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Istituto Nazionale
di Fisica Nucleare

# Strong dynamics beyond the hierarchy problem

Michele Redi

Based on: arxiv 1503.08749 +1707.05380
with Antipin, Mitridate, Smirnov, Strumia, Vigiani

ECT-Trento - September 14, 2017

# Baryonic Dark Matter

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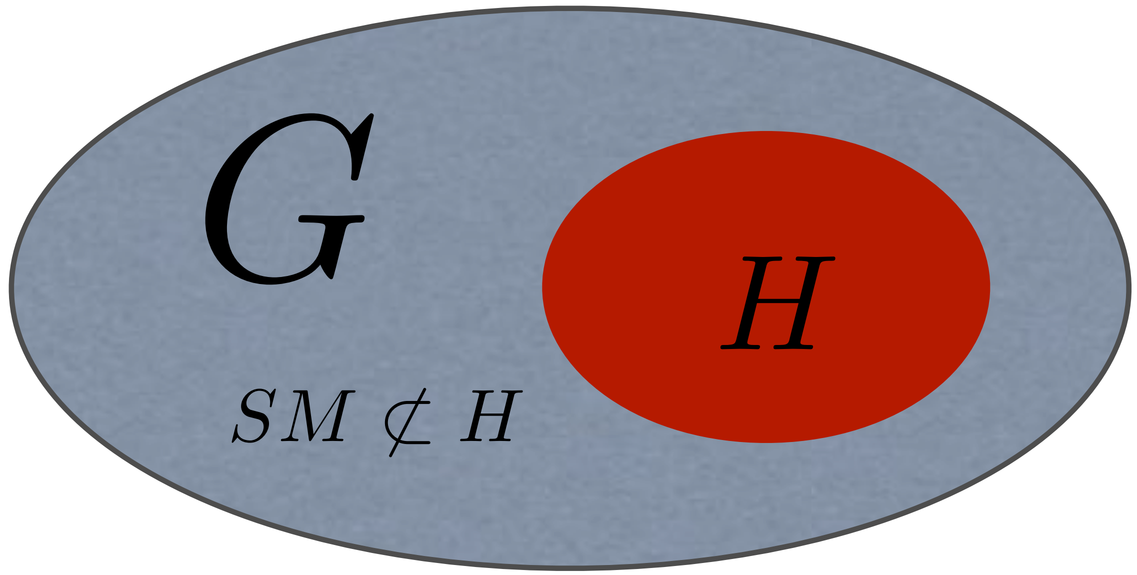
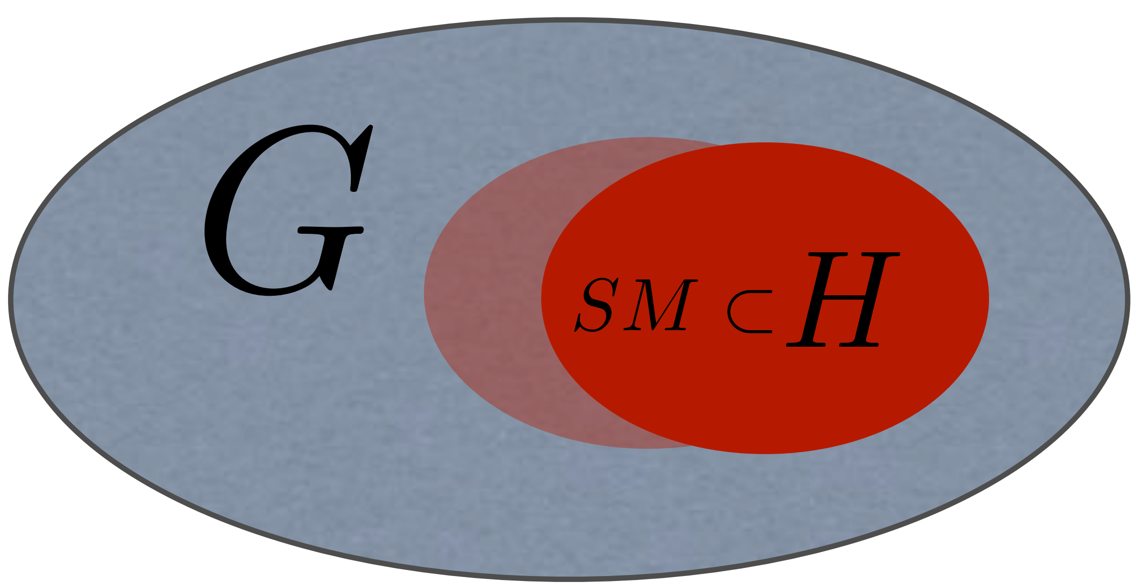
- Technicolor




$f = v$


- Composite Higgs




$f > v$

Higgs is a pseudo-Goldstone boson. Electro-weak scale determined by vacuum alignment.

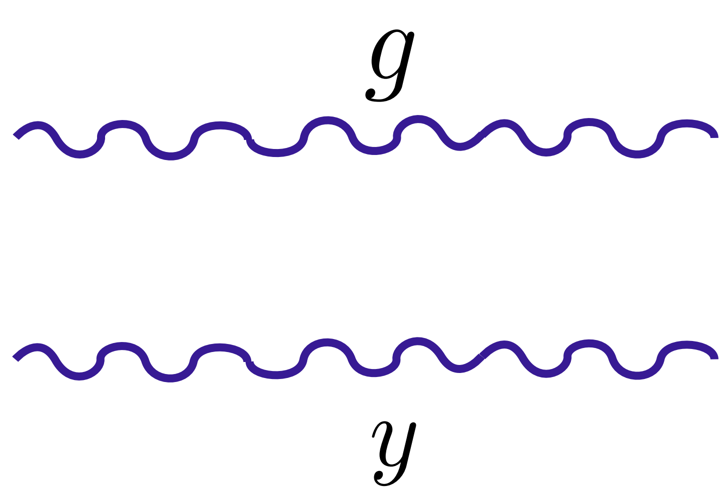
$$\text{DEVIATION SM} \sim \text{TUNING} \sim \frac{v^2}{f^2}$$

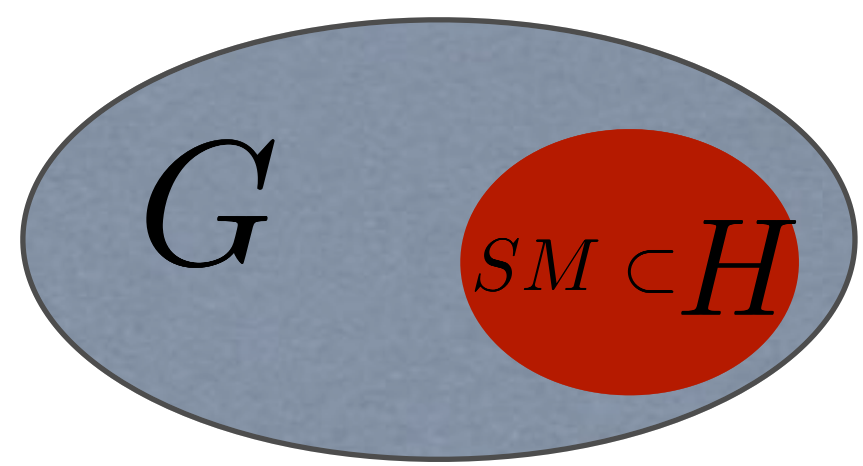
1984-?

- **SM preserving strong dynamics:**

see Contino's talk

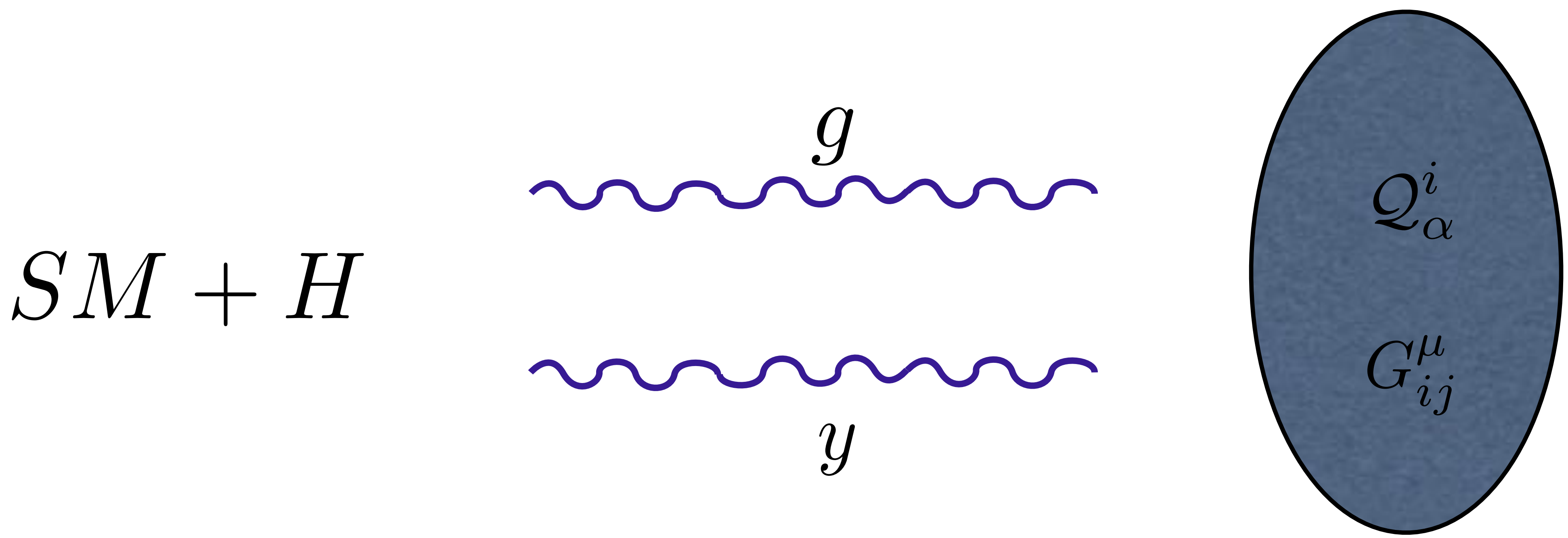
$$SM + H$$




Higgs is elementary.

## Confining gauge theory with fermions vectorial under SM




$$Q = (N_{\rm DC}, SM) + (\overline{N}_{\rm DC}, \overline{SM})$$

SM including elementary Higgs couples to the strong sector with renormalizable couplings:

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

## Very weak bounds:

- Automatic MFV
- Precision tests ok
- LHC: $\Lambda > 1 - 2\,\mathrm{TeV}$

## Interesting phenomenology:

- Accidental dark matter candidates
- Plausible signatures for LHC and cosmology
- Composite Higgs — see Contino's talk
- (Rel)axions

# Accidental symmetries:

- Dark-Baryon number

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

- Dark-Species number

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

- G-parity

$$\mathcal{Q} \to e^{-i\pi J_2}\mathcal{Q}^c \longrightarrow M = (\bar{\mathcal{Q}}\mathcal{Q})_{\text{triplet}}$$

Dark baryons robustly cosmologically stable as the proton.

# Majorana vs. Dirac

## - Q-complex (SU(N))

Baryons are Dirac particles that can be produced thermally or asymmetrically.  Strong direct detection constraints from tree level Z-couplings.

## - Q-real (SO(N))

Baryon and anti-baryons are the same particle so 2 DM particles can annihilate. Only thermally produced. Direct detections constraints avoided.

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

Strongly coupled dynamics, DM simple.

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

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

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

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

# Light Quarks

- with O. Antipin, A. Strumia, E. Vigiani '15

# SU(N)

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

| Fermions | $SM$ | $SU(n)_{\rm TC}$ |
|---|---|---|
| $\Psi_L$ | $\sum_i r_i$ | $n$ |
| $\Psi_R$ | $\sum_i \bar{r}_i$ | $\bar{n}$ |

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

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

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**

Pions behave as elementary minimal dark matter candidates.

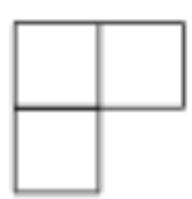
Strumia, Cirelli '05

$$m_{I=1} \sim 2.5\,\mathrm{TeV} \qquad \sigma_{SI} = 0.12 \pm 0.03 \times 10^{-46}\,\mathrm{cm}^2$$

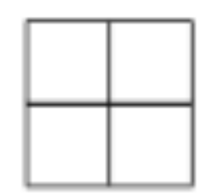
- **Dark-Baryons**

Lightest multiplet has minimum spin. Flavor rep:

$N_{DC} = 3$



$N_{DC} = 4$



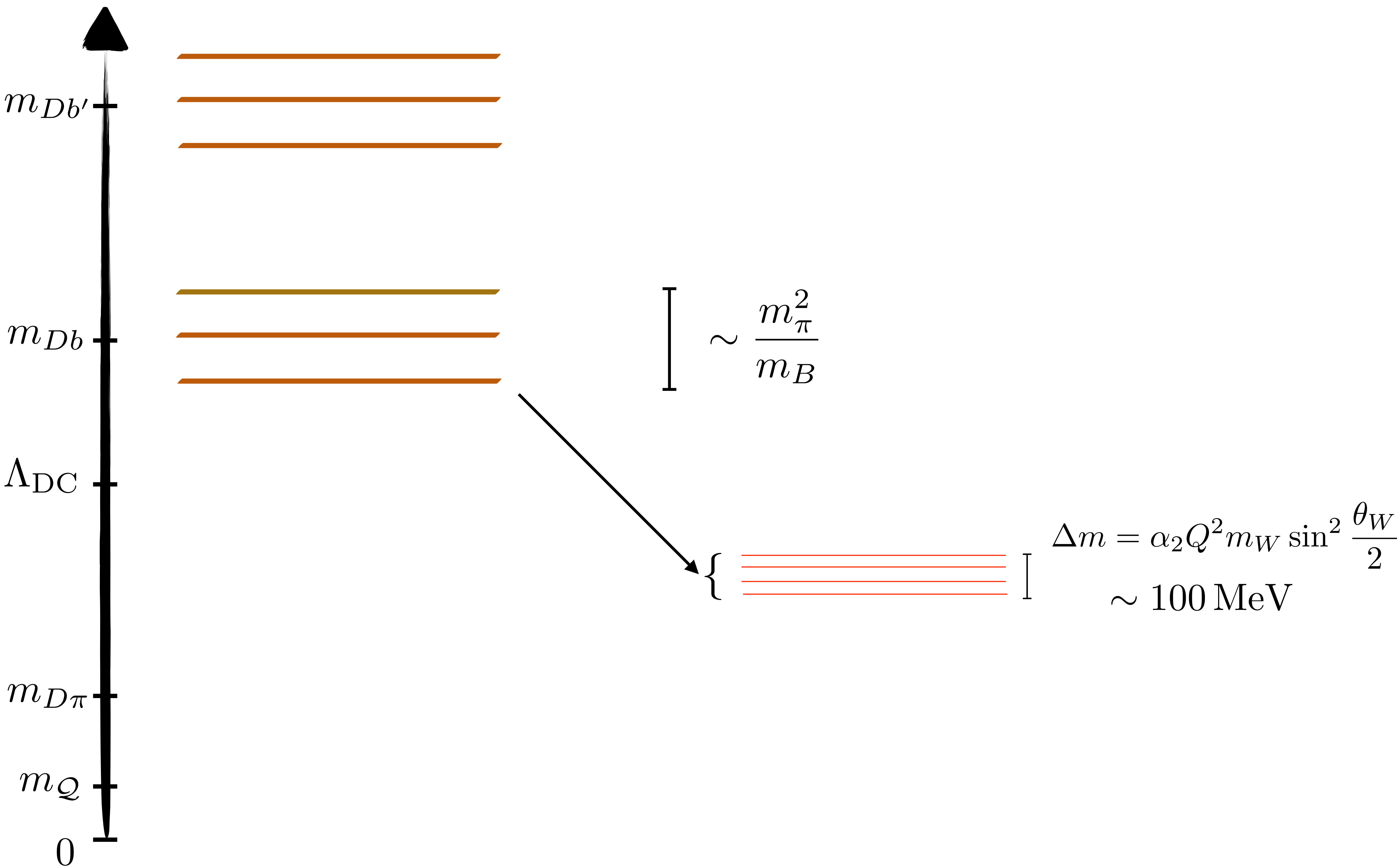
**DM candidate:**

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

$$Y_{DB} = 0$$

→ **I=0,1,2,...**

Flavor multiplets are split by fermion masses and gauge interactions:



# Classification:

$$R = (N, SM) \oplus (\bar{N}, S\bar{M})$$

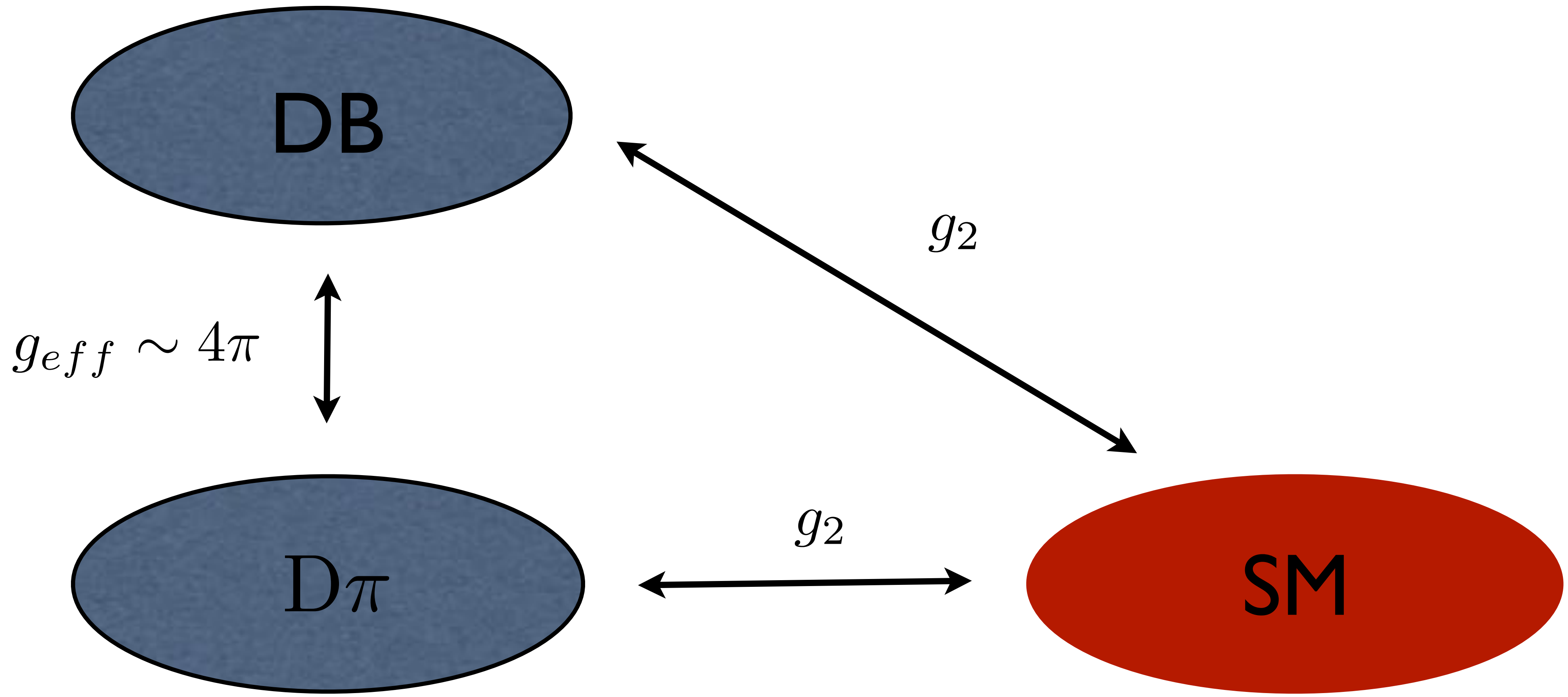
| SU(5) | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | charge | name |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 0 | 0 | $N$ |
| $\bar{5}$ | $\bar{3}$ | 1 | $-1/3$ | $-1/3$ | $D$ |
| | 1 | 2 | $1/2$ | $0, 1$ | $L$ |
| 10 | $\bar{3}$ | 1 | $-2/3$ | $-2/3$ | $U$ |
| | 1 | 1 | 1 | 1 | $E$ |
| | 3 | 2 | $1/6$ | $-1/3, 2/3$ | $Q$ |
| 15 | 3 | 2 | $1/6$ | $-1/3, 2/3$ | $Q$ |
| | 1 | 3 | 1 | $0, 1, 2$ | $T$ |
| | 6 | 1 | $-2/3$ | $-2/3$ | $S$ |
| 24 | 1 | 3 | 0 | $-1, 0, 1$ | $V$ |
| | 8 | 1 | 0 | 0 | $G$ |
| | $\bar{3}$ | 2 | $5/6$ | $1/3, 4/3$ | $X$ |
| | 1 | 1 | 0 | 0 | $N$ |

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

# Golden models:

| 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 | $3\times 3$ | $VVV, VNN=3,\ VVN=1$ | $\mathrm{SU}(2)_L$ |
| $\Psi = N \oplus L \oplus \tilde{E}$ | 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 | $QQ\tilde{D}, \tilde{D}\tilde{D}\tilde{U}=1$ | $\mathrm{SU}(2)_L$ |

# Relic abundance:



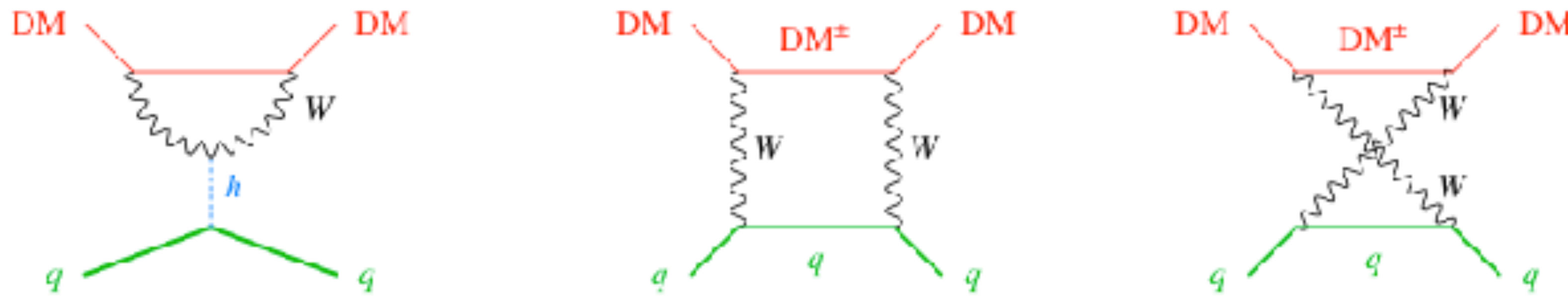

$$\langle \sigma_{B\bar{B}}^{ANN} v \rangle \sim \frac{4\pi}{m_B^2}$$

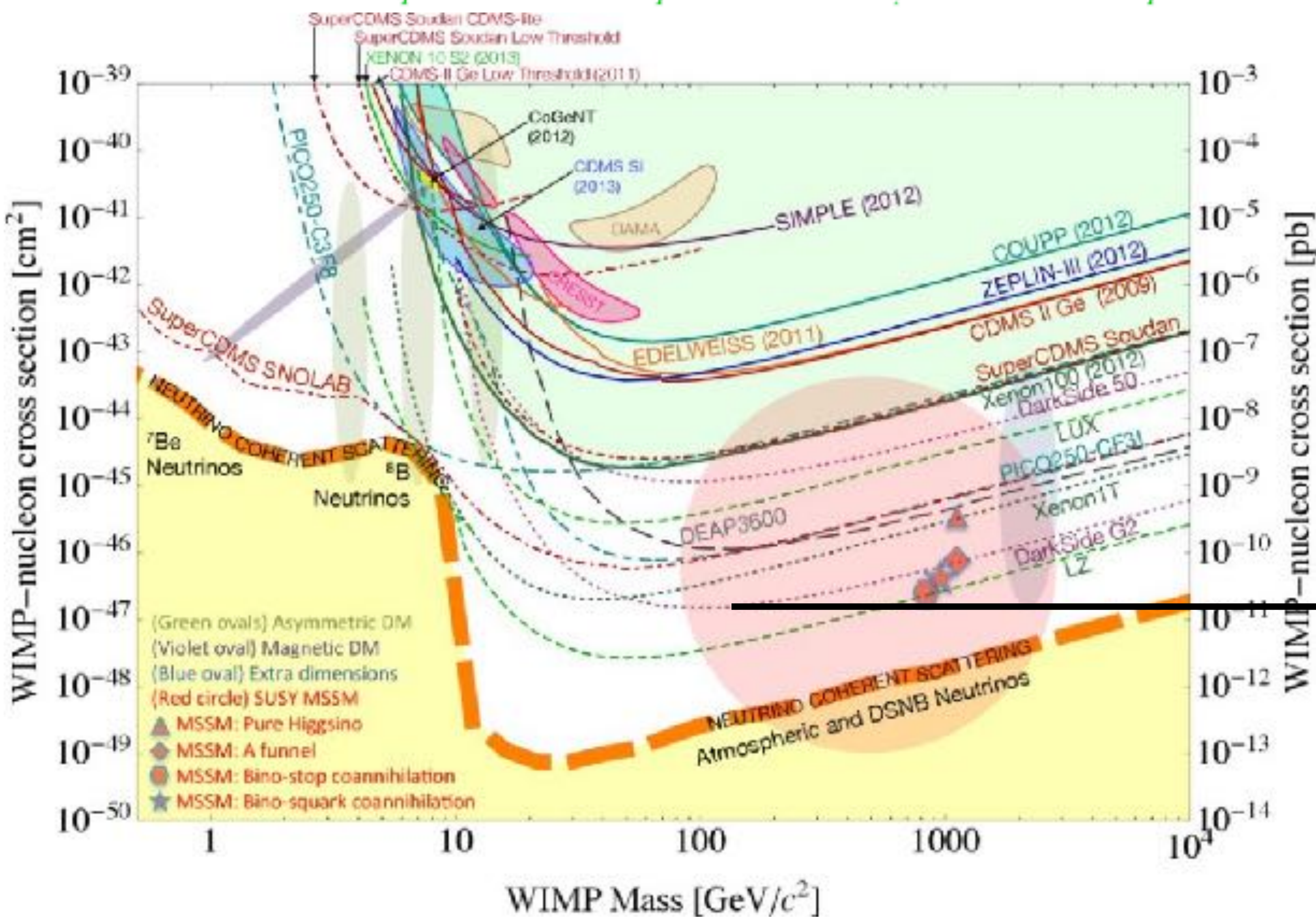
THERMAL ABUNDANCE

$$m_B \sim 100\,\mathrm{TeV}$$

DM could also be produced asymmetrically.

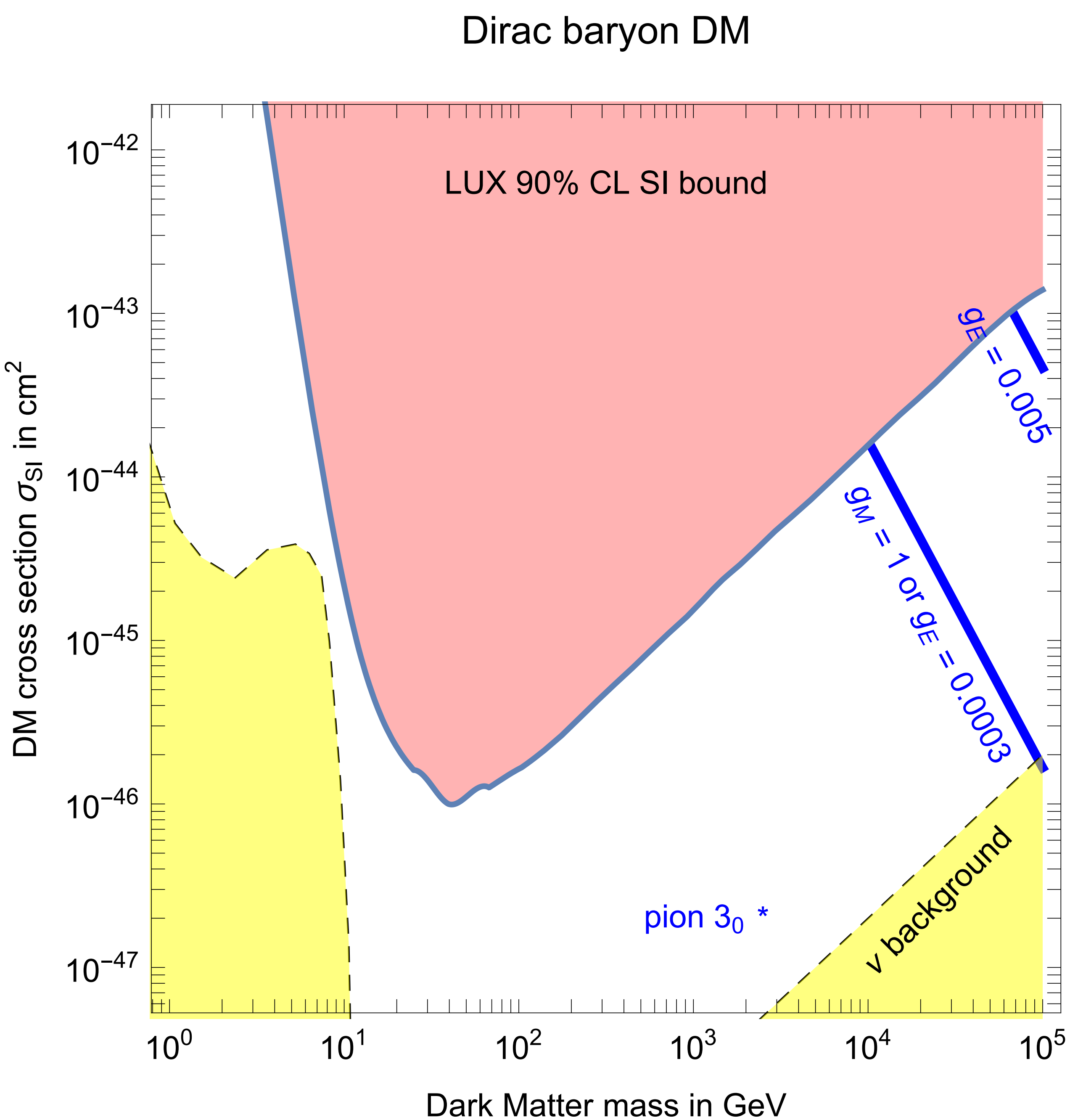
# If DB has SM charges it interacts as WIMPS.




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

Yukawa couplings very constrained.




# Dipole interactions:

$$\frac{d\sigma}{dE_R} \approx \frac{e^2 Z^2}{16\pi\, m_B^2\, E_R}\left(g_M^2 + \frac{g_E^2}{v^2}\right) \longrightarrow g_M^2 + 10^7 g_E^2 < \left(\frac{m_B}{5\,\mathrm{TeV}}\right)^3$$

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

# SO(N)

With NF flavors in the vector rep:

$$\langle 0|q_i^a q_i^b|0\rangle \sim 4\pi f^3 \delta^{ab} \longrightarrow \frac{SU(N_F)}{SO(N_F)}$$

Fermions are in a real dark color rep:

- No difference between baryons and anti-baryons.

Two baryons can annihilate into N pions

$$\epsilon^{i_1 i_2 \ldots i_N} \epsilon^{j_1 j_2 \ldots j_N} = (\delta_{i_1 j_1} \delta_{i_2 j_2} \ldots \delta_{i_N j_N} \pm \text{permutations})$$

- Real SM fermions have Majorana masses

$NN$ $VV$ $GG$

After electro-weak symmetry breaking neutral mass eigenstates are Majorana particles. Analogous to SUSY neutralinos.

SO(N) DM candidates are Majorana fermions or real scalars:

- **production**

  Cannot be produced through an asymmetry.
  Thermal abundance:

$$m_B \sim 100\,\mathrm{TeV}$$

- **detection**

  There are no vector couplings with Z eliminating spin independent bounds. No dipole interactions.

# Golden models:

| SO($N$) techni-color. Techni-quarks | Yukawa couplings | Allowed $N$ | Techni-pions | Techni-baryons | under |
|---|---|---|---|---|---|
| $N_{\rm TF}=3$ | | | 5 | $3,1,...$ for $N=3,4,...$ | $\mathrm{SO}(3)_{\rm TF}$ |
| $\Psi=V$ | 0 | $3,4,..,7$ | unstable | $V^N=3,1,...$ | $\mathrm{SU}(2)_L$ |
| $N_{\rm TF}=4$ | | | 9 | $4,1,...$ | $\mathrm{SO}(4)_{\rm TF}$ |
| $\Psi=N\oplus V$ | 0 | $3,4,..,7$ | 3 | $VVN=1, V(VV+NN)=3,$ | $\mathrm{SU}(2)_L$ |
| | | | | $VV(VV+NN)=1,...$ | $\mathrm{SU}(2)_L$ |
| $N_{\rm TF}=5$ | | | 14 | $5,1...$ | $\mathrm{SO}(5)_{\rm TF}$ |
| $\Psi=L\oplus N$ | 1 | $3,4,..,14$ | unstable | $L\bar{L}N=1,$ | $\mathrm{SU}(2)_L$ |
| | | | | $L\bar{L}(L\bar{L}+NN)=1,...$ | $\mathrm{SU}(2)_L$ |
| $N_{\rm TF}=7$ | | | 27 | $1,...$ | $\mathrm{SO}(7)_{\rm TF}$ |
| $\Psi=L\oplus V$ | 1 | 4 | unstable | $(L\bar{L}+VV)^2=1$ | $\mathrm{SU}(2)_L$ |
| $\Psi=L\oplus E\oplus N$ | 2 | $4,5$ | unstable | $(E\bar{E}+L\bar{L})^2+NN(L\bar{L}+E\bar{E})=1$ | $\mathrm{SU}(2)_L$ |
| $N_{\rm TF}=8$ | | | 35 | 1 | $\mathrm{SO}(8)_{\rm TF}$ |
| $\Psi=G$ | 0 | 4 | unstable | $GGGG=1$ | $\mathrm{SU}(2)_L$ |
| $\Psi=L\oplus N\oplus V$ | 2 | 4 | unstable | $(L\bar{L}+VV)^2+NN(L\bar{L}+VV)=1$ | $\mathrm{SU}(2)_L$ |
| $N_{\rm TF}=9$ | | | 44 | 1 | $\mathrm{SO}(9)_{\rm TF}$ |
| $\Psi=L\oplus E\oplus V$ | 2 | 4 | unstable | $(E\bar{E}+L\bar{L}+VV)^2=1$ | $\mathrm{SU}(2)_L$ |
| $N_{\rm TF}=10$ | | | 54 | 1 | $\mathrm{SO}(10)_{\rm TF}$ |
| $\Psi=L\oplus E\oplus V\oplus N$ | 3 | 4 | unstable | as $L\oplus E\oplus V+NN(L\bar{L}+E\bar{E}+VV)=1$ | $\mathrm{SU}(2)_L$ |

## Q=L+N

$$m_L \bar{L} L + \frac{m_N}{2} N N + y_L H^\dagger L N + y_R^* H \bar{L} N + h.c$$

$$N = 3 \quad : \qquad \left(\yng(2,2)\right)_{\mathrm{SU}(N_{\mathrm{TF}})} = \left(\yng(2,2) \oplus \yng(1)\right)_{\mathrm{SO}(N_{\mathrm{TF}})}$$

Lightest baryon is a quintuplet of SO(5) containing “Higgsino" + “bino” states

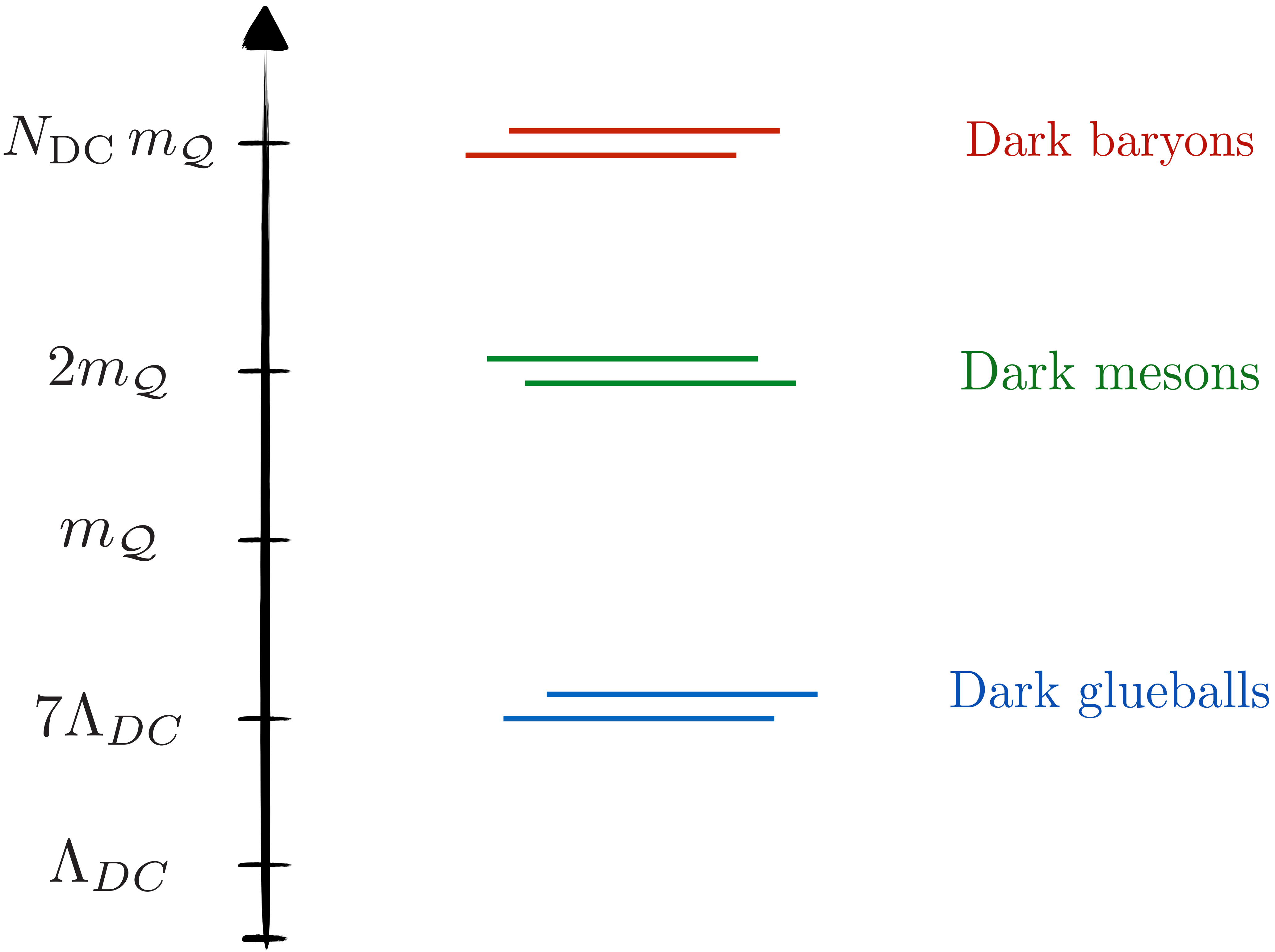
$$\begin{array}{c} \\ 1_0 \\ 2_{1/2} \\ 2_{-1/2} \\ \vdots \end{array} \begin{array}{c} \begin{array}{cccc} 1_0 & 2_{1/2} & 2_{-1/2} & \cdots \end{array} \\ \begin{pmatrix} m_{1_0} & y_L v & y_R v & \cdots \\ y_L^* v & 0 & m_{2_{1/2}} & \cdots \\ y_R^* v & m_{2_{1/2}} & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \end{array}$$

- “Higgsino DM” $\qquad m_L \ll m_N$

$$\Delta m_M \sim \frac{y^2 v^2}{m_N}$$

# Heavy quarks

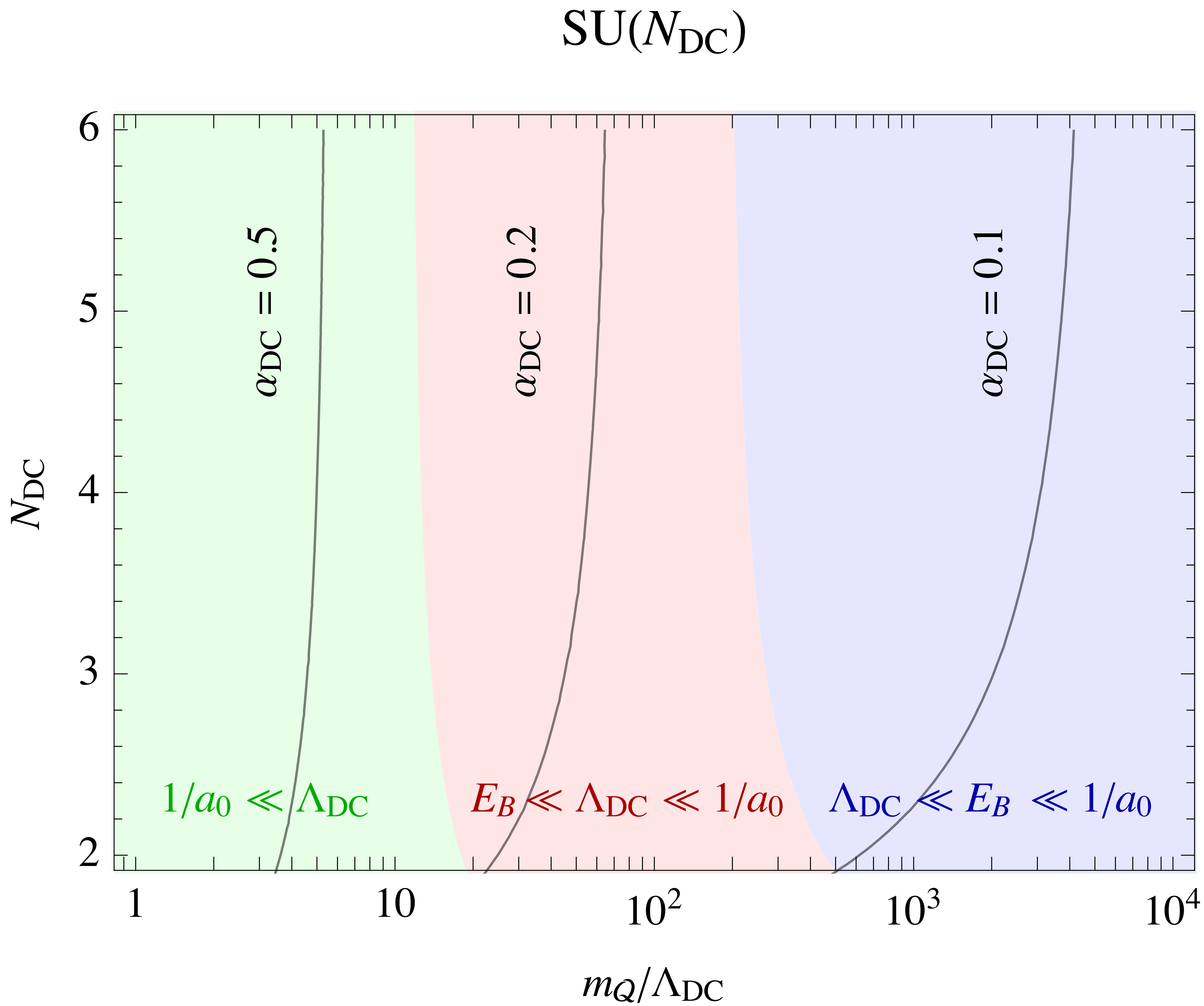
- 1707.05380 with A. Mitridate, J. Smirnov, A. Strumia



$N_{\rm DC}\, m_{\mathcal{Q}}$
$2m_{\mathcal{Q}}$
$m_{\mathcal{Q}}$
$7\Lambda_{DC}$
$\Lambda_{DC}$
Dark baryons
Dark mesons
Dark glueballs

# Non-relativistic bound states N fermions:

$$V \sim -\frac{\alpha_{DC}}{r} + \Lambda_{DC}^2 r$$



Lightest baryons are naturally made of a single specie.

- $SU(3)$

$$\Psi = N \oplus \dots \qquad \mathrm{DM} = NNN\,, \qquad I(J^P) = 0\left(\frac{3}{2}^+\right)$$

$$\Psi = V \oplus \dots \qquad \mathrm{DM} = VVV\,, \qquad I(J^P) = 1\left(\frac{1}{2}^+\right)$$

- $SO(3)$

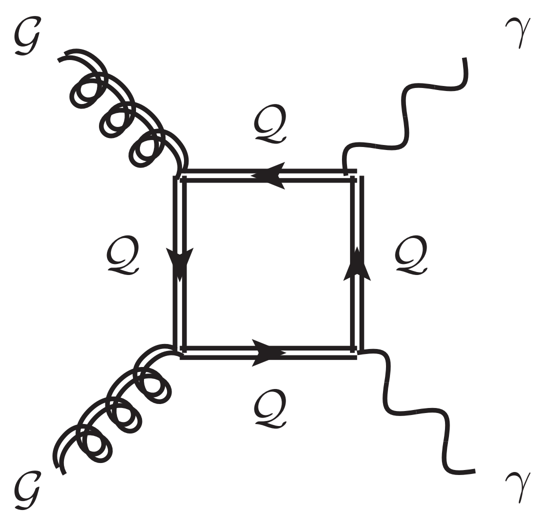
$$\Psi = L \oplus N \oplus V + \dots \qquad DM = LL\bar{L} \qquad I(J^P) = \frac{1}{2}\left(\frac{1}{2}^+\right)$$

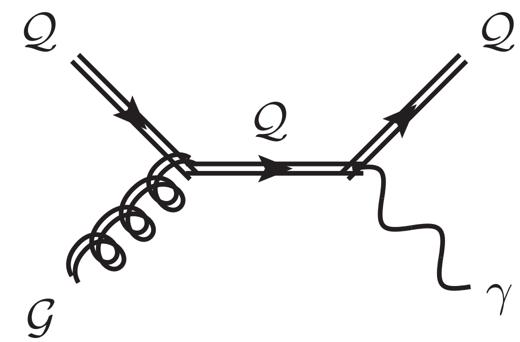
Static properties of bound states:

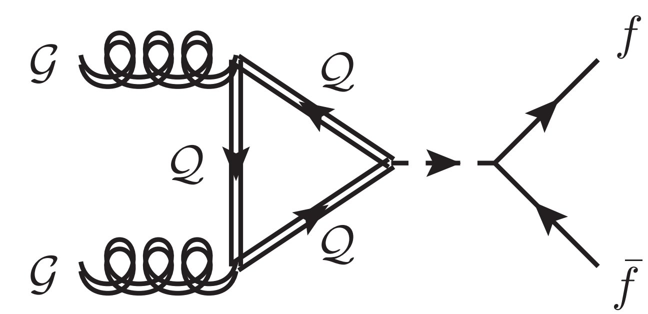
$$m_B \approx N_{\mathrm{DC}} m_Q \qquad E_B \sim \alpha_{\mathrm{DC}}^2 N_{\mathrm{DC}}^3 m_Q$$

# Glueballs:

$$M_{0^{++}} \approx 7\Lambda_{DC}$$




$$\tau_{\rm DG}^{\gamma\gamma} \sim 10{\rm sec}\left(\frac{10\,{\rm GeV}}{m_{\rm DG}}\right)^9\left(\frac{m_Q}{\rm TeV}\right)^8 \qquad \tau_{\rm DG}^{b\bar{b}} \sim 10^{-3}{\rm sec}\left(\frac{0.1}{y}\right)^4\left(\frac{10\,{\rm GeV}}{m_{\rm DG}}\right)^7\left(\frac{m_Q}{\rm TeV}\right)^4$$

Glueballs need to decay before BBN:

$$\tau_{DG} + t_{\Lambda_{DC}} < 1{\rm s}$$

Non standard cosmological histories:

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

Baryons form before thermal free-out.

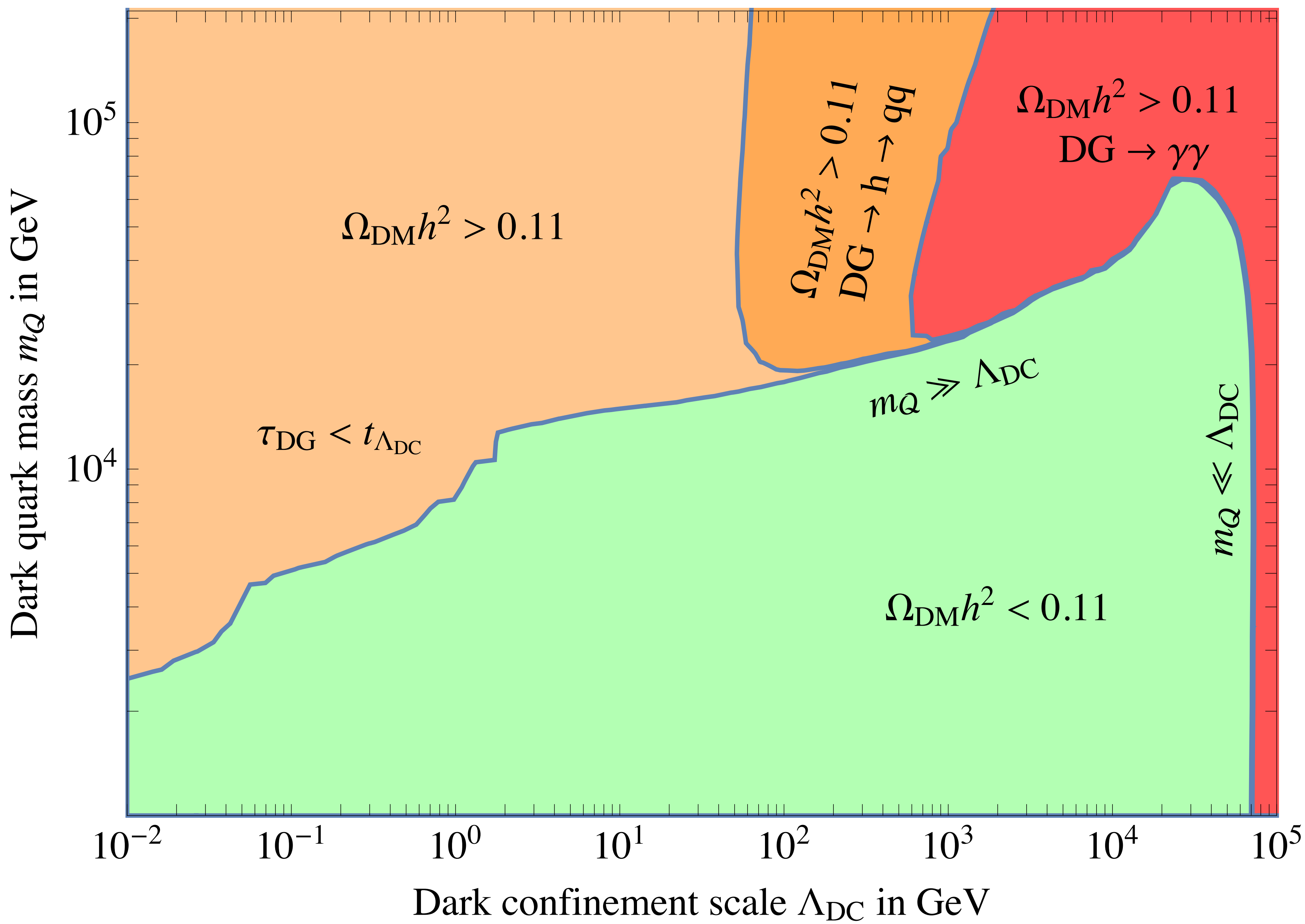
$$\langle \sigma v \rangle = \frac{4\pi\alpha_{eff}^2}{m_B^2} + \langle \sigma v \rangle_{SM} \qquad m_Q < 100\,\mathrm{TeV}$$

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

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

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

Glueball decays may dilute abundance, late time annihilations, thermal excitement…

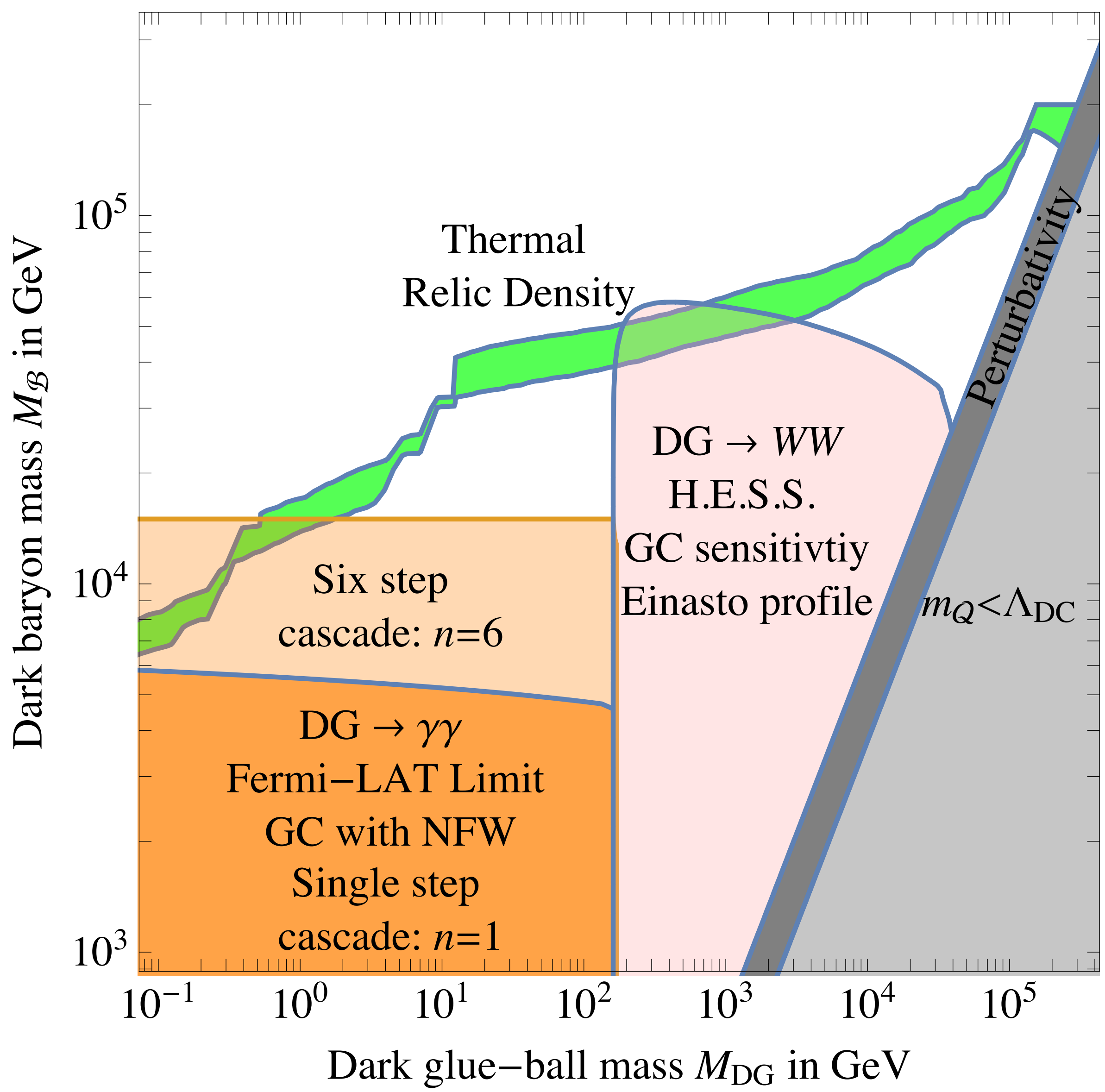



In the non-relativistic regime thermal abundance of DM can be obtained for masses down to few TeV.

# Indirect detection:

At low energies annihilation cross-section can be huge for extended objects:

$$(\mathcal{Q}^{N_{DC}}) + (\bar{\mathcal{Q}}^{N_{DC}}) \to (\mathcal{Q}\bar{\mathcal{Q}}) + (\mathcal{Q}^{N_{DC}-1})(\bar{\mathcal{Q}}^{N_{DC}-1})$$




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

# OTHER PHENO

(O. Antipin, MR, arxiv:1508.01112
Agugliaro, Antipin, Becciolini, De Curtis, MR 1609.07122)

# COLLIDER SIGNATURES

- $m_Q < \Lambda_{DC}$

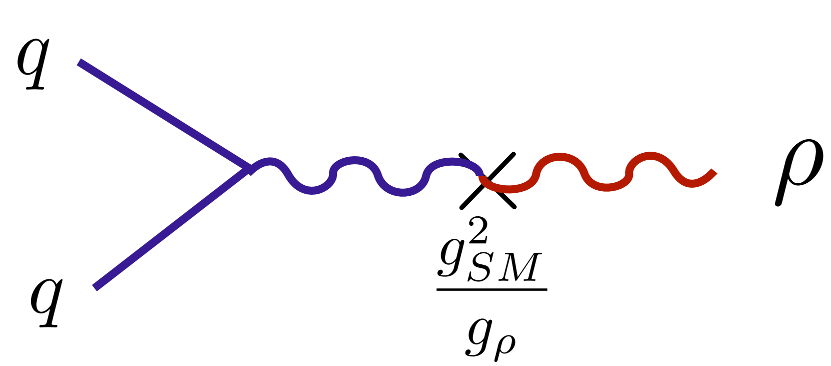
Kilic, Okui, Sundrum '09

Goldstone bosons and vector bosons with SM charges:

$$\langle 0|\bar{\Psi}\gamma^{\mu}T^{a}\Psi|\rho^{b}\rangle = -\delta^{ab}\, m_{\rho} f_{\rho}\epsilon^{\mu}$$

$$\langle 0|\bar{\Psi}\gamma^{\mu}\gamma^{5}T^{a}\Psi|\pi^{b}\rangle = -i\delta^{ab}\, f\, p^{\mu}$$

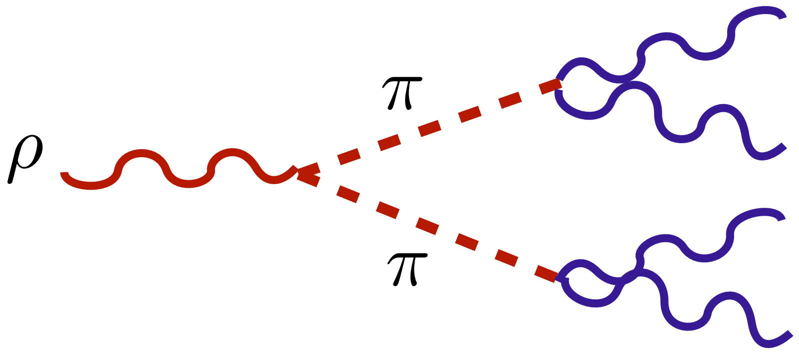
Heavy vectors mix with SM gauge bosons

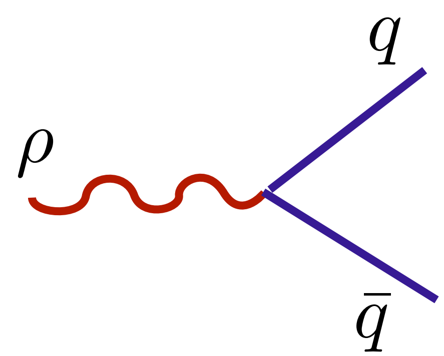



$$m_\rho \sim g_\rho f$$

Unlike composite Higgs fermions are elementary.

Decay to hidden pions and back to SM gauge bosons through anomalies or quarks




$$\mathrm{Br}(\rho \to q\bar{q}) \propto \frac{g_2^4}{g_\rho^4}$$

Pions can also be collider stable or long lived.

Pions can also be produced through SM interactions

$$pp \to W^{\pm} \to \pi_3^{\pm}\pi_3^{0} \to 3\gamma \; + \; W^{\pm}$$

Best bound from CDF!

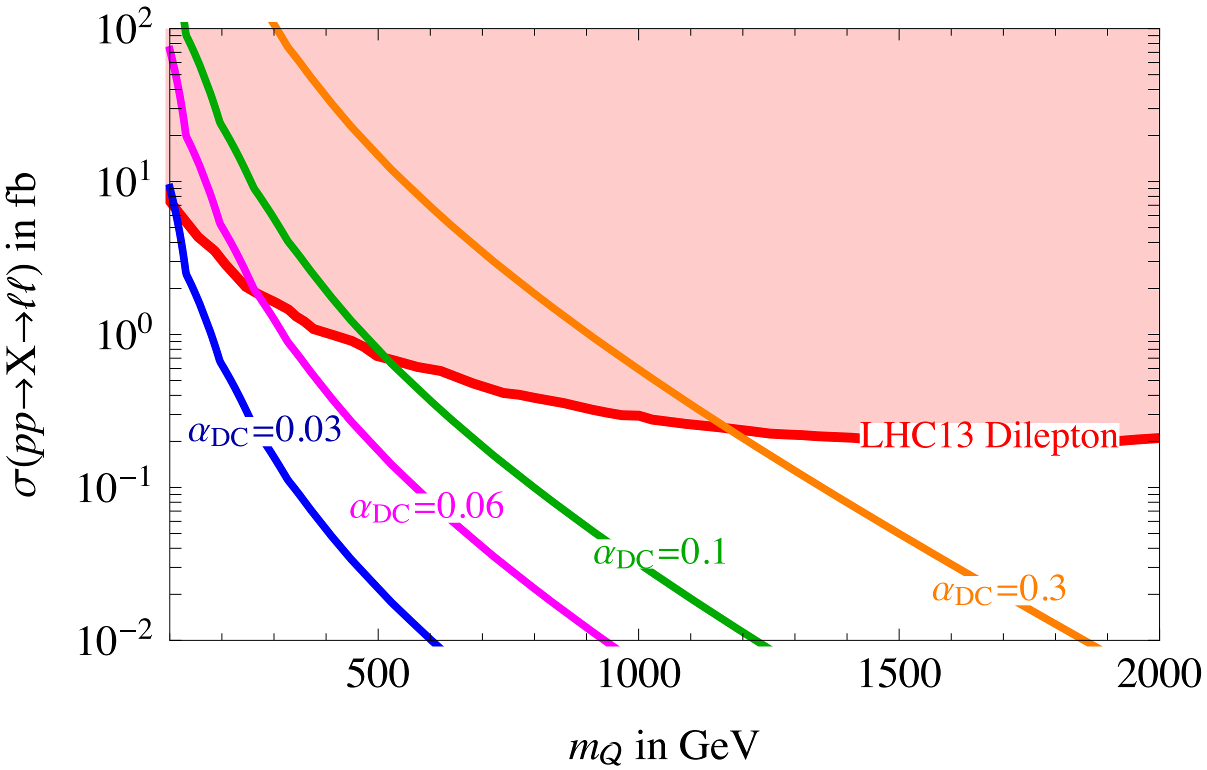
$$m_K > 230\,\mathrm{GeV}$$

• $m_Q > \Lambda_{DC}$

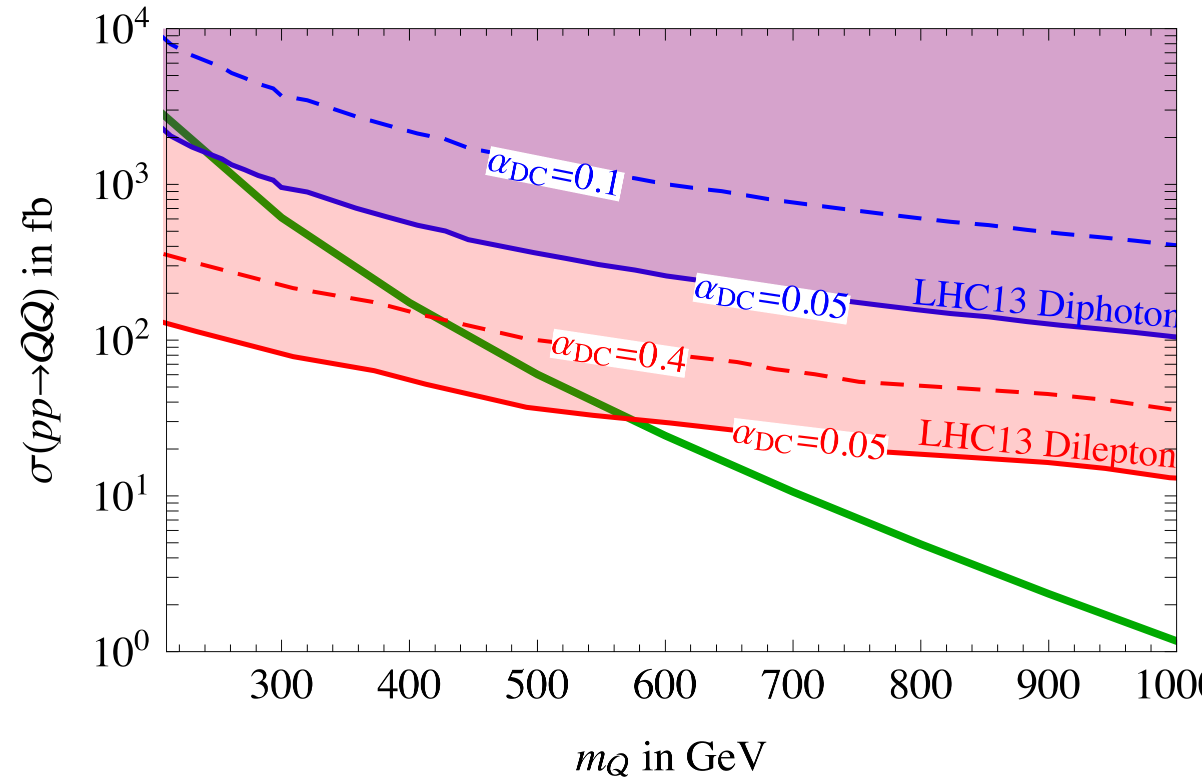
Mitridate, MR, Smirnov, Strumia '17

Mesons can be produced singly or through hadronization. Spin-0 resonances decay to SM gauge bosons and spin-1 to fermions and scalars.

Most significant bound from resonant production of spin-1 particles decaying to leptons.




Single




Hadronization

# PARTIALLY COMPOSITE HIGGS

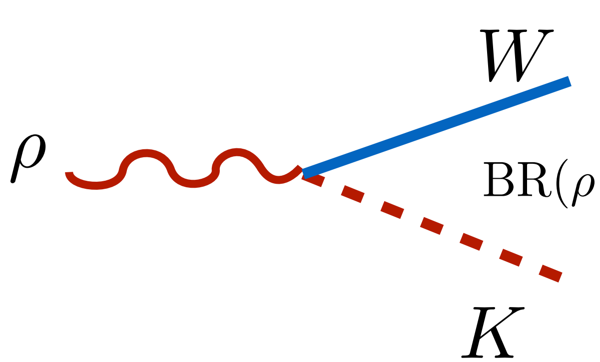
Antipin, MR '15

$$H\bar{Q}_i(y^L_{ij}P_L + y^R_{ij}P_R)Q_j \longrightarrow (y_L - y_R)m_\rho f\, HK + \ldots$$

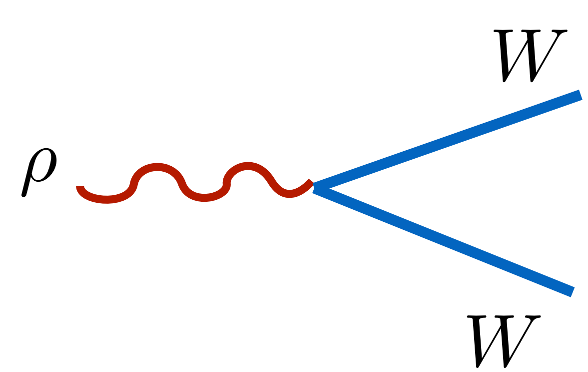
$$M^2 = \begin{pmatrix} m_H^2 & \epsilon m_K^2 \\ \epsilon^* m_K^2 & m_K^2 \end{pmatrix} \qquad \epsilon \sim (y_L - y_R)\frac{m_\rho f}{m_K^2}$$

Higgs interpolates between elementary and composite.

- $\epsilon < 1$ Elementary Higgs




$\mathrm{BR}(\rho \to KW) \sim \epsilon^2$




$\mathrm{BR}(\rho \to WW) \sim \epsilon^4$

- Small effects in precision tests, Higgs couplings etc…

$$\Delta\hat{T} \sim \frac{v^2}{f^2}\epsilon^4 \qquad \Delta\hat{S} \sim \frac{m_W^2}{m_\rho^2}\epsilon^2 \qquad \frac{\Delta h_{WW}}{h_{WW}^{SM}} \sim \frac{v^2}{f^2}\epsilon^3$$

- Pions with species number decay through Higgs:

$$K \to H + \eta$$

- $\epsilon > 1$ **Composite Higgs**

Kaplan Georgi '84
Agugliaro, Becciolini, De Curtis, MR '16

$$m_H^2 - |\epsilon|^2 m_K^2 \approx 0 \qquad m_h^{gauge} \approx 150\sqrt{\frac{3}{N_{DC}}}\,\mathrm{GeV}$$

Elementary Higgs generates vacuum misalignment of composite Higgs!

Viable UV completion of composite Higgs.
Not natural… supersymmetry? relaxion?

# CONCLUSIONS

- A strongly coupled sector that does not break the SM symmetry is a "natural" extension of the SM compatible with current data and potentially relevant for DM, collider…

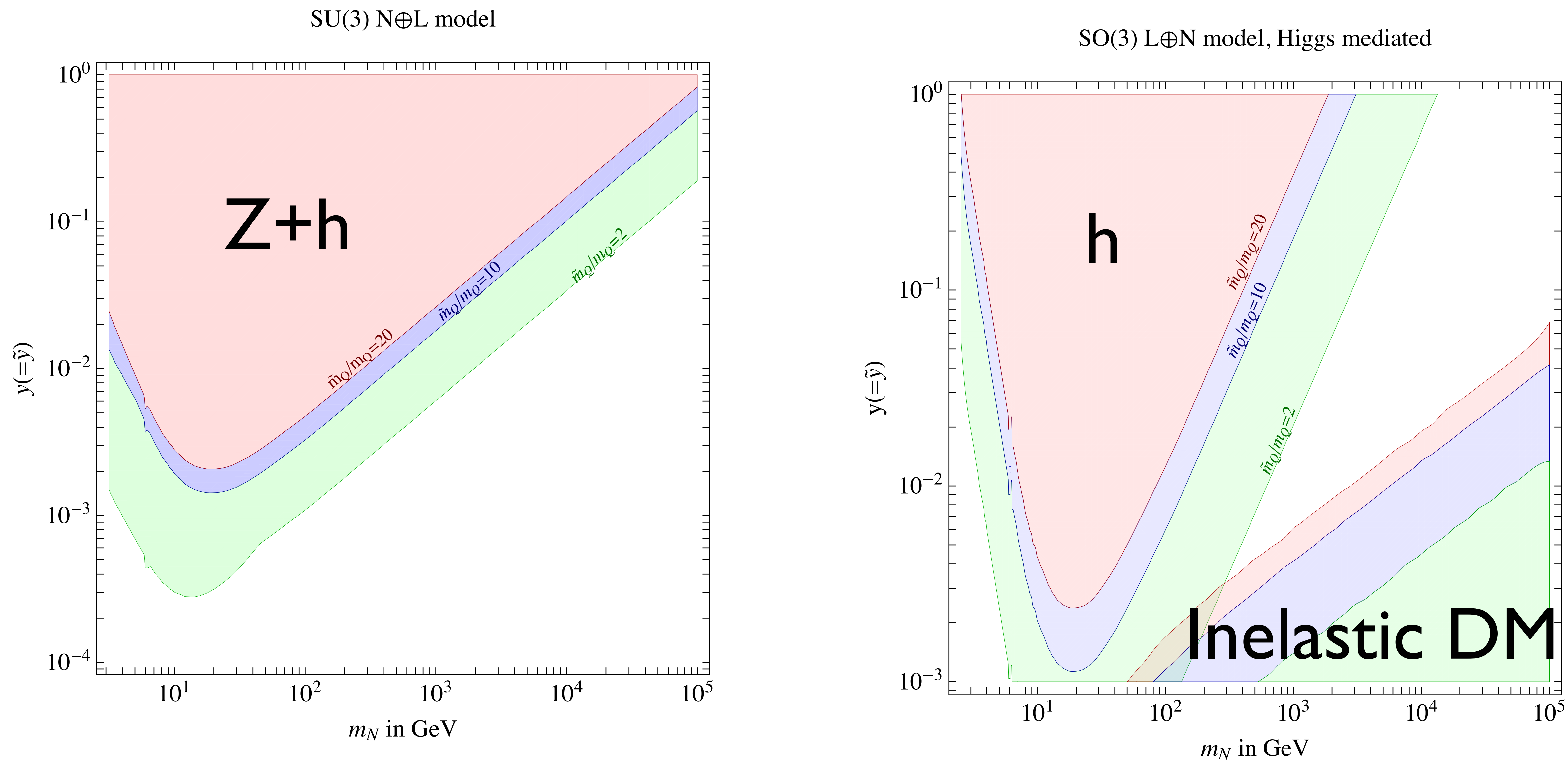
- SU(N) models generate complex DM while SO(N) models give real DM with very different phenomenology depending on the confinement scale. Thermal abundance of DM is obtained for masses 1-100 TeV. With heavy quarks cosmology is non standard.

- Dark color could be accessible to colliders. Interesting effects include: resonance production, long lived glueballs, compositeness, EDMs, gravitational waves, unification…

# Direct detection:

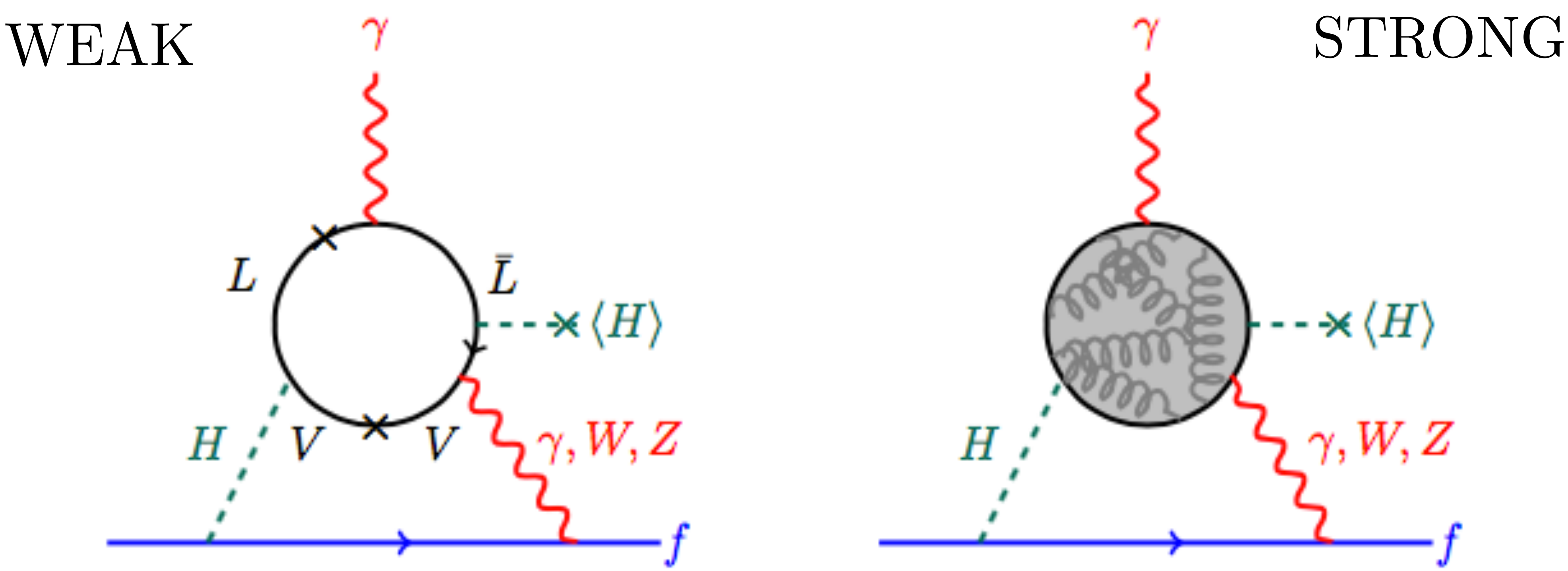
- **SU(N):** Z and Higgs mediated SI scatterings

- **SO(N):** Higgs SI x-sec and Z inelastic transitions.



# ELECTRIC DIPOLE MOMENTS

EDM for SM particles generated with complex Yukawas:




$$d_e \approx 10^{-27}\,\mathrm{e}\cdot\mathrm{cm} \times \mathrm{Im}(y_L y_R) \times \frac{N_{DC}}{3} \times \left(\frac{\mathrm{TeV}}{m_{\pi,\eta}}\right)^2 \times \left(\frac{\Lambda_{DC}}{\mathrm{TeV}}\right)^2$$

$$d_e < 8.7 \times 10^{-29}\ \mathrm{e\,cm} \qquad @\,90\%\ \mathrm{C.L.}$$

# GRAVITATIONAL WAVES

Confinement phase transition often 1st order:

$$3 \leq N_F \leq 4N \quad \text{and} \quad N > 3$$

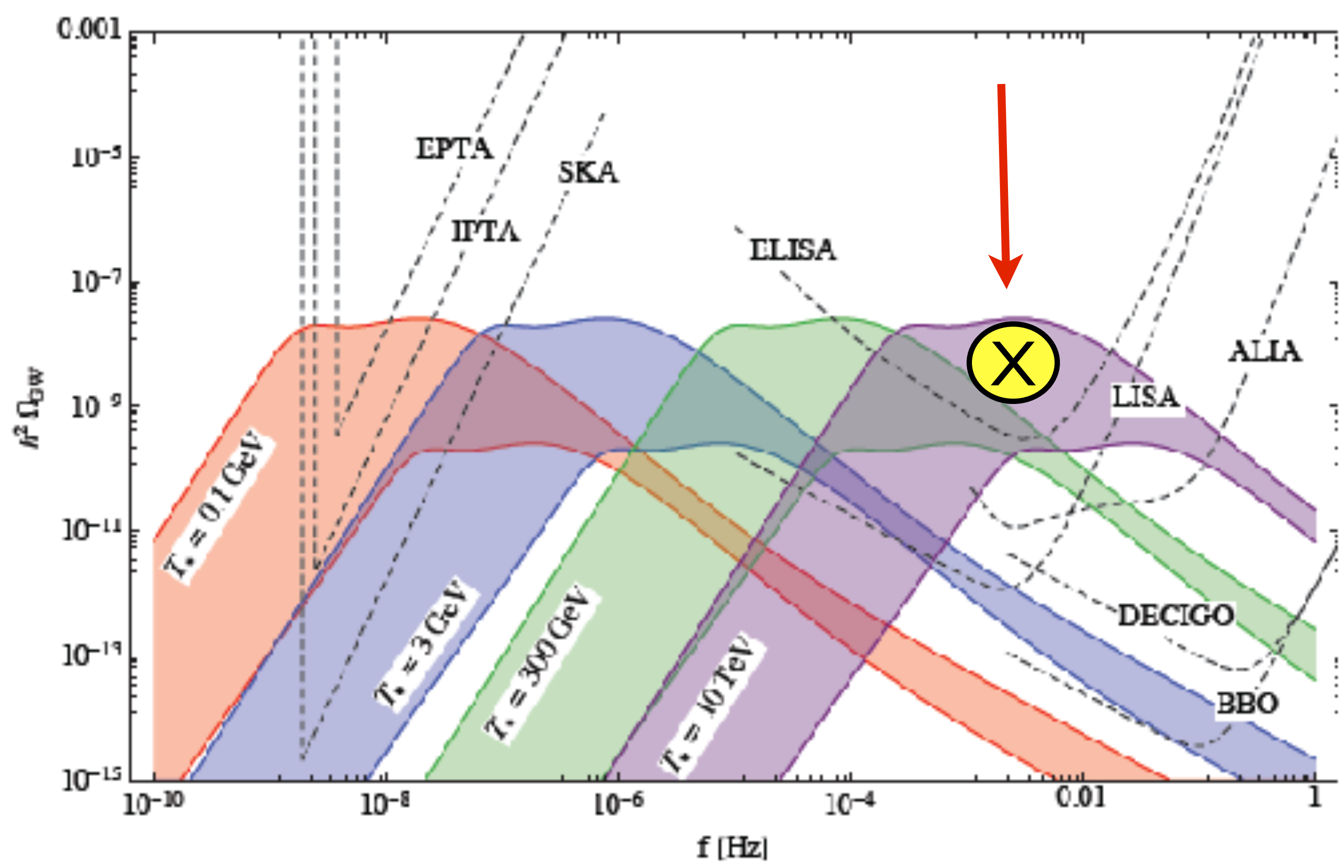
Phase transition : $T \sim \Lambda_{\rm DC}$

Peak frequency: $f_{\rm peak} = 3.3 \times 10^{-3}\ {\rm Hz} \times \left(\frac{T}{10\,{\rm TeV}}\right) \times \left(\frac{\beta}{10H}\right)$

Amplitude of the GW signal :

$$h^2\Omega_{\rm GW} \sim 10^{-9}$$

P. Schwaller 15'



# UNIFICATION

Incomplete SU(5) reps modify SM running

| SU(5) | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | charge | name | $\Delta b_3$ | $\Delta b_2$ | $\Delta b_Y$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 0 | 0 | $N$ | 0 | 0 | 0 |
| $\bar{5}$ | $\bar{3}$ | 1 | 1/3 | 1/3 | $D$ | 1/3 | 0 | 2/9 |
| | 1 | 2 | −1/2 | 0, −1 | $L$ | 0 | 1/3 | 1/3 |
| 10 | $\bar{3}$ | 1 | −2/3 | −2/3 | $U$ | 1/3 | 0 | 8/9 |
| | 1 | 1 | 1 | 1 | $E$ | 0 | 0 | 2/3 |
| | 3 | 2 | 1/6 | 2/3, −1/3 | $Q$ | 2/3 | 1 | 1/9 |
| 15 | 3 | 2 | 1/6 | 2/3, −1/3 | $Q$ | 2/3 | 1 | 1/9 |
| | 1 | 3 | 1 | 0, 1, 2 | $T$ | 0 | 4/3 | 2 |
| | 6 | 1 | −2/3 | −2/3 | $S$ | 5/3 | 0 | 8/9 |
| 24 | 1 | 3 | 0 | −1, 0, 1 | $V$ | 0 | 4/3 | 0 |
| | 8 | 1 | 0 | 0 | $G$ | 2 | 0 | 0 |
| | $\bar{3}$ | 2 | 5/6 | 4/3, 1/3 | $X$ | 2/3 | 1 | 25/9 |
| | 1 | 1 | 0 | 0 | $N$ | 0 | 0 | 0 |

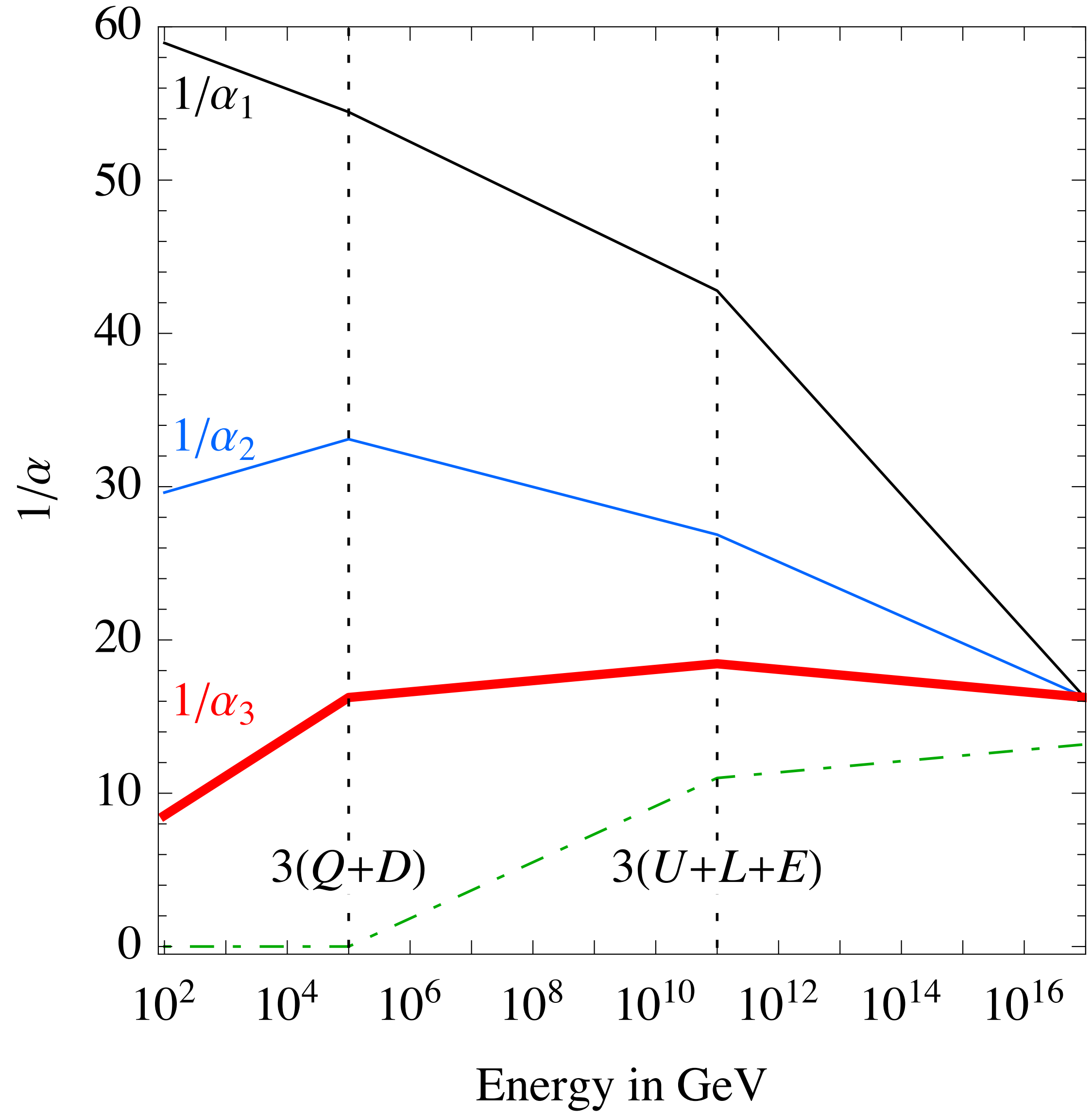
$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{\rm GUT}} + \frac{b_i^{\rm SM}}{2\pi}\log\frac{M_{\rm GUT}}{M_Z} + \frac{\Delta b_i}{2\pi}\log\frac{M_X}{\Lambda_{\rm TC}} + \frac{\Delta b}{2\pi}\log\frac{M_{\rm GUT}}{M_X}$$

$$\ln\frac{M_X}{\Lambda_{\rm TC}} = \frac{68}{\Delta b_{21} - 1.9\Delta b_{32}}, \qquad \ln\frac{M_{\rm GUT}}{M_X} = \frac{35.3\Delta b_{21} - 49.2\Delta b_{32}}{\Delta b_{21} - 1.9\Delta b_{32}}$$

# Ex:

$Q + \tilde{D}$

$\mathrm{DM} = QQ\tilde{D}$

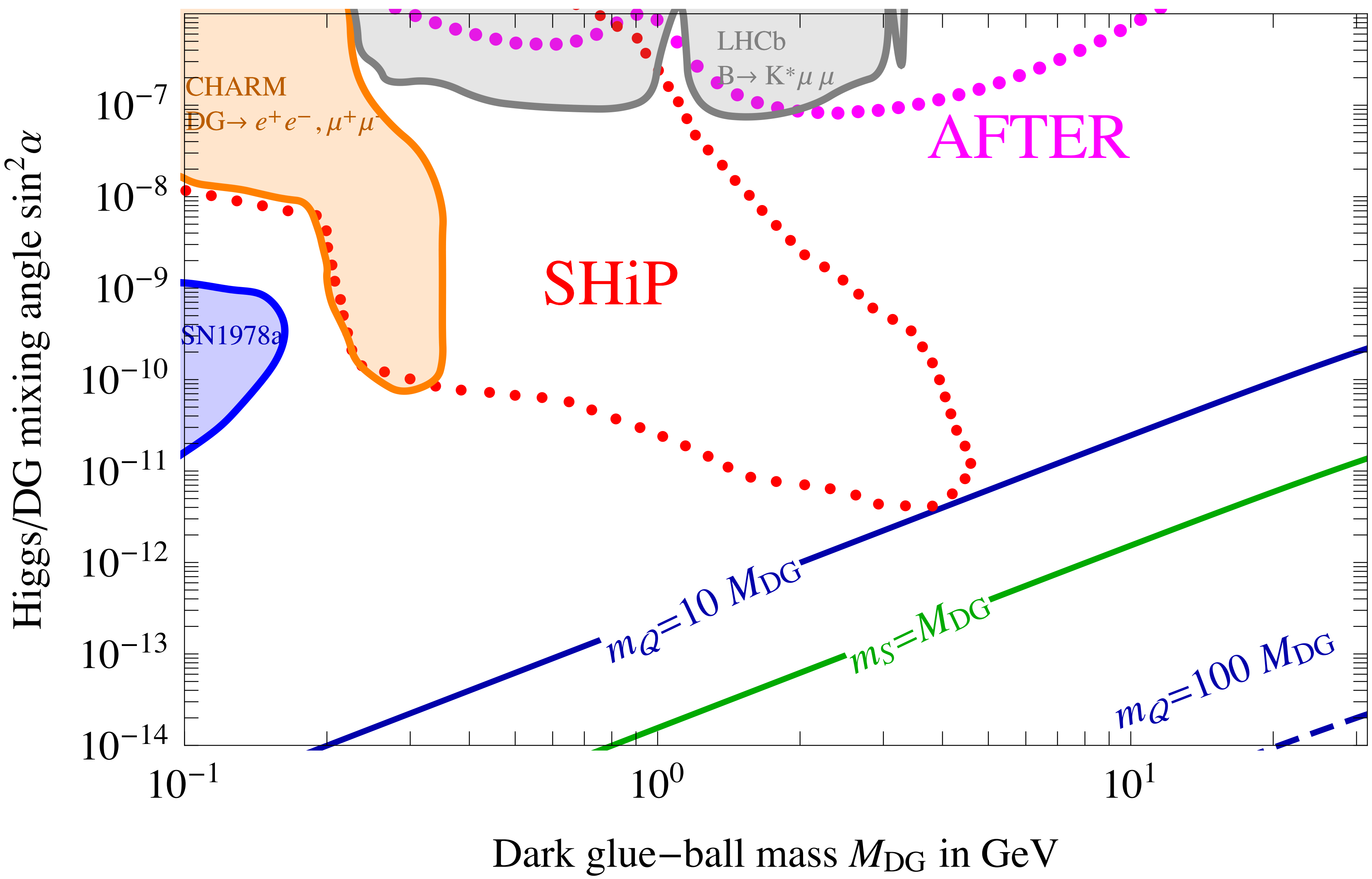



$\alpha_{\mathrm{GUT}} \approx 0.06$

$M_{\mathrm{GUT}} \approx 2 \times 10^{17}\,\mathrm{GeV}$

$\Lambda_{DC} = 100\,\mathrm{TeV}$ $M_X \approx 2 \times 10^{11}\ \mathrm{GeV}$

# SHIP




$$\mathcal{O}_6 = \frac{\alpha_{\rm DC}}{4\pi} H^\dagger H \mathcal{G}^A_{\mu\nu}\mathcal{G}^{\mu\nu A}$$

$$\sin\alpha \approx c_6 \frac{\alpha_{DC}}{4\pi}\frac{v f_{0S}}{M_h^2}$$