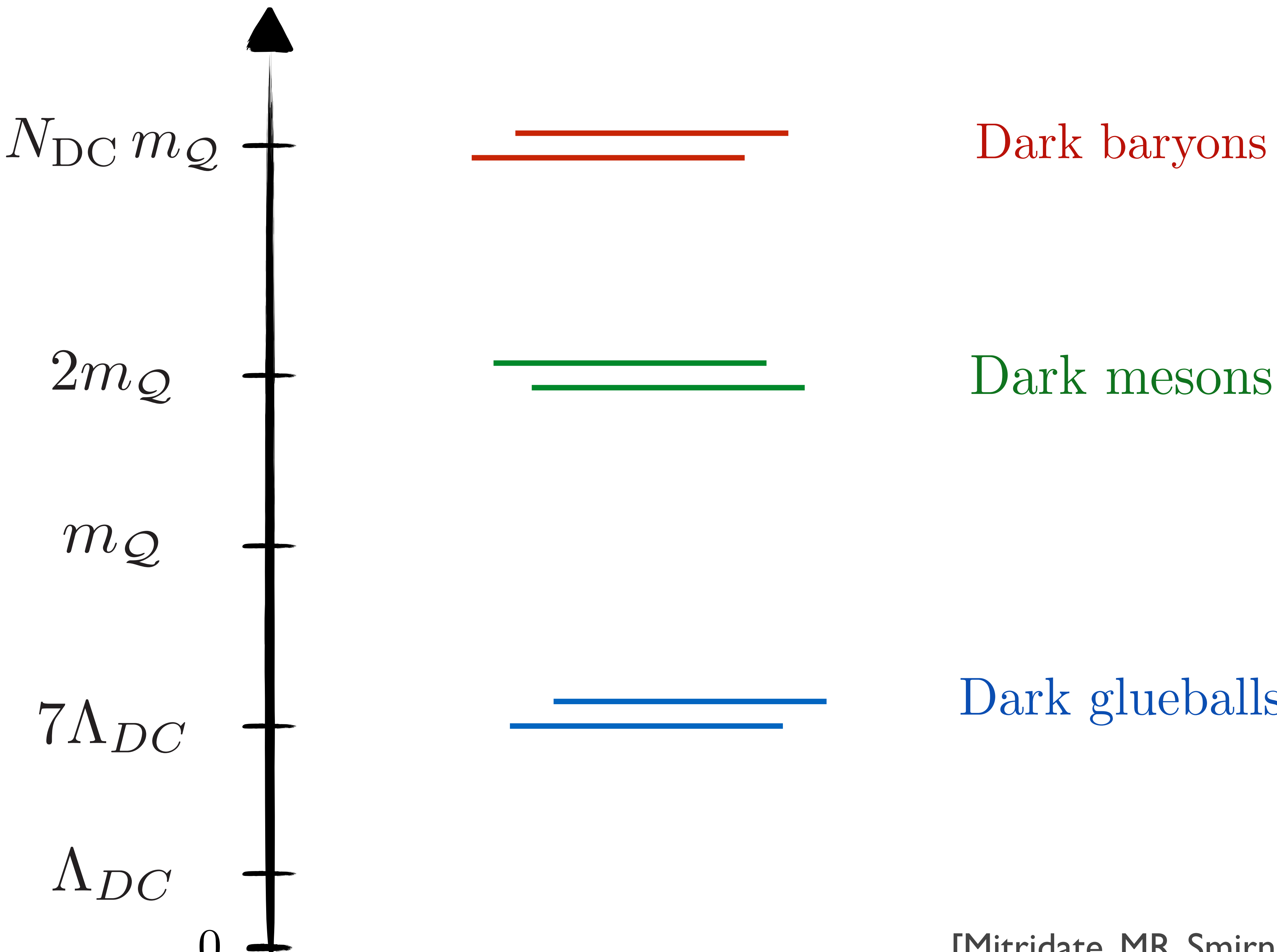


$$\frac{d\sigma}{dE_R} \approx \frac{e^2 Z^2}{16\pi\, m_B^2\, E_R}\left(g_M^2 + \frac{g_E^2}{v^2}\right)$$

$$g_M = \mathcal{O}(1) \qquad g_E \sim \frac{e\,\theta_{\mathrm{TC}}\min[m_Q]}{M_{\mathrm{DM}}}$$

- Heavy Dark Quarks:

$(m_Q > \Lambda_{DC})$



[Mitridate, MR, Smirnov, Strumia, 2017]
[Contino, Mitridate, Podo, MR, 2018]

Non standard cosmological histories:

- $\Lambda_{DC} < \frac{m_Q}{25}$

Dark quarks freeze-out in the perturbative regime. A fraction recombines into baryons after dark confinement.

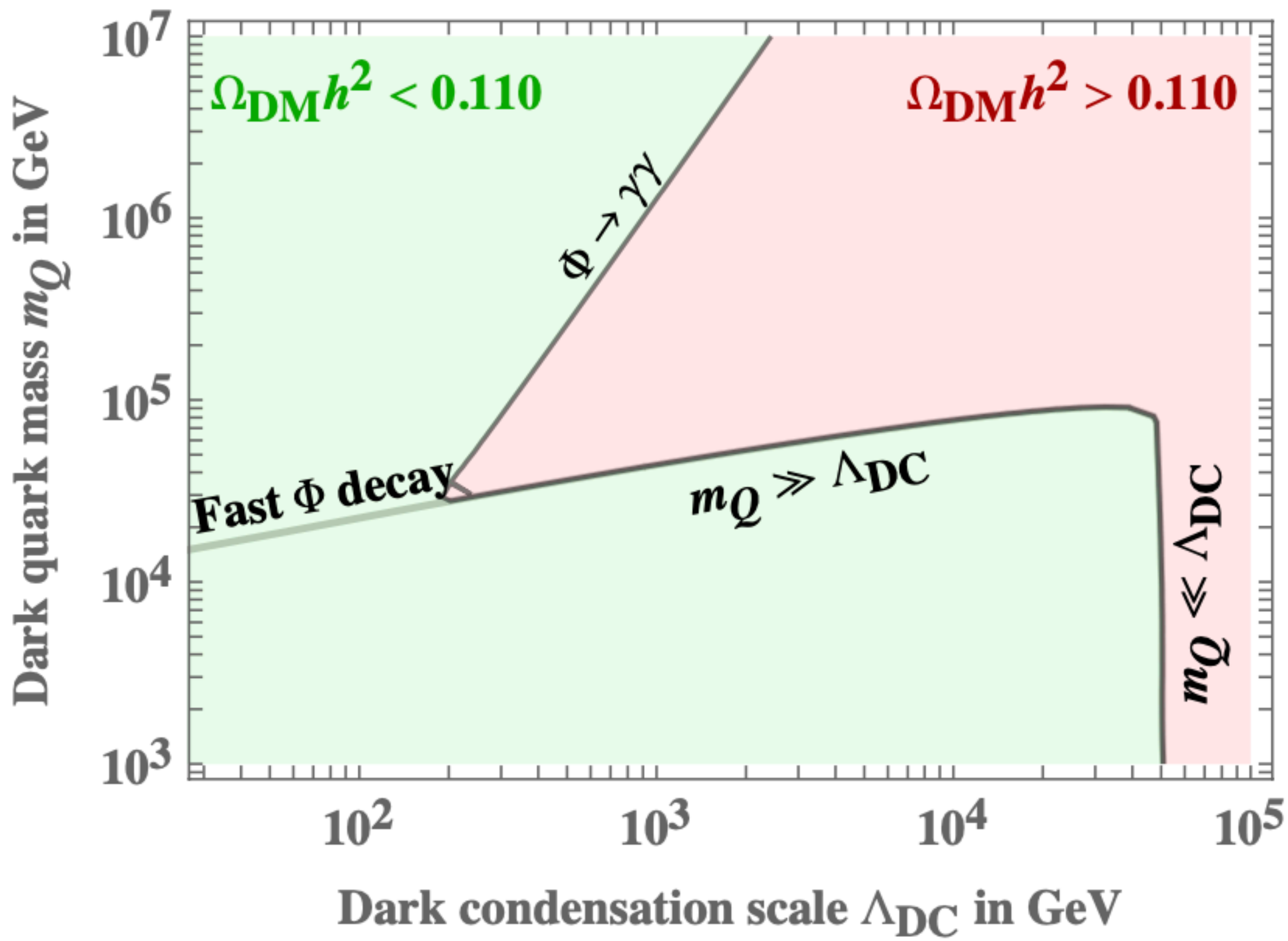
$$\Omega_{DM} = p_B \Omega_{Q+\bar{Q}} \qquad\qquad p_B = \mathcal{O}(1)$$

At temperatures below confinement baryons can re-annihilate reducing the abundance

$$\sigma_{B\bar{B}} v_{\rm rel} \sim \frac{1}{\alpha_{DC}} \frac{\pi}{m_Q^2} \qquad \text{or} \qquad \sigma_{B\bar{B}} \sim \frac{1}{\Lambda_{\rm DC}^2}$$

Late time decays of glueballs further dilute abundance.

[Mitridate, MR, Smirnov, Strumia, 2017]



In the non-relativistic regime thermal abundance of DM can be obtained for masses ~10 TeV.

Light Composite Fermions

[MR, 2008.12291 + work in progress]

Confinement w/out χSB

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

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

['t Hooft '80]

Recently new anomaly matching condition from gauging of higher form symmetries have also been discovered.

[Gaiotto et al. '14]

We will consider theories where composite fermions can acquire a small mass due to explicit breaking of global symmetries.

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

It decays through higher dimension operators to SM:

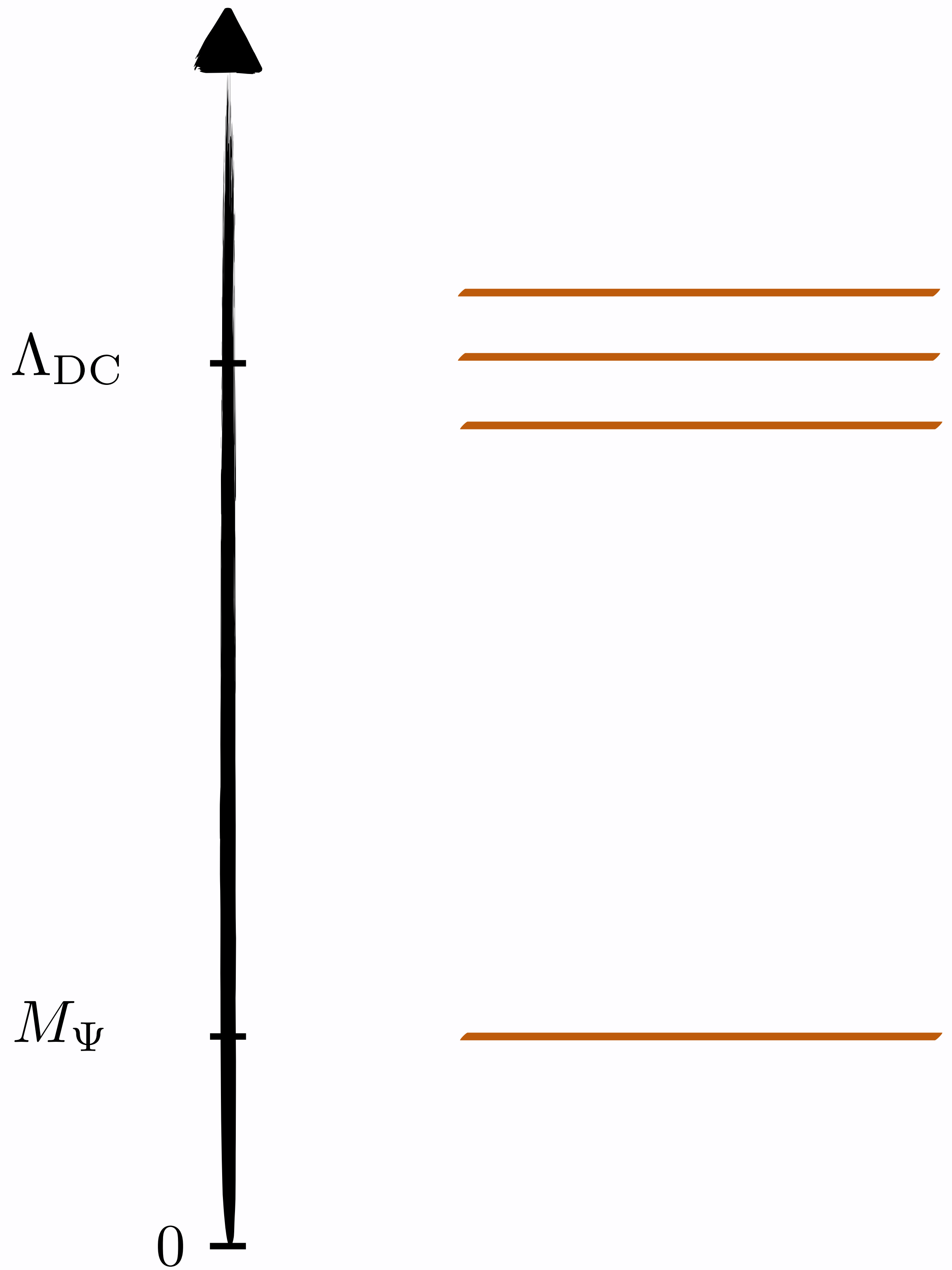
$$\frac{1}{\Lambda_{\rm UV}^{d_1+d_2-4}}\mathcal{O}_{DM}^{d_1}\mathcal{O}_{SM}^{d_2}$$

Ex: $\mathrm{d}_1 + d_2 = 6$

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

Lifetime enhanced by $\Lambda/M_{\rm DM}$ compared to baryons.

- Confinement w/out χSB:



Light composite fermions are excellent DM candidates.

As pions they behave 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:

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

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:

$$\langle V^{ai} V^{aj} \rangle \propto \delta^{ij} \longrightarrow \frac{SU(3)}{SO(3)} \longrightarrow \text{5 NGB}$$

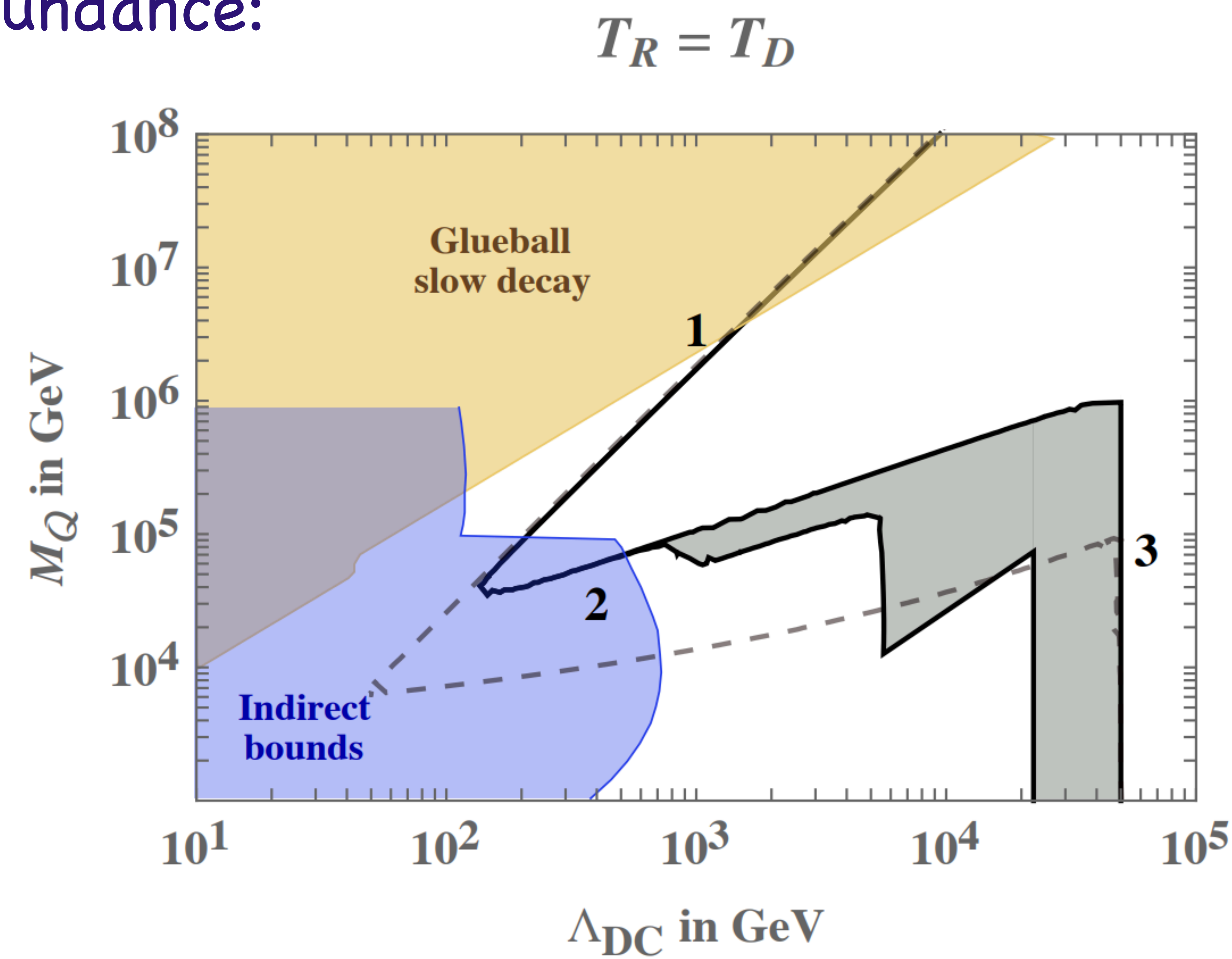
The lightest fermion is the "gluequark":

$$\Psi^i = V^{ai} \sigma^{\mu\nu} G^a_{\mu\nu} \qquad\qquad M_\Psi \sim \text{Max}[\Lambda, M_V]$$

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

[Contino, Mitridate, Podo, MR, 2018]

Abundance:



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

DM is typically heavy.

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

$$\lambda_n^i = \mathrm{Tr}[G_{\mu\alpha_1}\ldots G_\nu^{\alpha_n}(\sigma^{\mu\nu})V^i]$$

$$\delta L = -M_V V^{ai}V^{ai} + h.c. \longrightarrow \qquad M_n = c_n M_V$$

Radically different phenomenology: 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:

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

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

Diverse and rich pheno:

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

All triplets are stable:

$$\langle \sigma v_{\rm rel} \rangle_{eff} \approx \sum_{i=1}^{8} \frac{\pi \alpha_2^2}{M_i^2}$$

$$\sum_{i=1}^{8} M_i^2 \approx (3\,\mathrm{TeV})^2 \longrightarrow M_i \sim 1\,\mathrm{TeV}$$

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

Lifetime longer than age of universe but fraction decays.

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

Heavier states decay after freeze-out modifying abundance:

$$M_1 \sum_{i=1}^{8} M_i \approx (3\,\text{TeV})^2$$

Possible effects from energy injection at CMB and BBN.

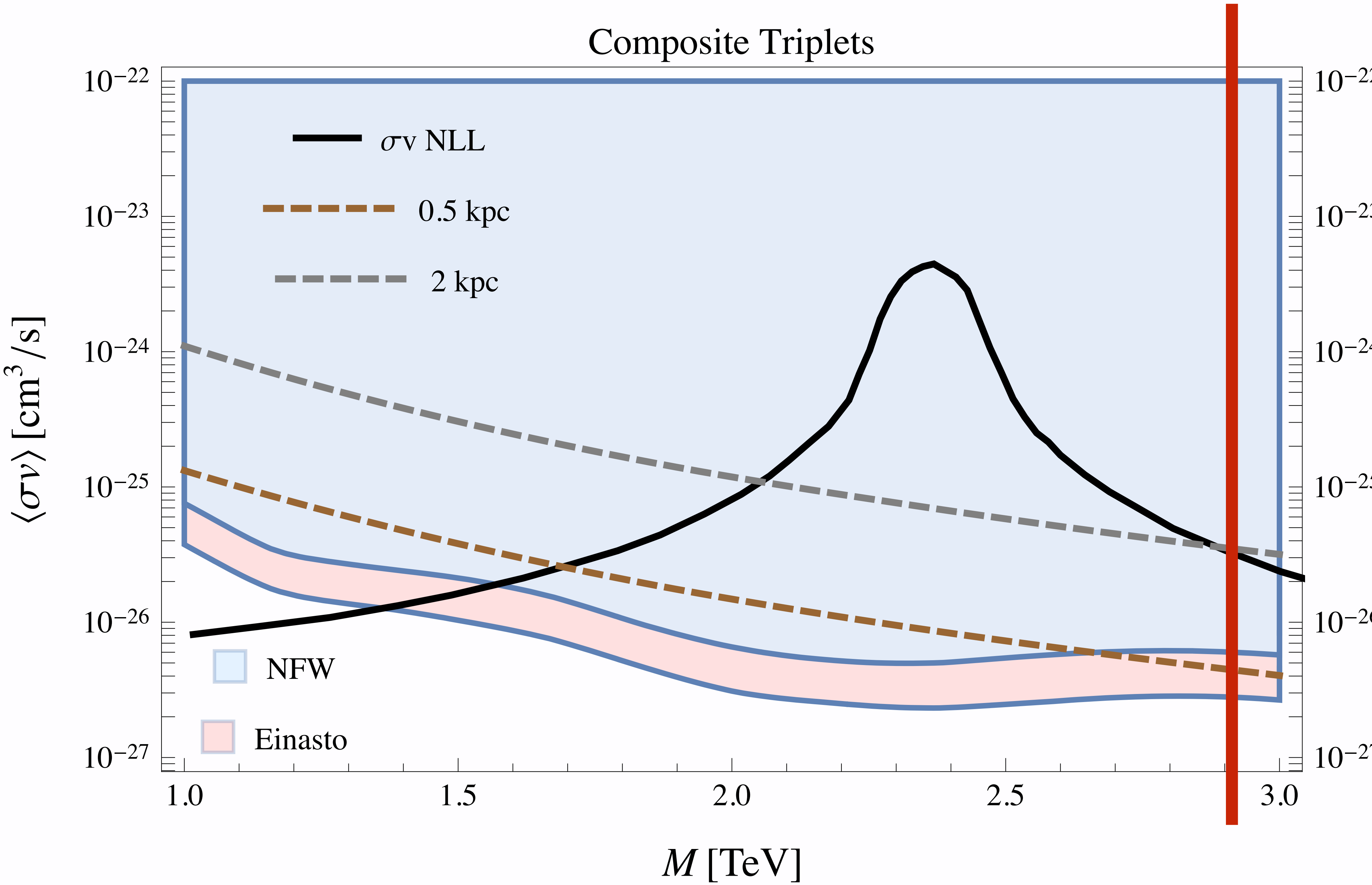
- $\Lambda \lesssim 10^5\,\text{GeV}$

For small splittings heavier states co-annihilate.

$$1\,\text{TeV} < M_1 < 3\,\text{TeV}$$

Indirect Detection:

Wino



For large compositeness scale multiple photon lines **@ 1 TeV.**
Composite triplets will be seen at FCC or even HL-LHC!

SO(N) + (N-4) x F + 1 adj

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

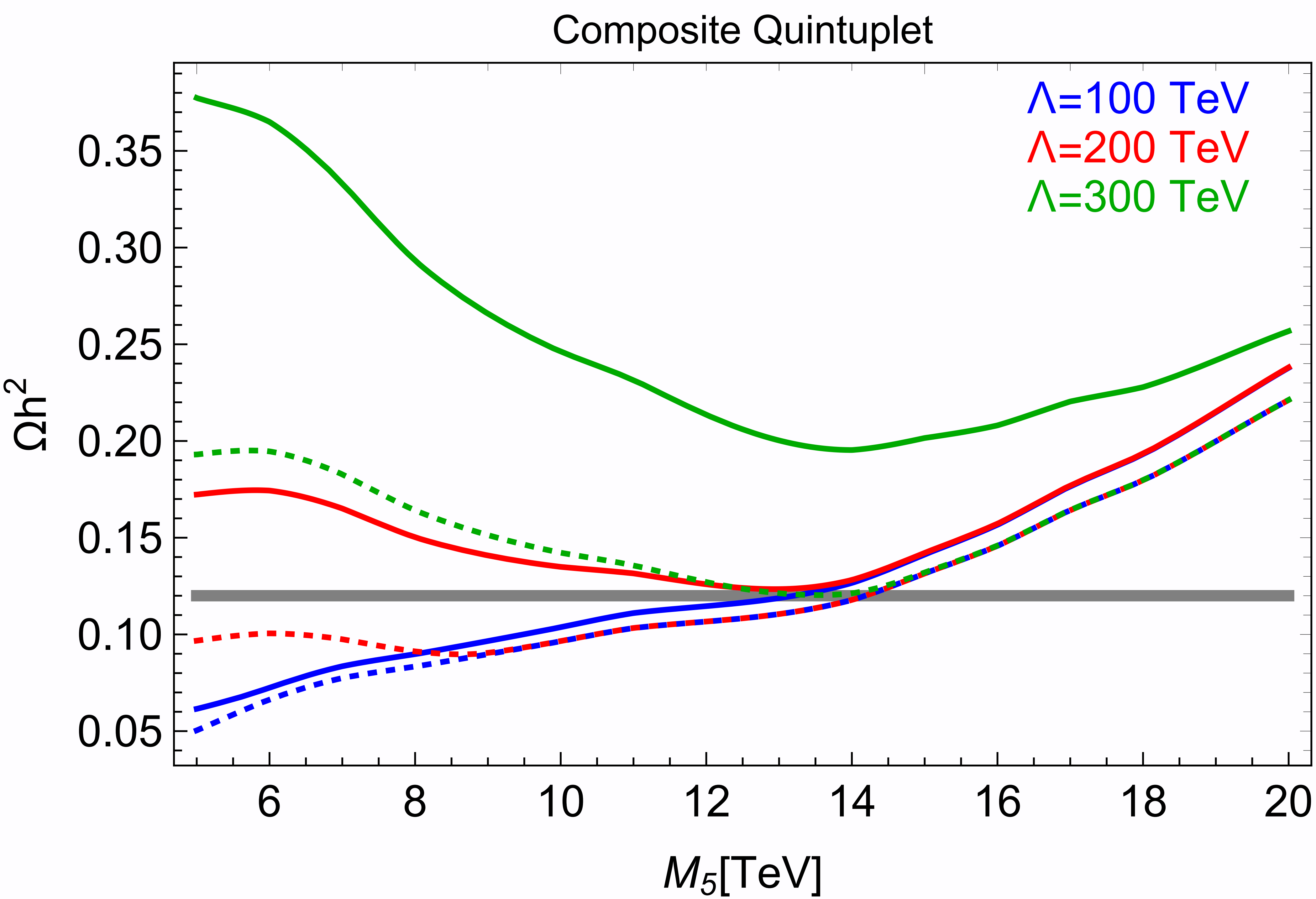
Anomaly free global symmetry SU(N-4) x U(1).
Anomalies can be matched by:

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

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

- $N_F = 3\ : V$

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



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

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

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

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.

SUSY example

Canonical example of confinement without χSB exist in SUSY gauge theories:

Ex: SU(N) $\quad N_F = N + 1 \quad$ [Seiberg 90's]

Name	$SU(N)$	$SU_L(N+1)$	$SU_R(N+1)$	$U(1)_B$	$U(1)_R$
Q	$\square$	$\square$	1	1	$\frac{1}{N+1}$
$\tilde{Q}$	$\overline{\square}$	1	-1	$\overline{\square}$	$\frac{1}{N+1}$
q	1	$\overline{\square}$	1	N	$\frac{N}{N+1}$
$\tilde{q}$	1	1	$\square$	-N	$\frac{N}{N+1}$
M	1	$\square$	$\overline{\square}$	0	$\frac{2}{N+1}$

$$q^i \sim \epsilon^{ij_1\dots j_n} Q^{j_1} \dots Q^{j_n} \qquad M^{ij} \sim Q^i \tilde{Q}^j$$

This theory breaks spontaneously supersymmetry when SUSY masses are included. This can be established studying the low energy magnetic dual theory:

[Intriligator-Seiberg-Shih, '06]

$$W = \lambda q M \tilde{q} + \Lambda \mathrm{Tr}[mM]$$

Degenerate masses:

$$M_{ij} = 0 \qquad\qquad q_i = \tilde{q}_i = \sqrt{\frac{m\Lambda}{\lambda}}\delta_{i1}$$

Massless particles:

NGB: $SU(N_F) \to SU(N_F - 1)$

Fermions: $\tilde{M}_{ab}$ $\quad a, b > 1$

Goldstino: $q - \tilde{q}$

Upon breaking explicitly SUSY composite fermions and NGBs acquire mass and can realize composite DM.

EX:V+N

NGB: $3+3+1$

Fermions: $V \times V = 1+3+5$

The existence of scalars can be dangerous for cosmological stability:

$$\frac{1}{\Lambda_{UV}} \tilde{V}^i N L \sigma^i H$$

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 and novel signatures.

- Better understanding of strong dynamics is necessary to determine when confinement w/out χSB takes place. Adding scalars is expected to lead to new classes of theories.