Composite Dark Matter

Michele Redi

Many thanks!

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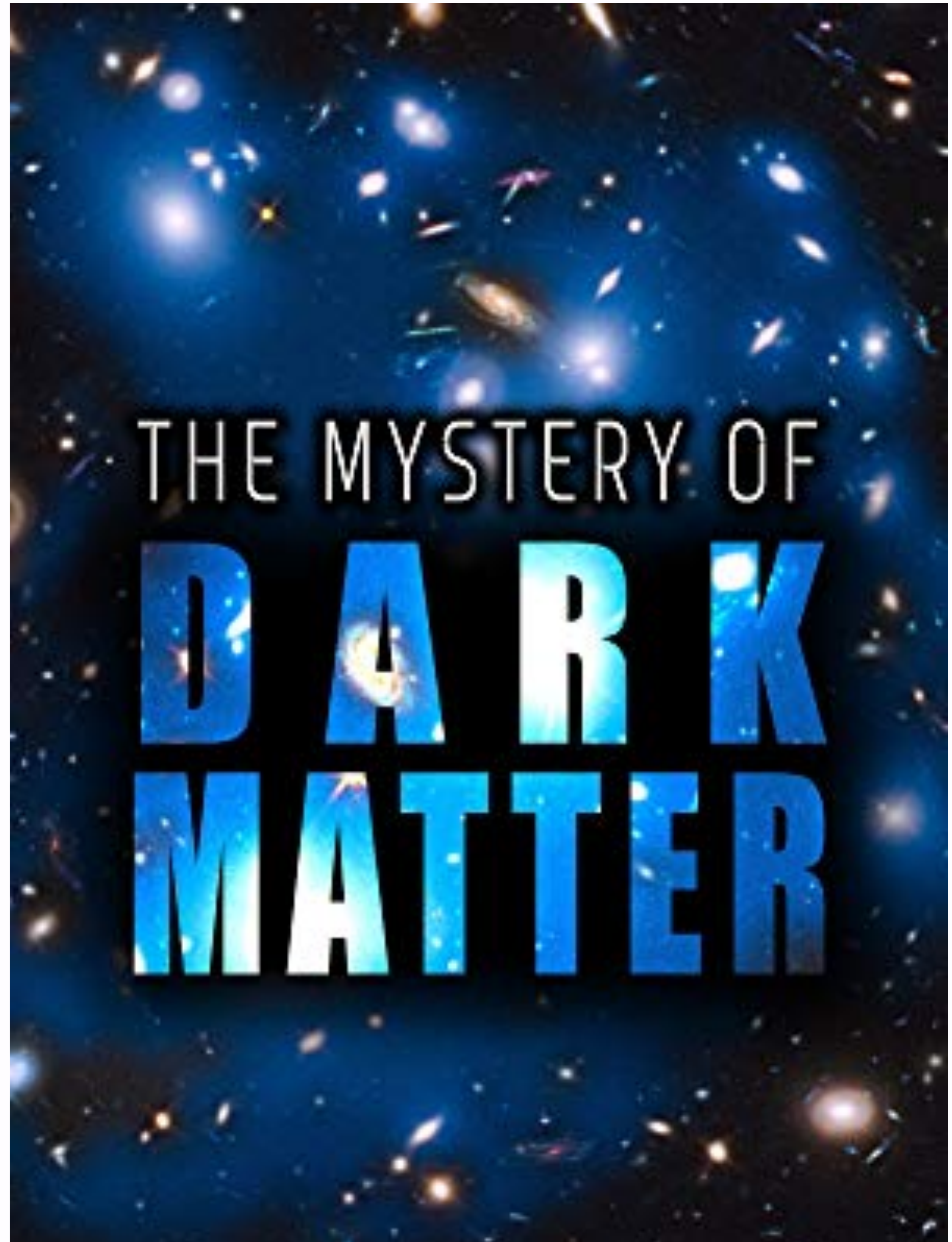
PRIN

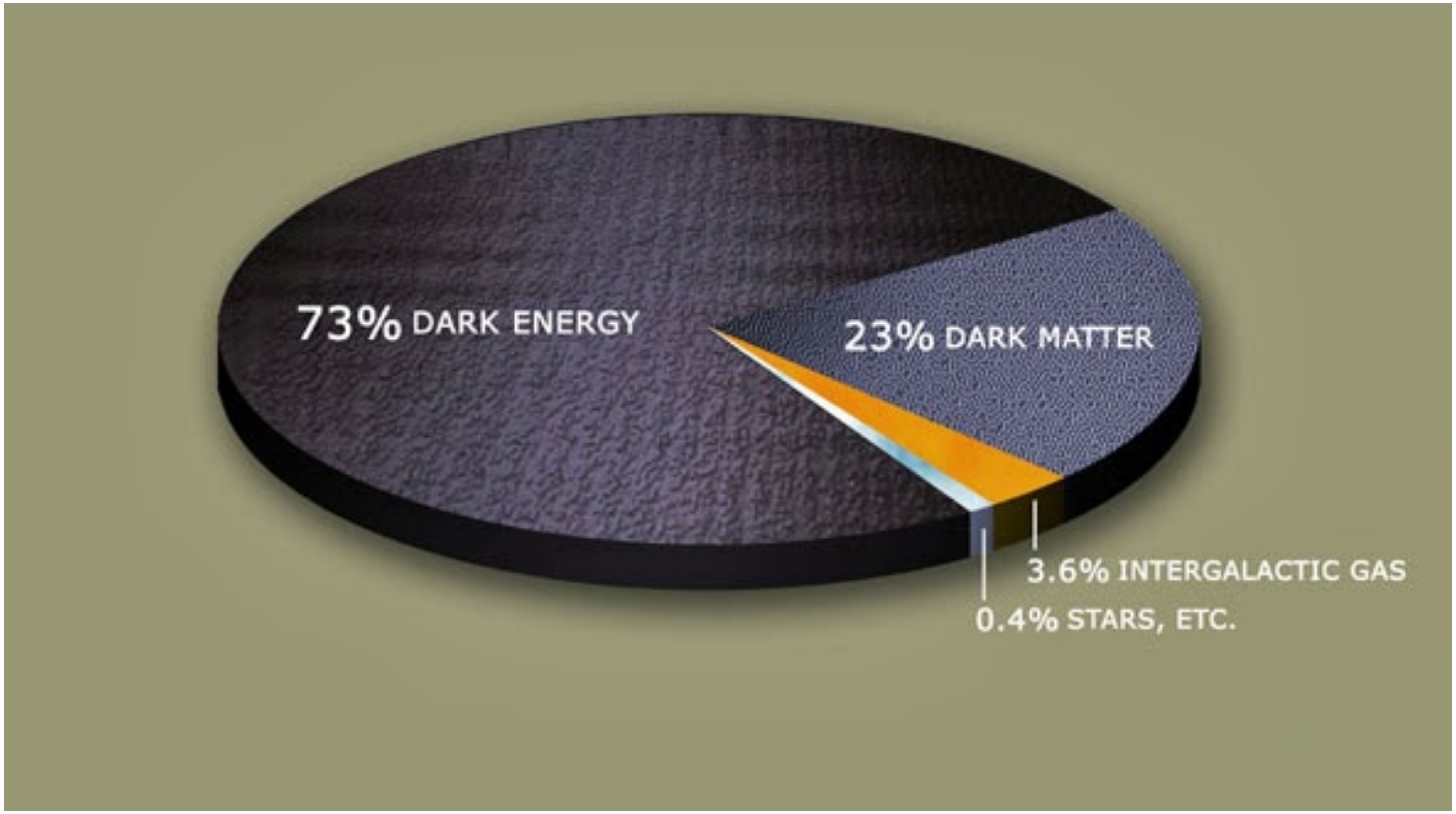
MIUR

New avenues in strong dynamics: from collider physics to the early Universe

ENTE
CASSA DI RISPARMIO
DI FIRENZE

Una nuova forza per la materia oscura: implicazioni cosmologiche, bosone di Higgs e onde gravitazionali

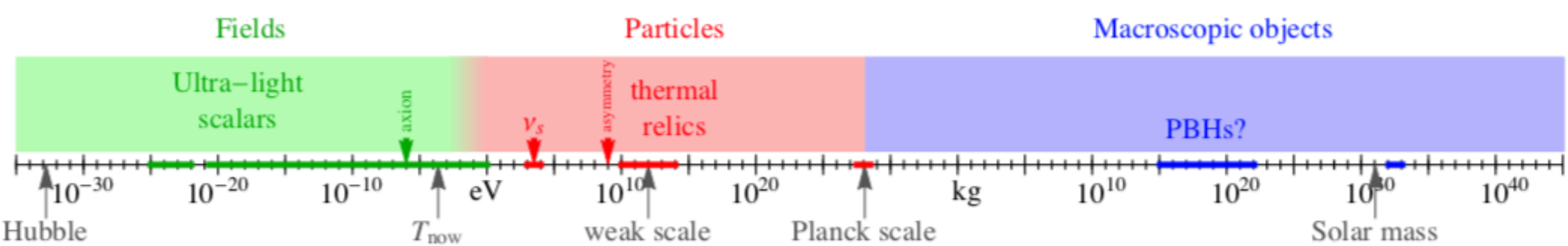




Rotation curves, structure formation, weak lensing, BBN and CMB measurements agree on the existence of a non-relativistic, non-baryonic and collision-less component of matter.

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

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

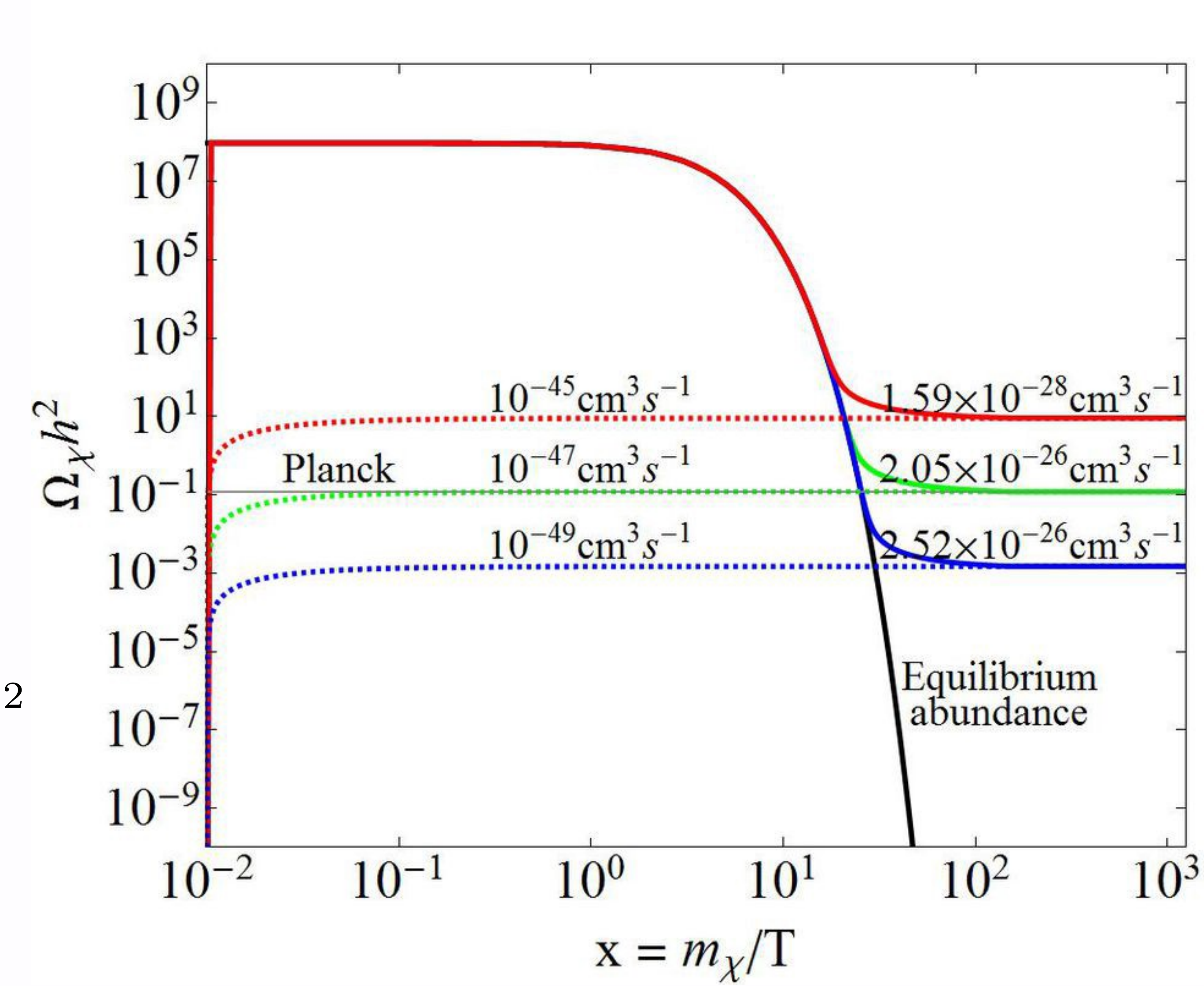


"WIMP Miracle"

Thermal relic:

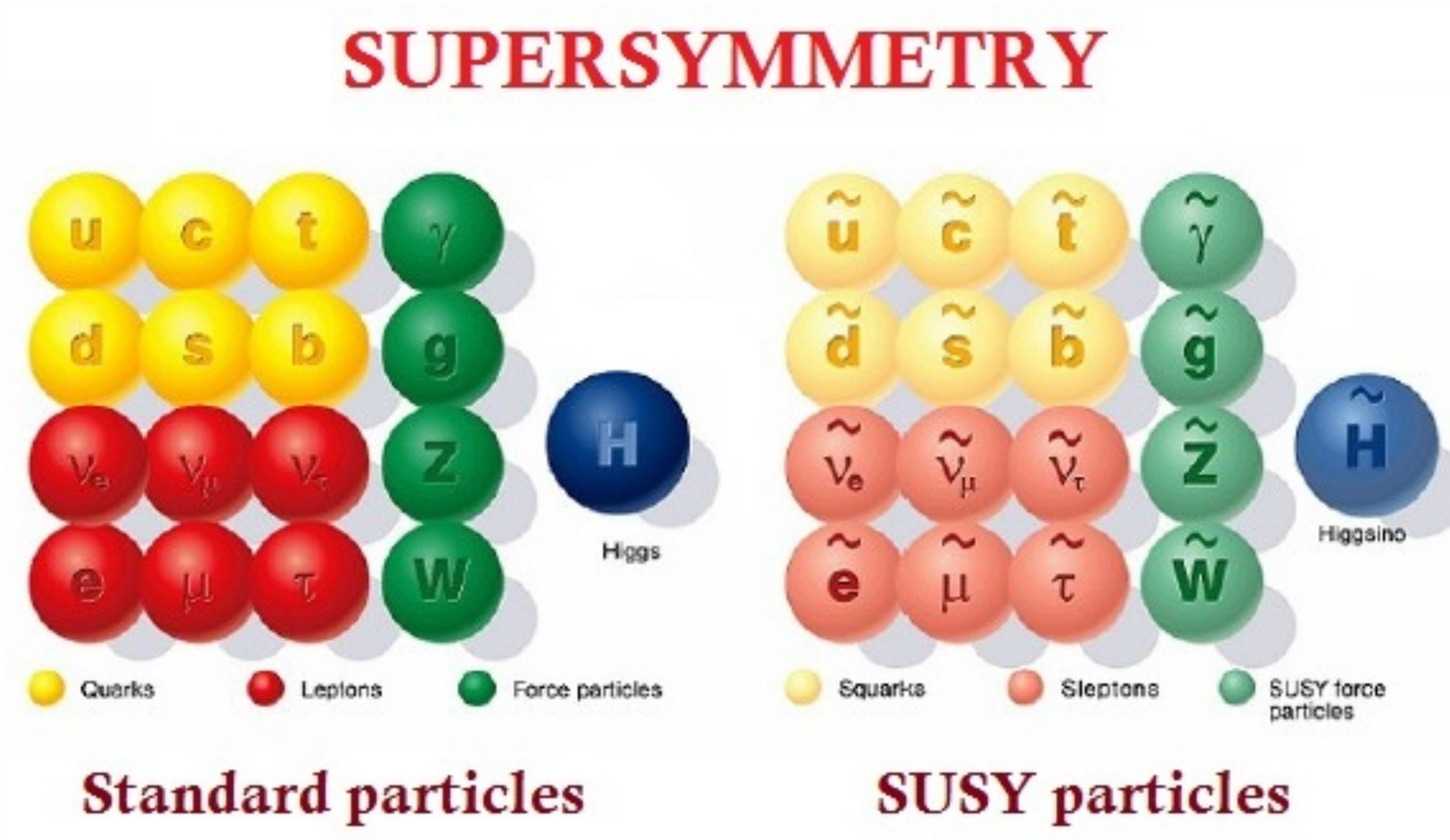
$$\Omega_{\rm DM} \sim \frac{1}{M_p \times {\rm eV} \times \langle \sigma v \rangle_{\rm ann}}$$

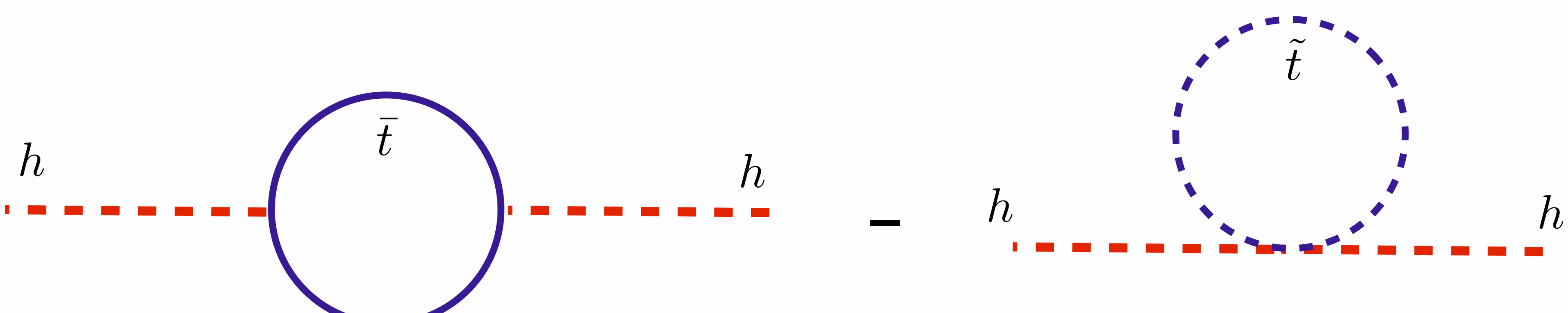
$$\langle \sigma v \rangle_{\rm ann} \sim \frac{\alpha_{eff}^2}{M_{\rm DM}^2} \sim 10^{-26} \frac{{\rm cm}^3}{\rm s} \left(\frac{\rm TeV}{M_{\rm DM}} \right)^2$$



Numerically a stable Weakly Interacting Massive Particle (WIMP) reproduces the DM abundance.

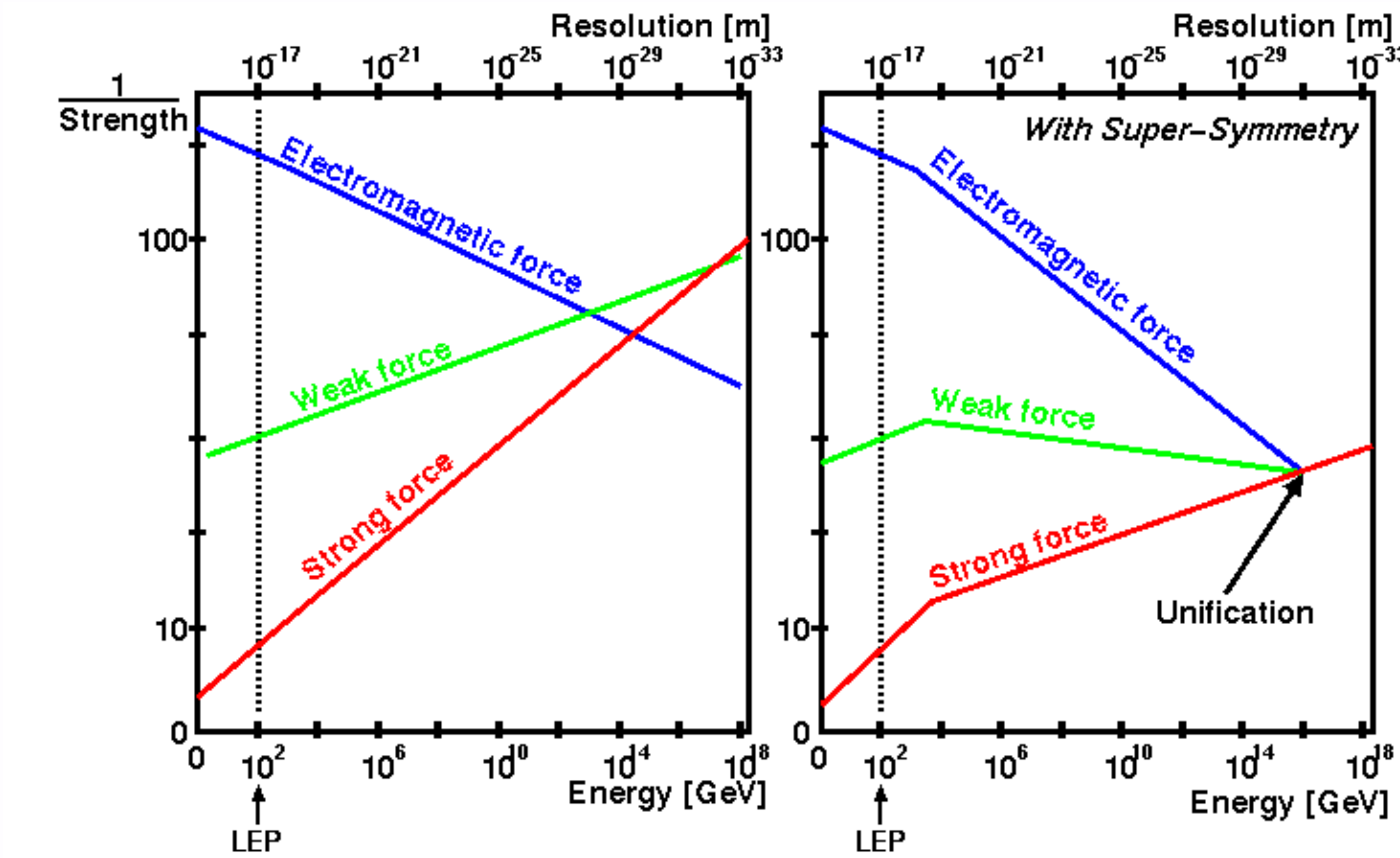
Particle physics suggests the existence of new physics around the electro-weak scale to explain the lightness of the Higgs mass.





$\sim 100\,\mathrm{GeV}$

Explains unification of gauge couplings:



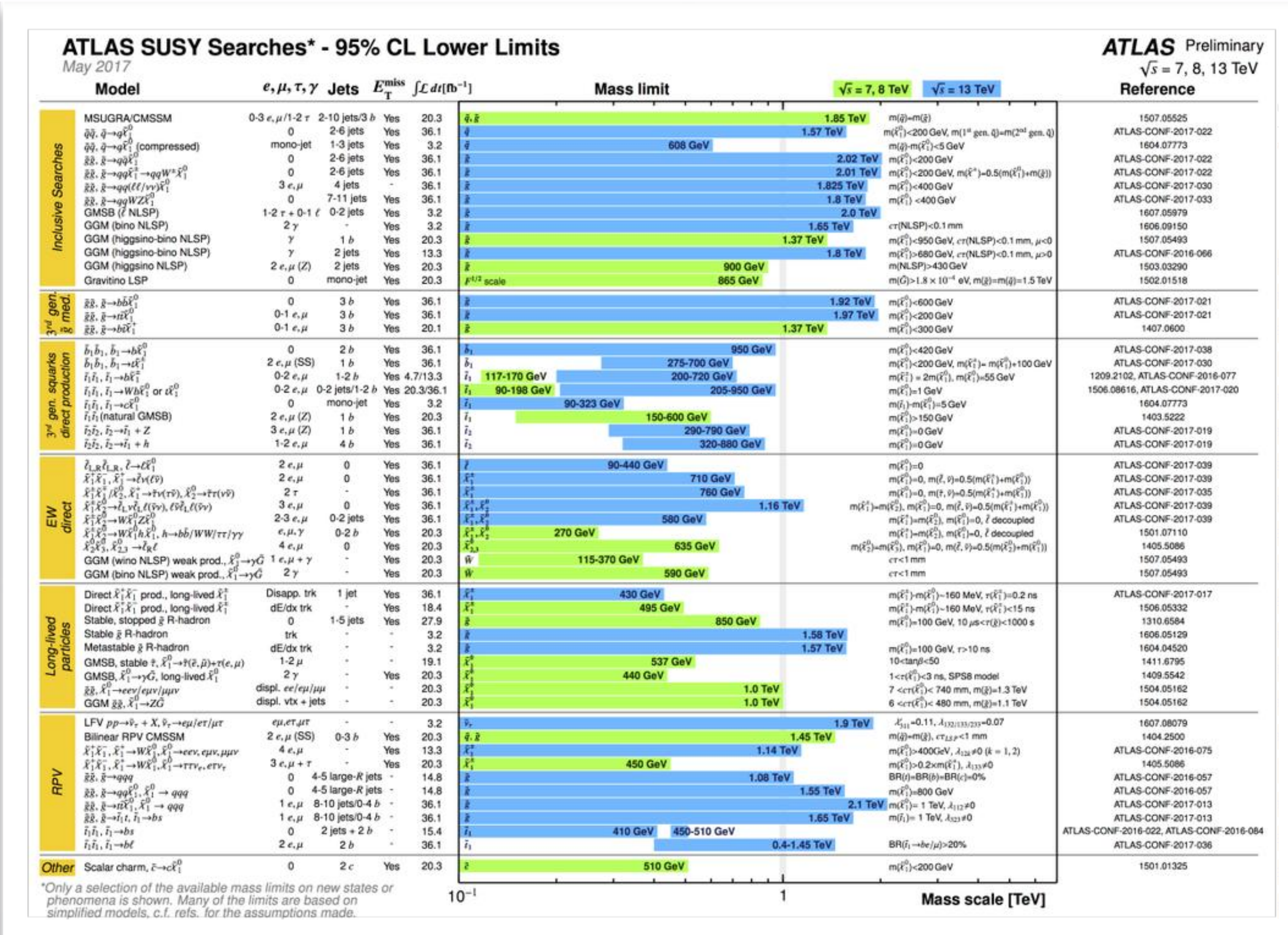
Predicts stable electro-weak DM candidates (neutralinos)

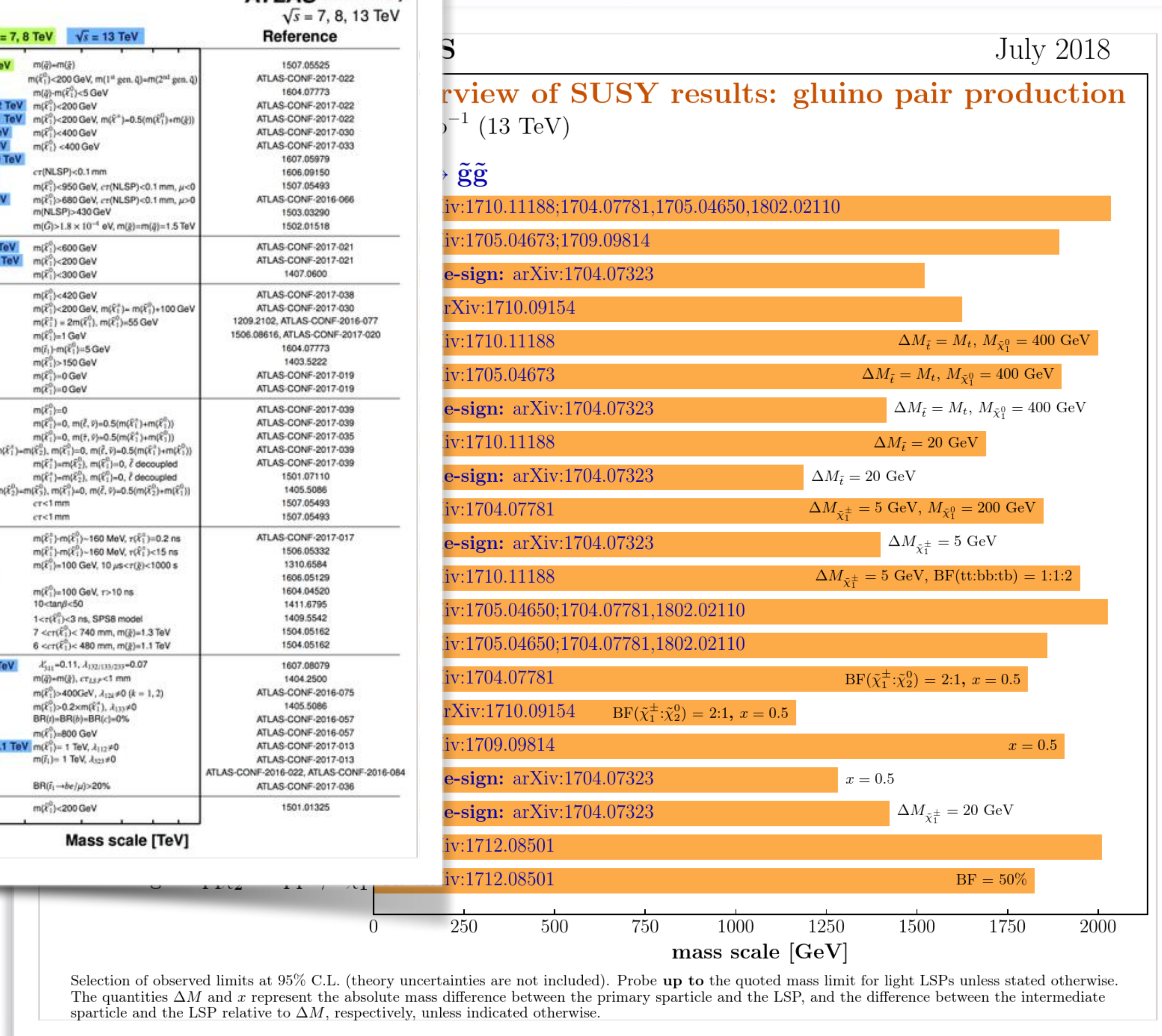
$\tilde{B}$	$\tilde{W}$	$\tilde{H}$
$(1,1)_0$	$(1,3)_0$	$(1,2)_{\frac{1}{2}}$

But...

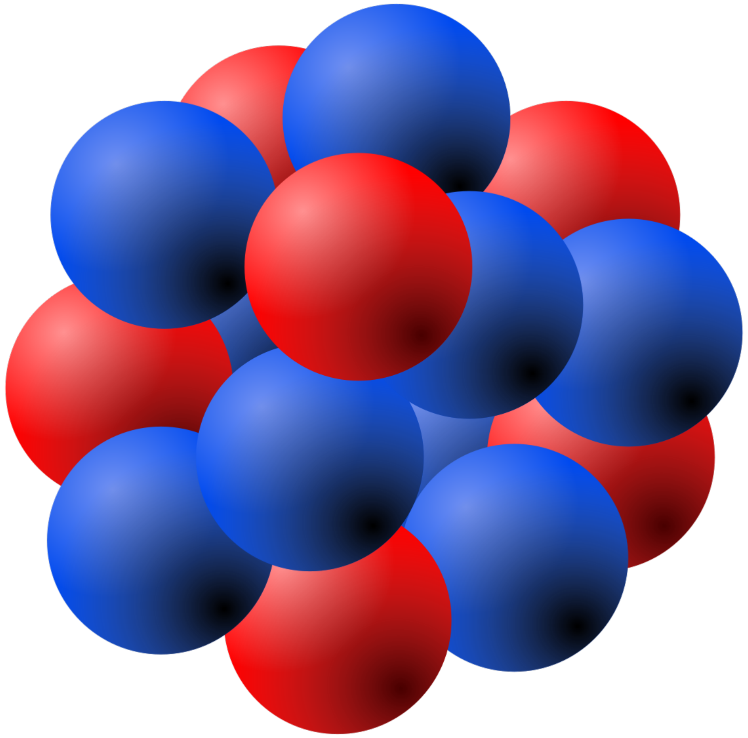

HAVE YOU SEEN ME?
NEUTRALINO
Age: As old as the universe
Weight: Unknown
Size: Tiny
If you have any information on this Neutralino, please contact the nearest scientist.
Dark Matter
100% FAT FREE

LHC:



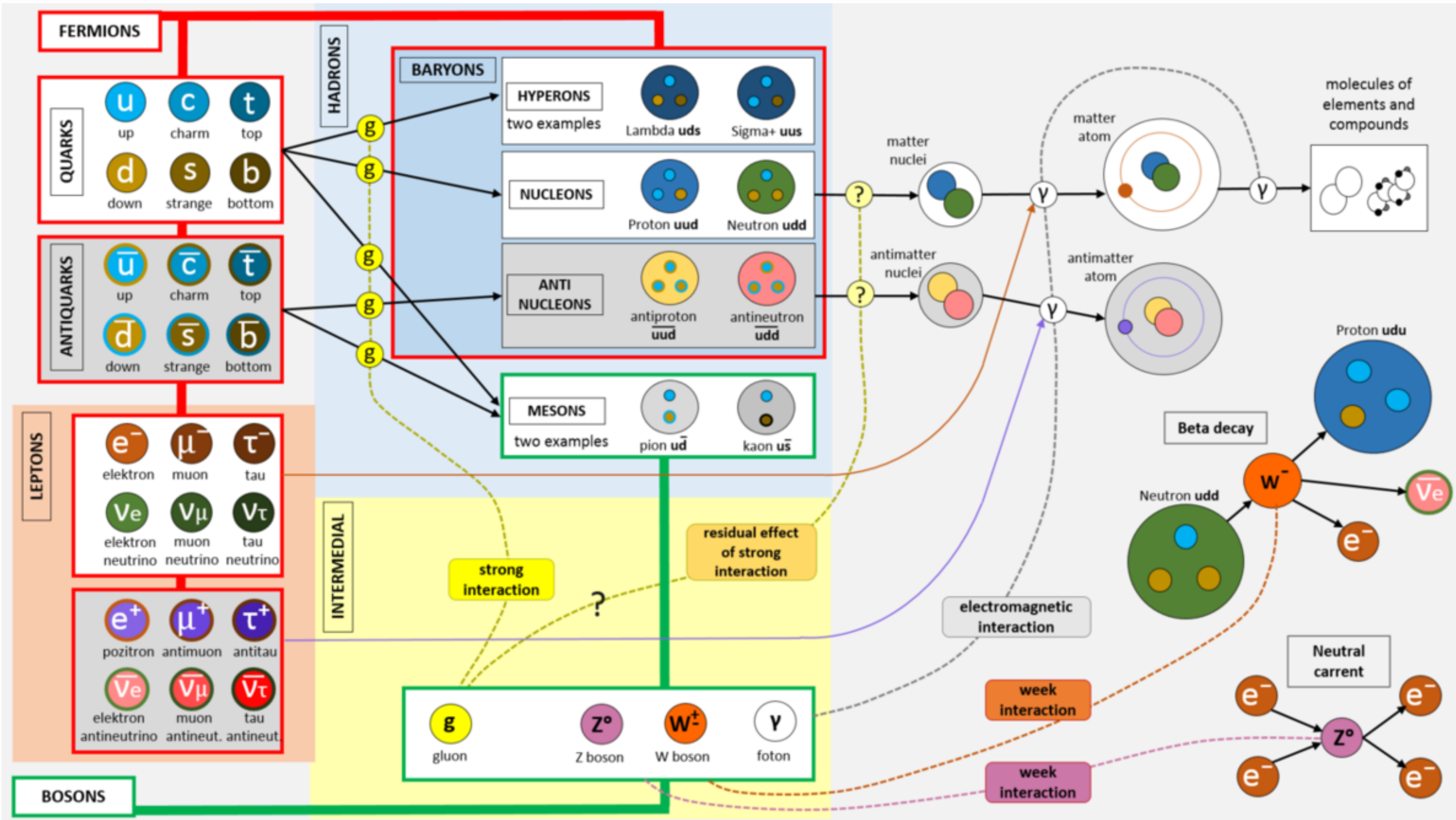


Beside LHC new physics at the electro-weak scale is controversial: flavour, precision tests, simplicity.

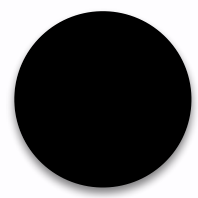


Composite Dark Matter

Standard Model:



Dark Matter:



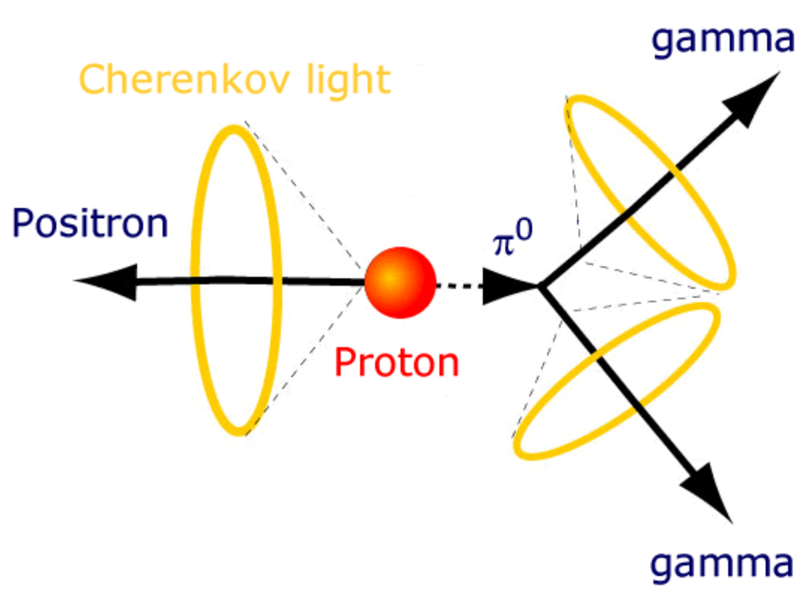
$$(M, s)$$

$$\frac{\text{DM}}{\text{SM}} = 5$$

Maybe too simple?

STABILITY:

The proton lifetime is extremely long:



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

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

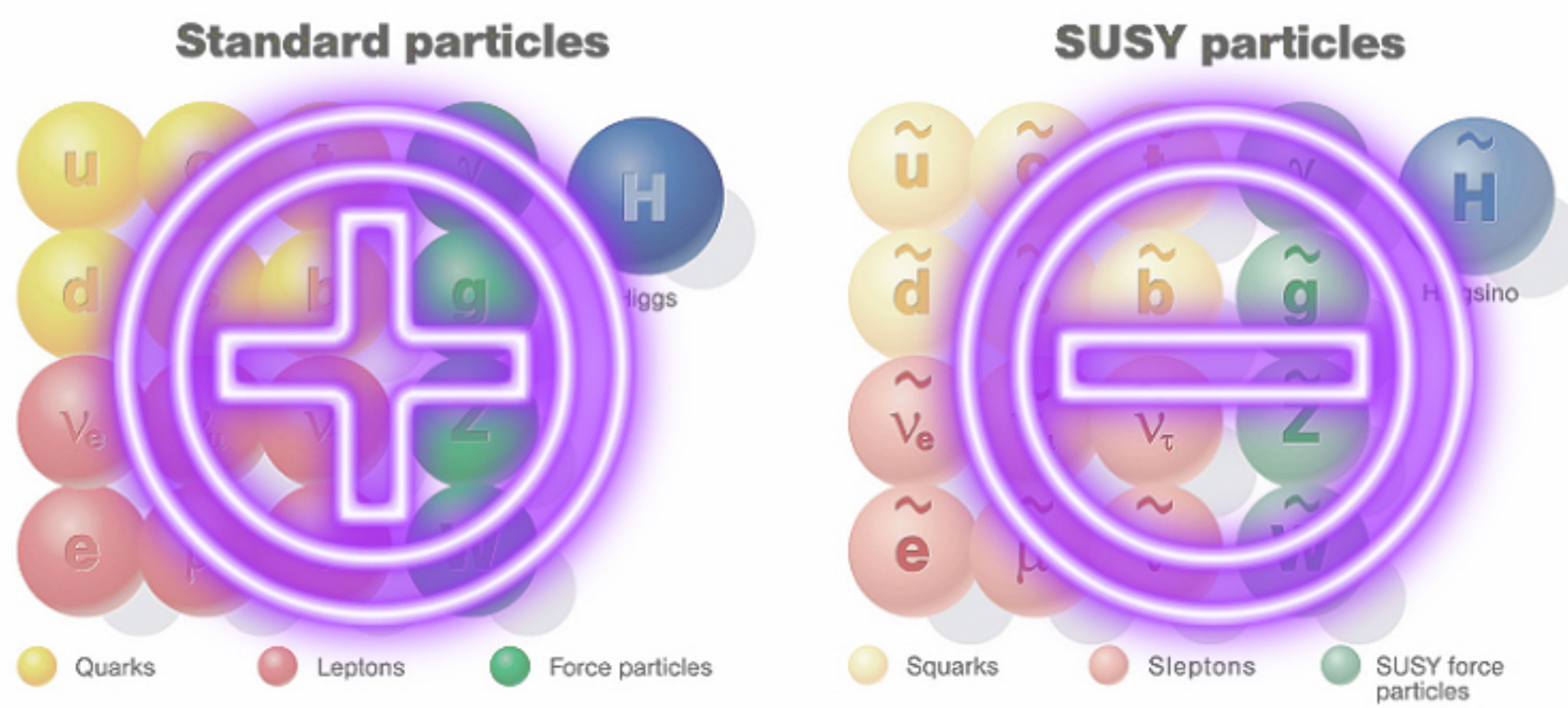
$$U(1)_B \qquad\qquad q \to e^{i\alpha} q$$

Violation:

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

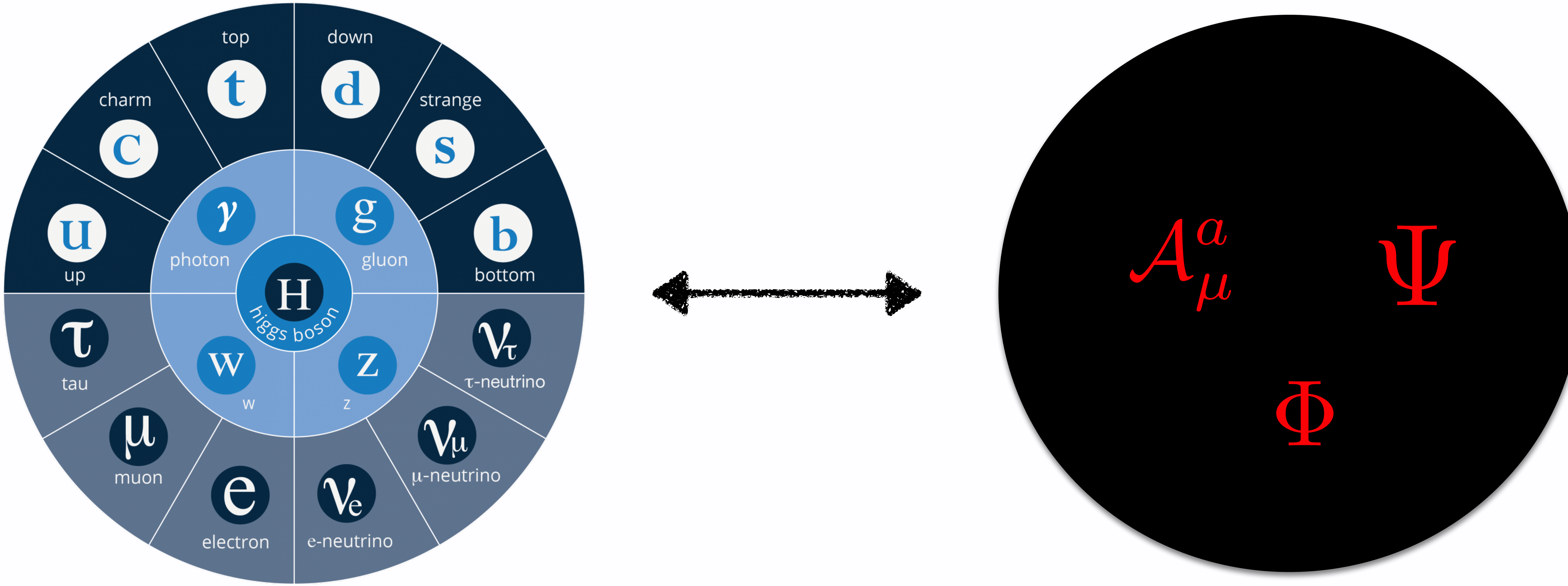
Cosmological stability of DM is often obtained imposing ad hoc global symmetries. In supersymmetry:

R-parity:



Can DM be accidentally stable as the proton?

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



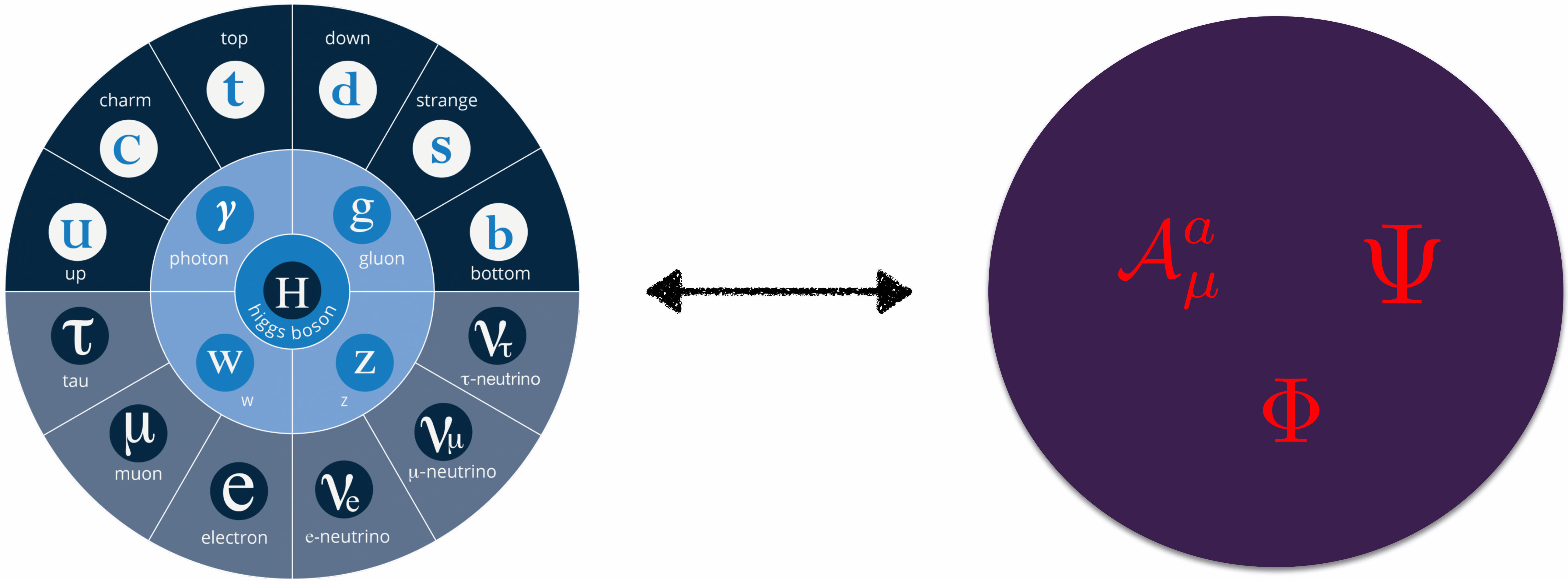
DM is a composite state of a dark sector:

- SM neutral

Interactions with visible sector model dependent

- SM charged

Interactions determined by SM quantum numbers



DM is a composite state of a dark sector:

- SM neutral

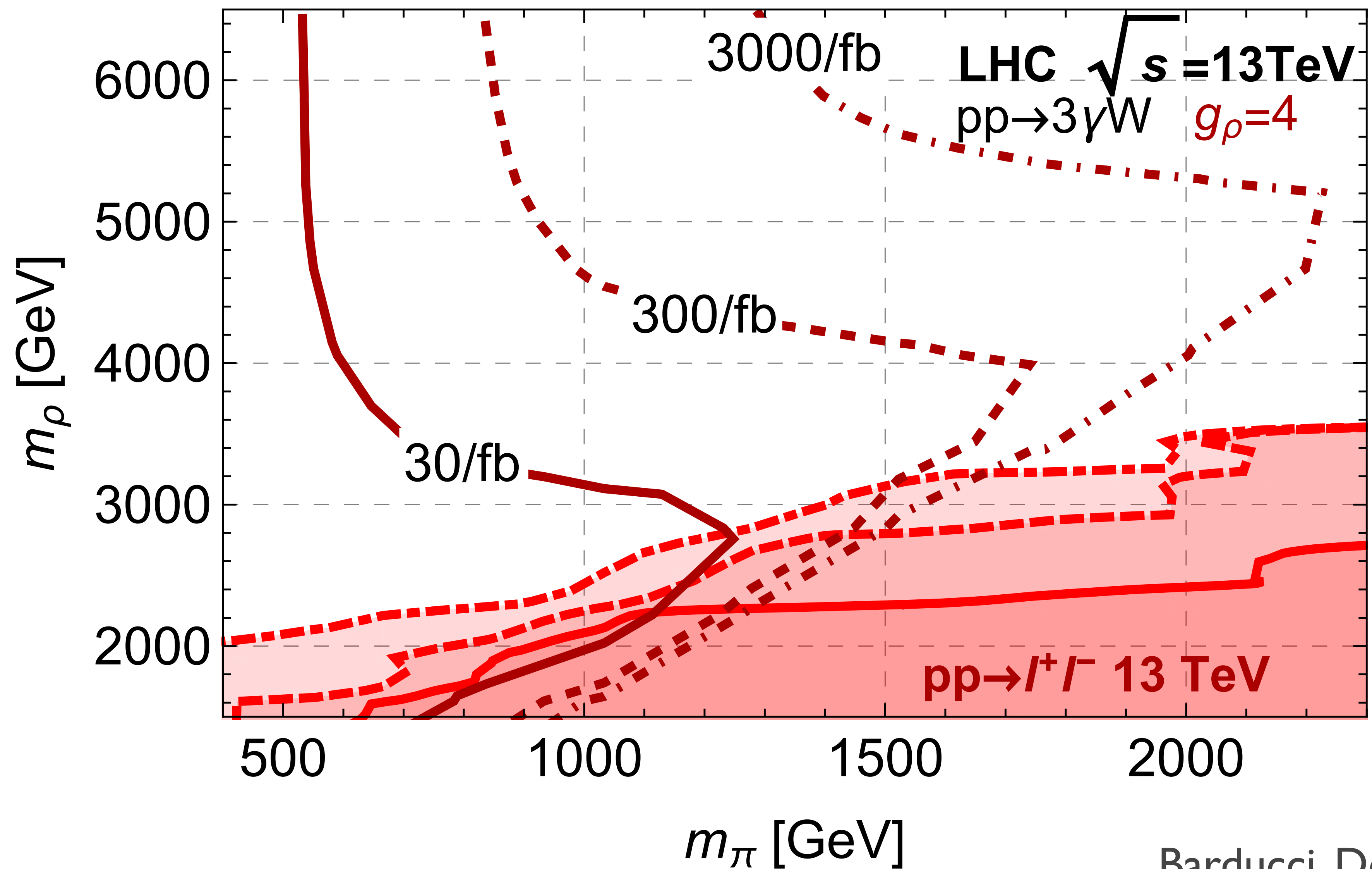
Interactions with visible sector model dependent

- SM charged

Interactions determined by SM quantum numbers

Rich collider phenomenology:

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



Barducci, De Curtis, MR, Tesi '18

LHC: $M_{\rm DM} \gtrsim \rm TeV$

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:

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

Models

- Q-complex (SU(N) fundamental)

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

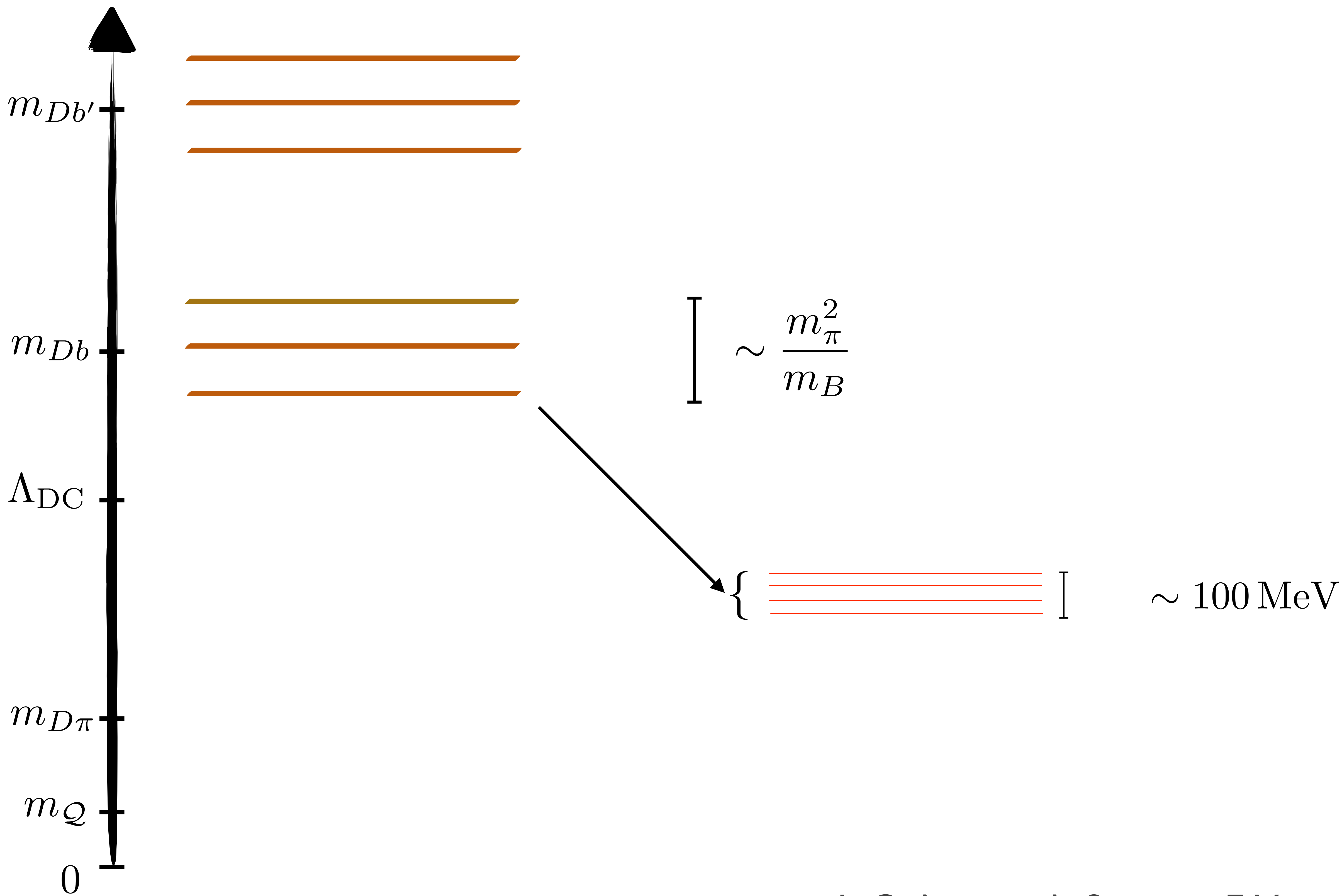
- Q-real (SO(N) fundamental)

Baryon and anti-baryons are the same particle so 2 DM particles can annihilate. Only thermal production.

- Q-adjoint

Bound state of dark quarks and dark gluons.

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



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

Classification:

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

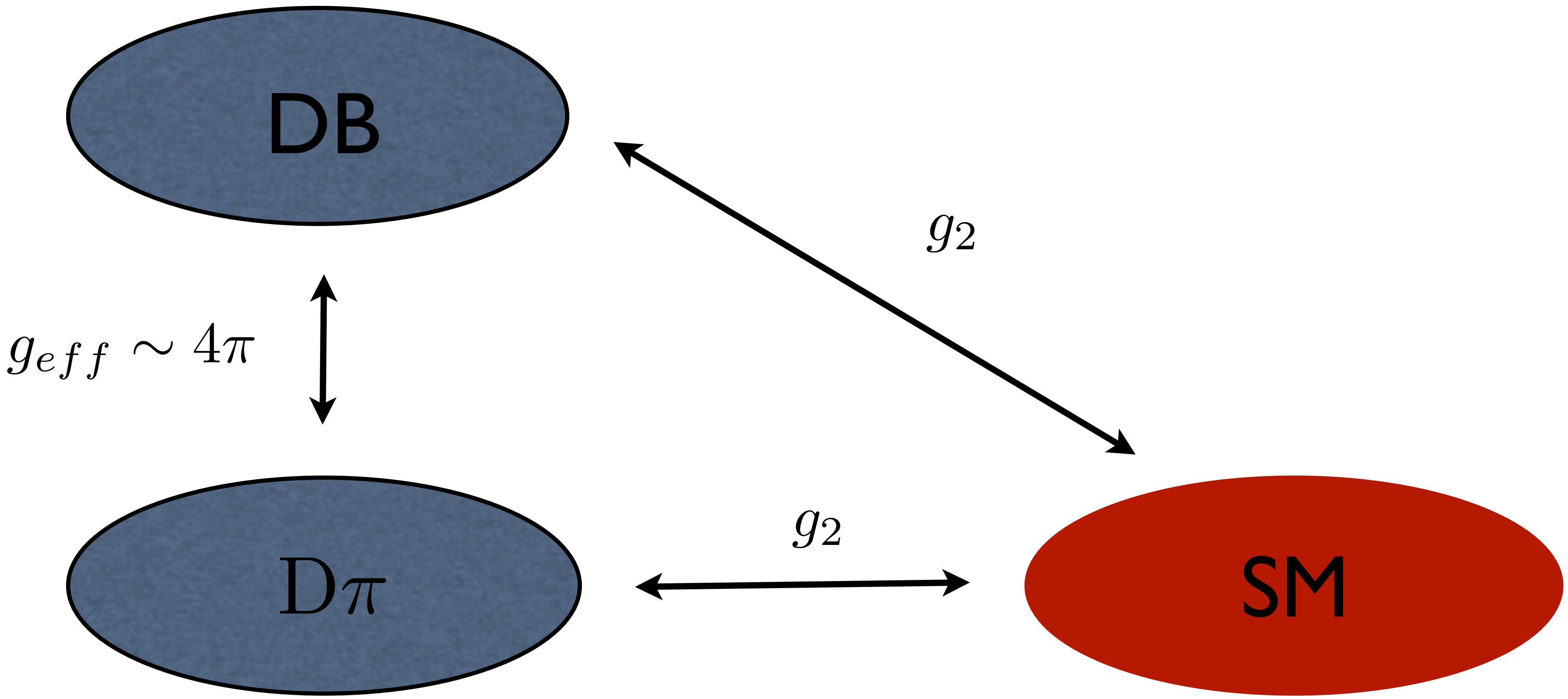
SU(5)	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	charge	name
1	1	1	0	0	N
$\bar{5}$	$\bar{3}$	1	$-1/3$	$-1/3$	D
	1	2	$1/2$	$0, 1$	L
10	$\bar{3}$	1	$-2/3$	$-2/3$	U
	1	1	1	1	E
	3	2	$1/6$	$-1/3, 2/3$	Q
15	3	2	$1/6$	$-1/3, 2/3$	Q
	1	3	1	$0, 1, 2$	T
	6	1	$-2/3$	$-2/3$	S
24	1	3	0	$-1, 0, 1$	V
	8	1	0	0	G
	$\bar{3}$	2	$5/6$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

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 $N = 3, 4, \ldots$	SU(3)$_{\rm TF}$
$\Psi = V$	0	3	3	$VVV = 3$	SU(2)$_L$
$\Psi = N \oplus L$	1	3, .., 14	unstable	$N^{N*} = 1$	SU(2)$_L$
$N_{\rm TF} = 4$			15	$\overline{20}, 20', \ldots$	SU(4)$_{\rm TF}$
$\Psi = V \oplus N$	0	3	3×3	$VVV, VNN = 3,\ VVN = 1$	SU(2)$_L$
$\Psi = N \oplus L \oplus \tilde{E}$	2	3, 4, 5	unstable	$N^{N*} = 1$	SU(2)$_L$
$N_{\rm TF} = 5$			24	$\overline{40}, \overline{50}$	SU(5)$_{\rm TF}$
$\Psi = V \oplus L$	1	3	unstable	$VVV = 3$	SU(2)$_L$
$\Psi = N \oplus L \oplus \tilde{L}$	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)$_L$
$N_{\rm TF} = 6$			35	$70, \overline{105'}$	SU(6)$_{\rm TF}$
$\Psi = V \oplus L \oplus N$	2	3	unstable	$VVV, VNN = 3, VVN = 1$	SU(2)$_L$
$\Psi = V \oplus L \oplus \tilde{E}$	2	3	unstable	$VVV = 3$	SU(2)$_L$
$\Psi = N \oplus L \oplus \tilde{L} \oplus \tilde{E}$	3	3	unstable	$NL\tilde{L}, \tilde{L}\tilde{L}\tilde{E} = 1$	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)$_L$
$N_{\rm TF} = 7$			48	112	SU(7)$_{\rm TF}$
$\Psi = L \oplus \tilde{L} \oplus E \oplus \tilde{E} \oplus N$	4	3	unstable	$LLE, \tilde{L}\tilde{L}\tilde{E}, L\tilde{L}N, E\tilde{E}N = 1$	SU(2)$_L$
$\Psi = N \oplus L \oplus \tilde{E} \oplus V$	3	3	unstable	$VVV, VNN = 3,\ VVN = 1$	SU(2)$_L$
$N_{\rm TF} = 9$			80	240	SU(9)$_{\rm TF}$
$\Psi = Q \oplus \tilde{D}$	1	3	unstable	$QQ\tilde{D} = 1$	SU(2)$_L$
$N_{\rm TF} = 12$			143	572	SU(12)$_{\rm TF}$
$\Psi = Q \oplus \tilde{D} \oplus \tilde{U}$	2	3	unstable	$QQ\tilde{D}, \tilde{D}\tilde{D}\tilde{U} = 1$	SU(2)$_L$

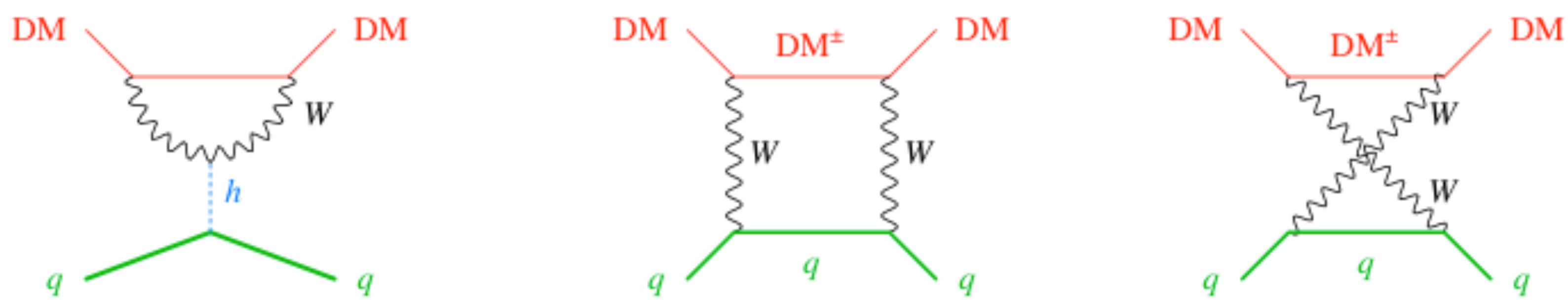
Thermal abundance:

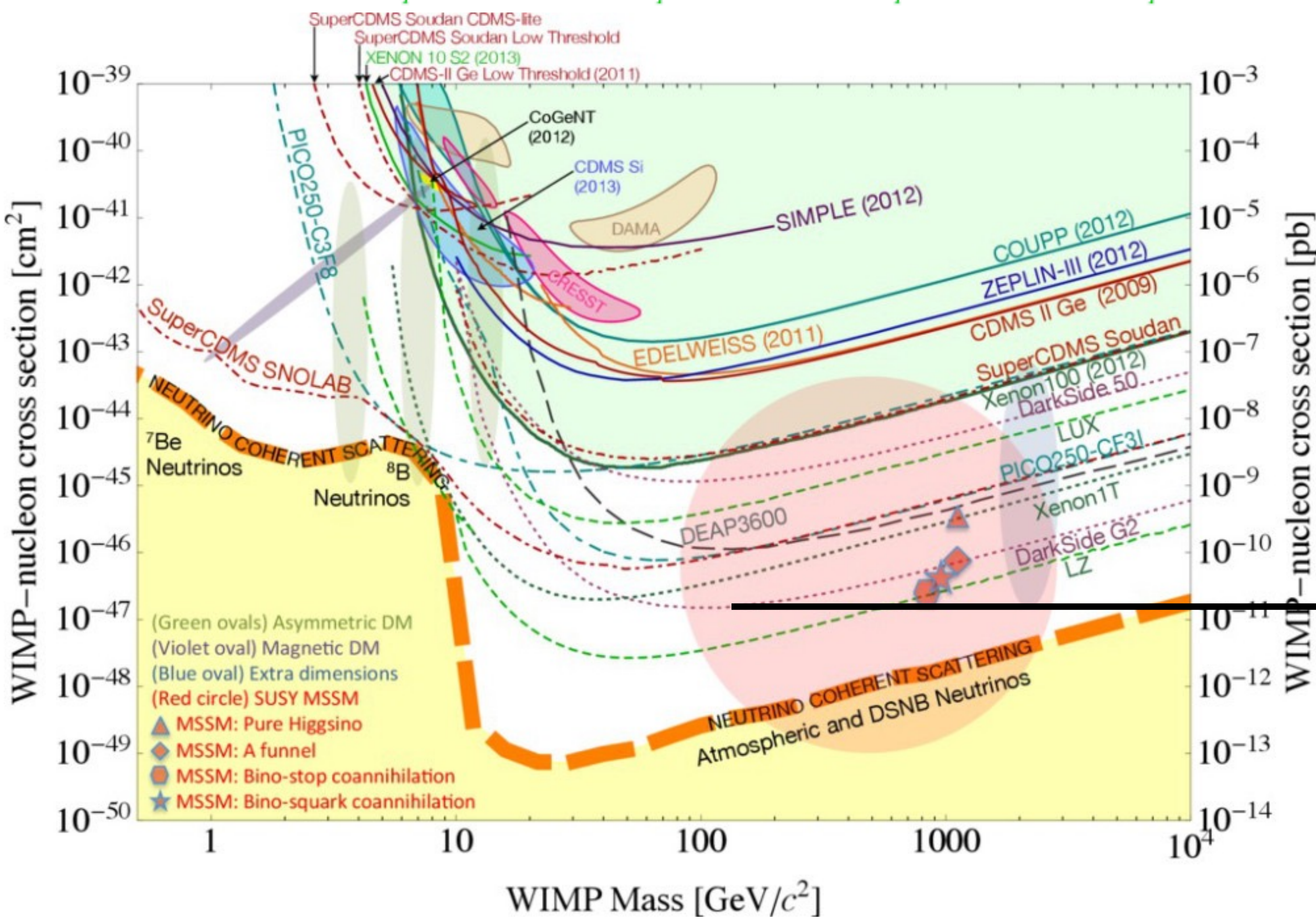


$$\langle \sigma_{B\bar{B}}^{ANN} v \rangle \sim \frac{4\pi}{m_B^2} \longrightarrow m_B \sim 100\,\mathrm{TeV}$$

DM could also be asymmetric.

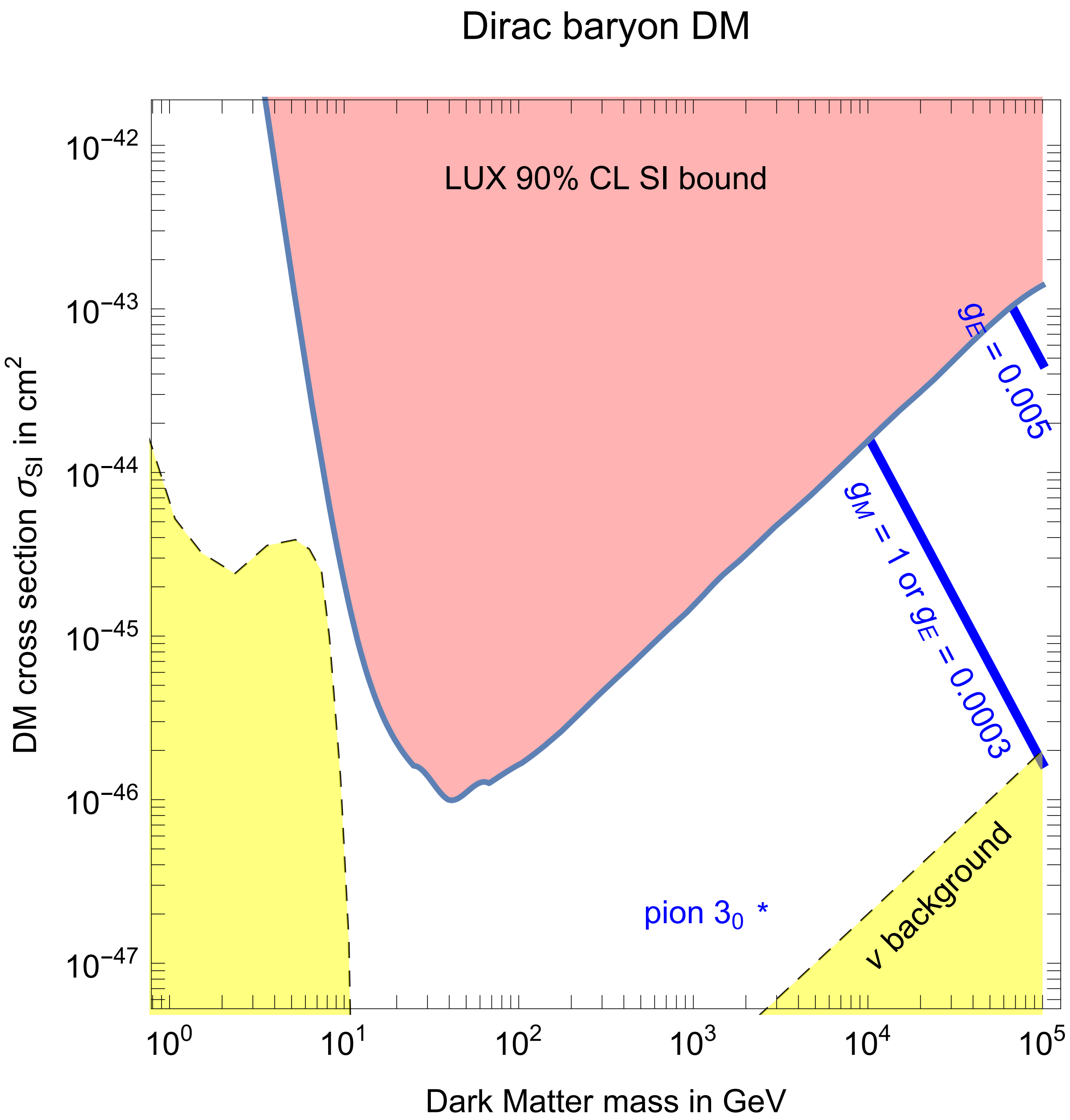
If DB has SM charges it interacts as WIMPS.





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

Yukawa couplings very constrained.

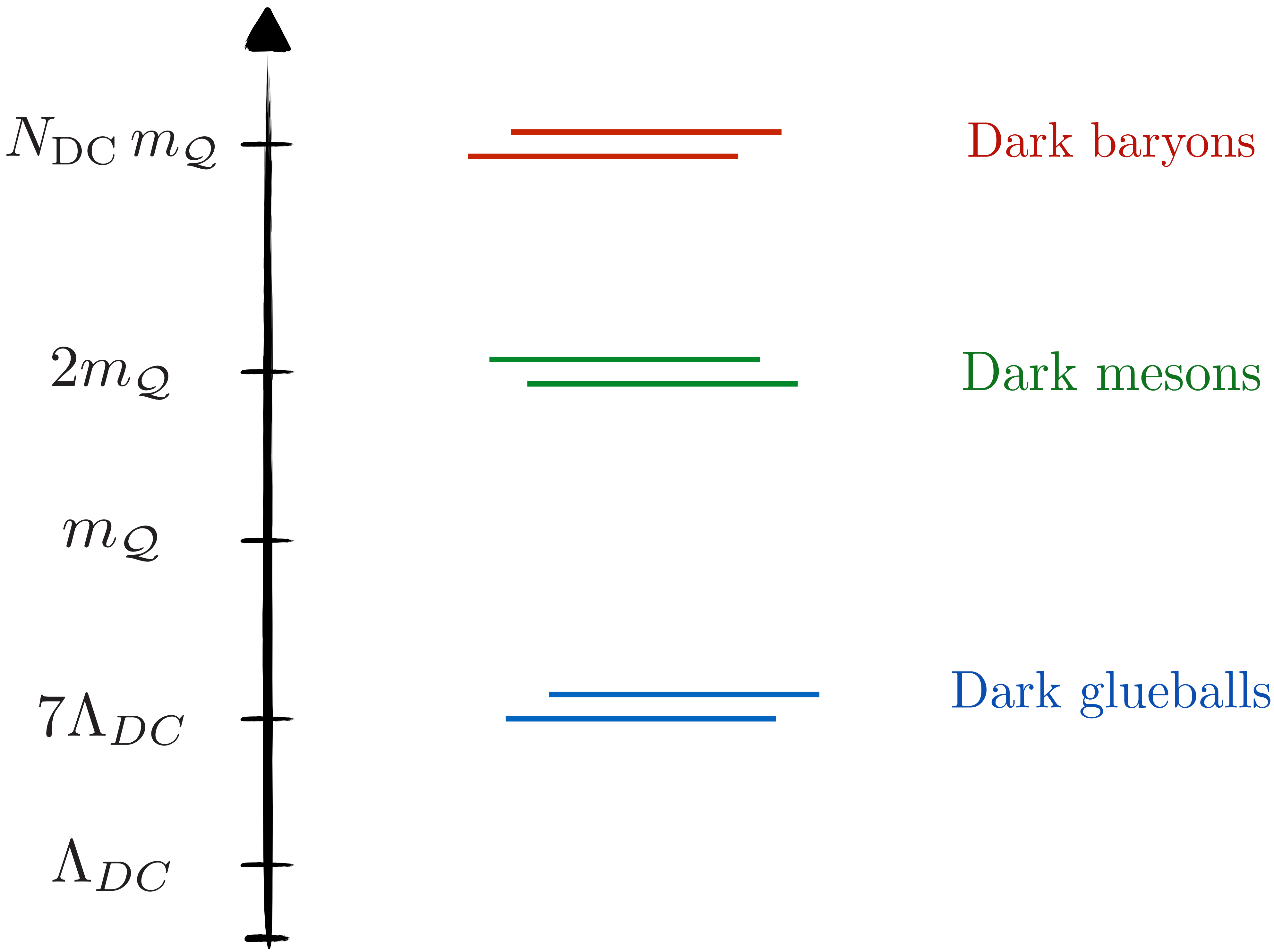


Dark baryons can have large electric and magnetic dipole moments relevant for direct detection:

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

- Heavy Dark Quarks:

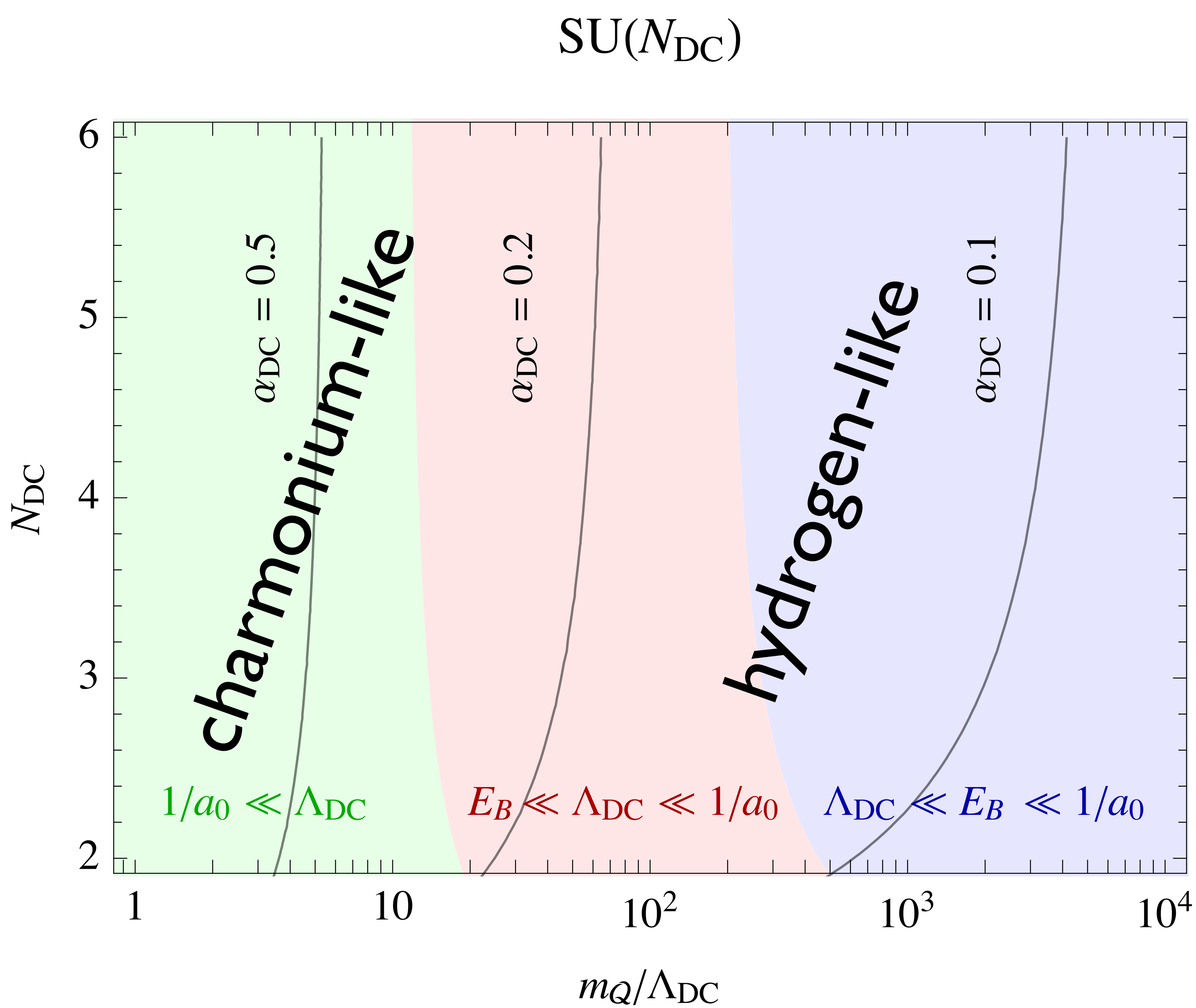
$(m_Q > \Lambda_{DC})$

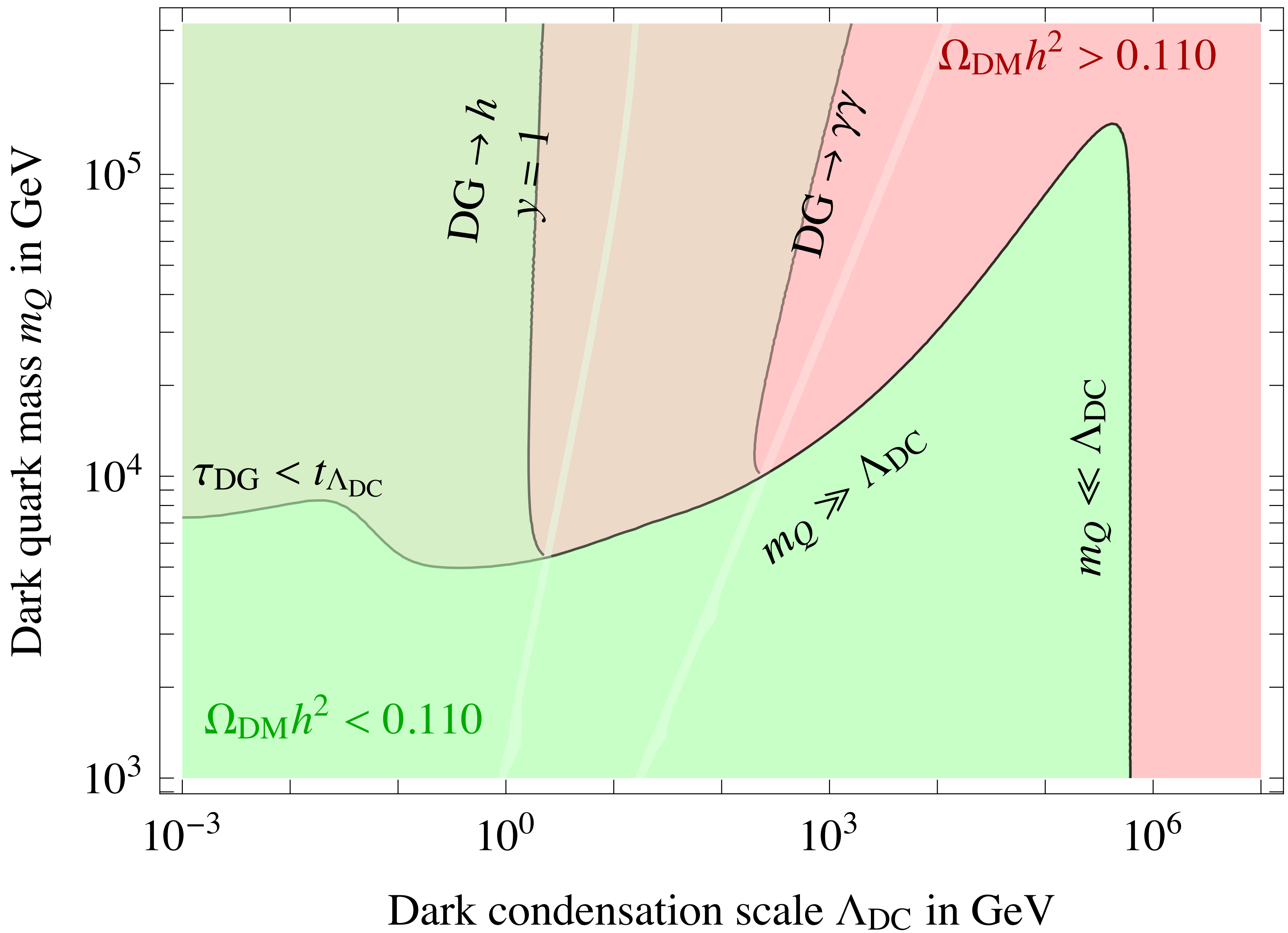


- 1707.05380 with A. Mitridate, J. Smirnov, A. Strumia

DM is a non-relativistic bound states N fermions:

$$V \sim -\frac{\alpha_{DC}}{r} + \Lambda_{DC}^2 r \qquad \Lambda_{DC} \sim m_Q \exp\left[-\frac{6\pi}{11 C_2(G)\alpha_{DC}(m_Q)}\right]$$

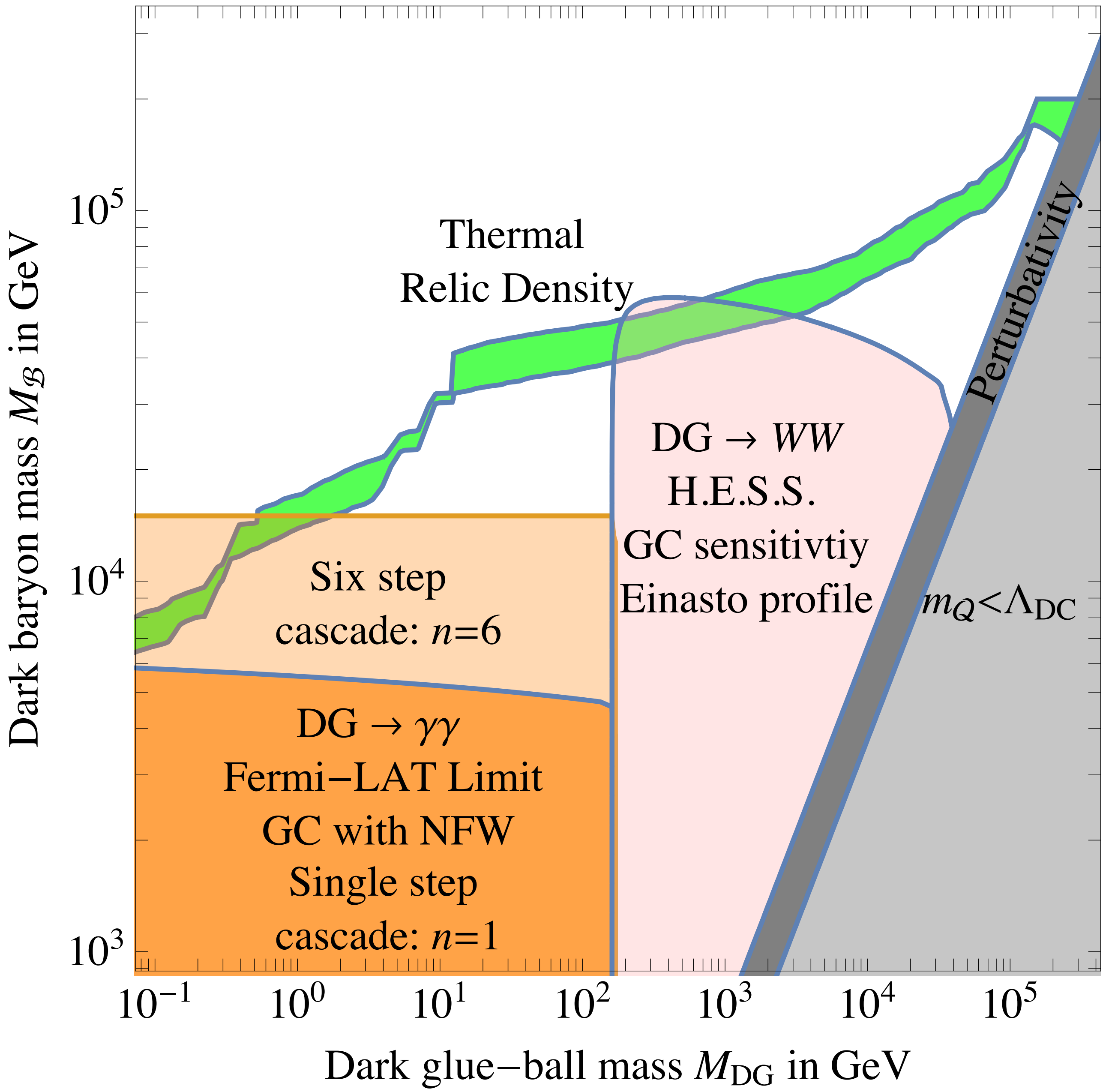




In the non-relativistic regime thermal abundance of DM can be obtained for masses down to 5 TeV.

Indirect detection:

At low energies annihilation cross-section of extended objects is larger than particle physics size:



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

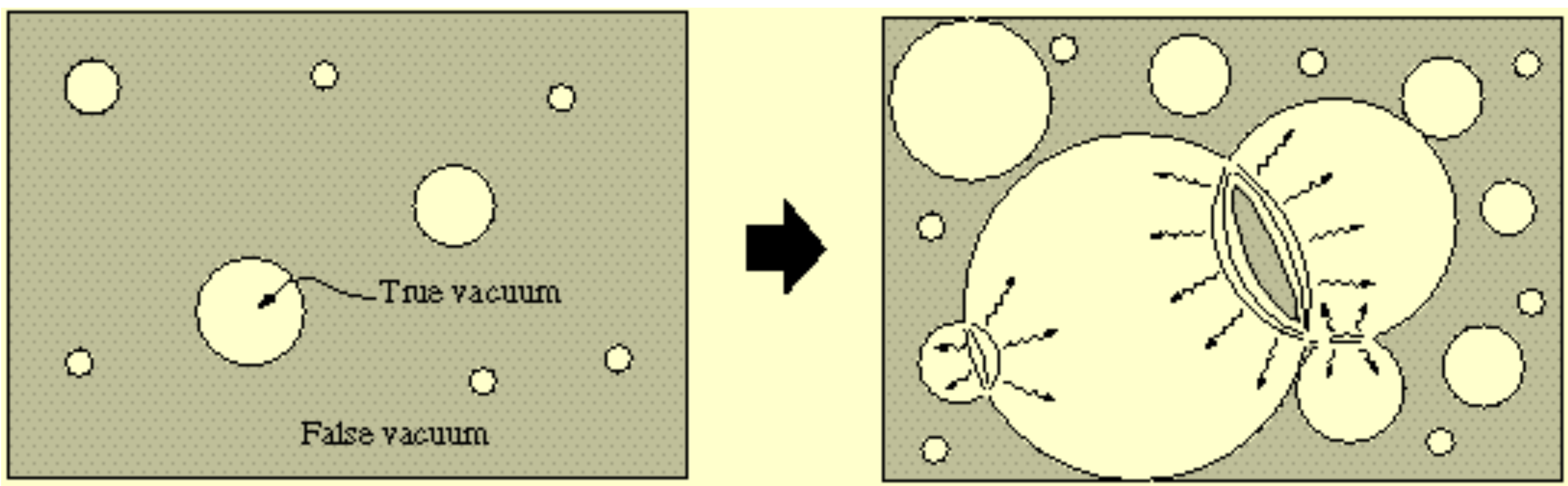
$$\sigma_{B\bar{B}} v_{\rm rel} \sim \frac{1}{\alpha_{DC}} \frac{\pi}{m_Q^2}$$

Gravity Waves

Confinement phase transitions are often 1st order:

$$3 \leq N_F \leq 4N \ \text{ and } \ N > 3 \qquad \textbf{or} \qquad N_F = 0$$

$$T_c \sim \Lambda_{\rm DC}$$



A background of stochastic gravitational waves is produced through the bubble dynamics.

Details difficult to compute. Sounds waves:

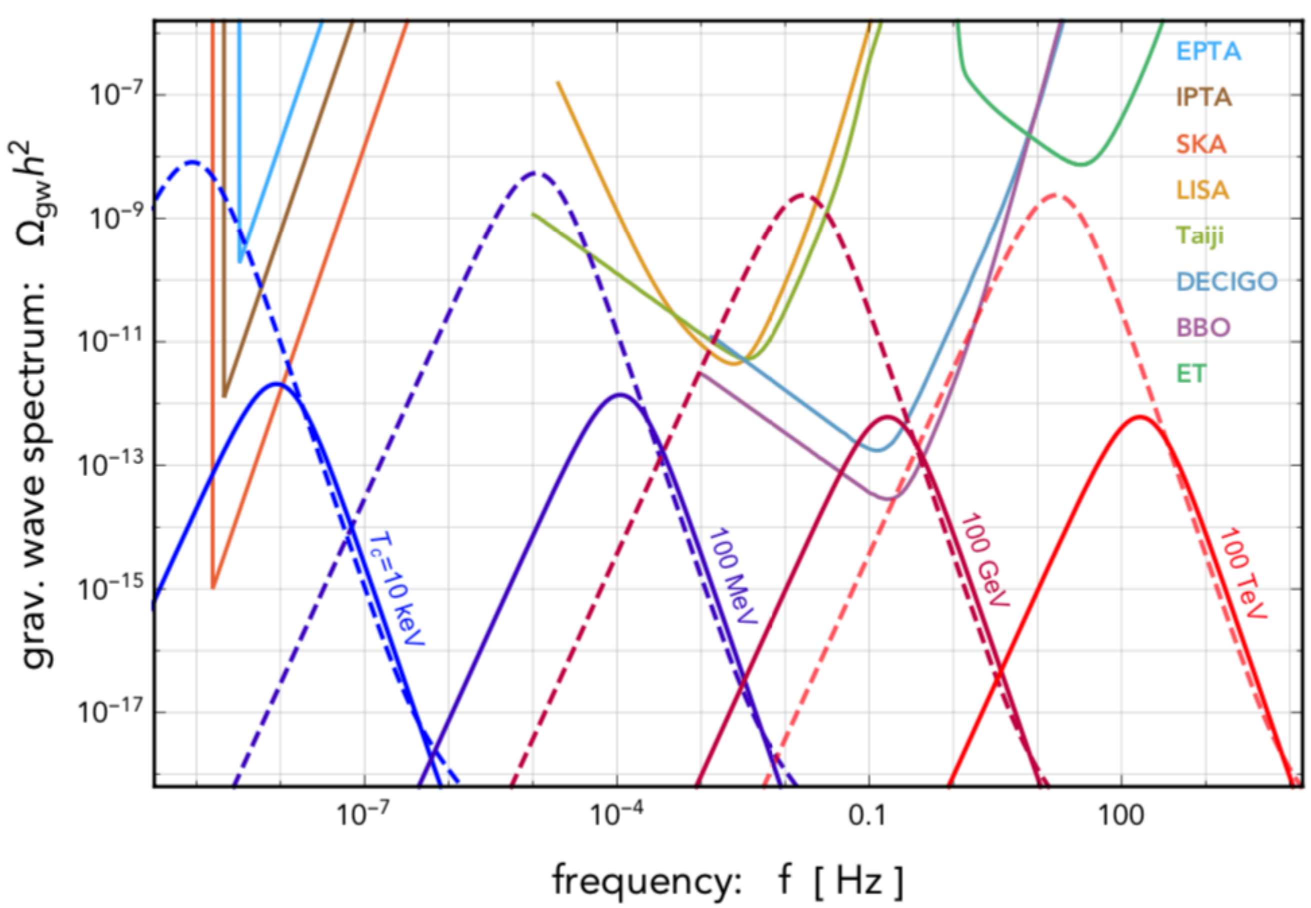
Frequency:

$$f_{\rm peak}^{\rm sw} \sim 10^{-2} \left(\frac{\beta}{100\,H}\right) \left(\frac{T_c}{\rm TeV}\right)$$

Amplitude:

$$\Omega_{\rm GW}^{\rm sw} \sim 10^{-8} \left(\frac{100\,H}{\beta}\right) \left(\frac{k_v \alpha}{1+\alpha}\right)^2$$

Possibly accessible to future experiments!



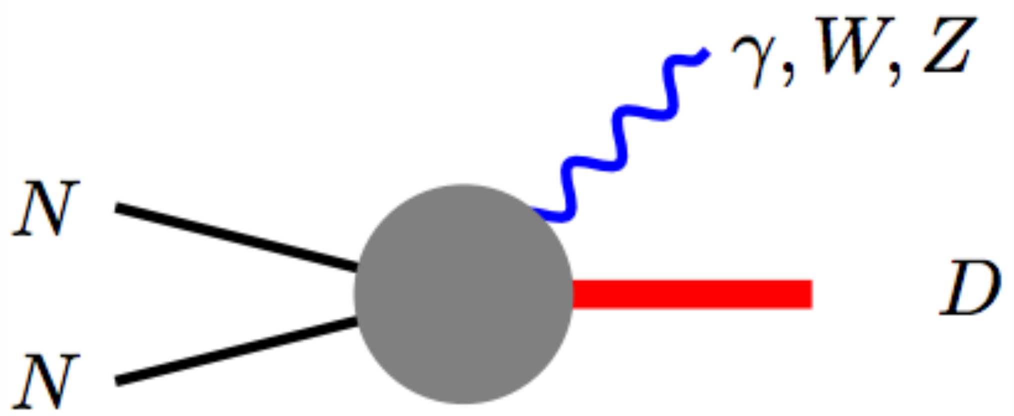
$$(\alpha,\, \beta/H) = (0.1/1,\, 10^4/10^3)$$

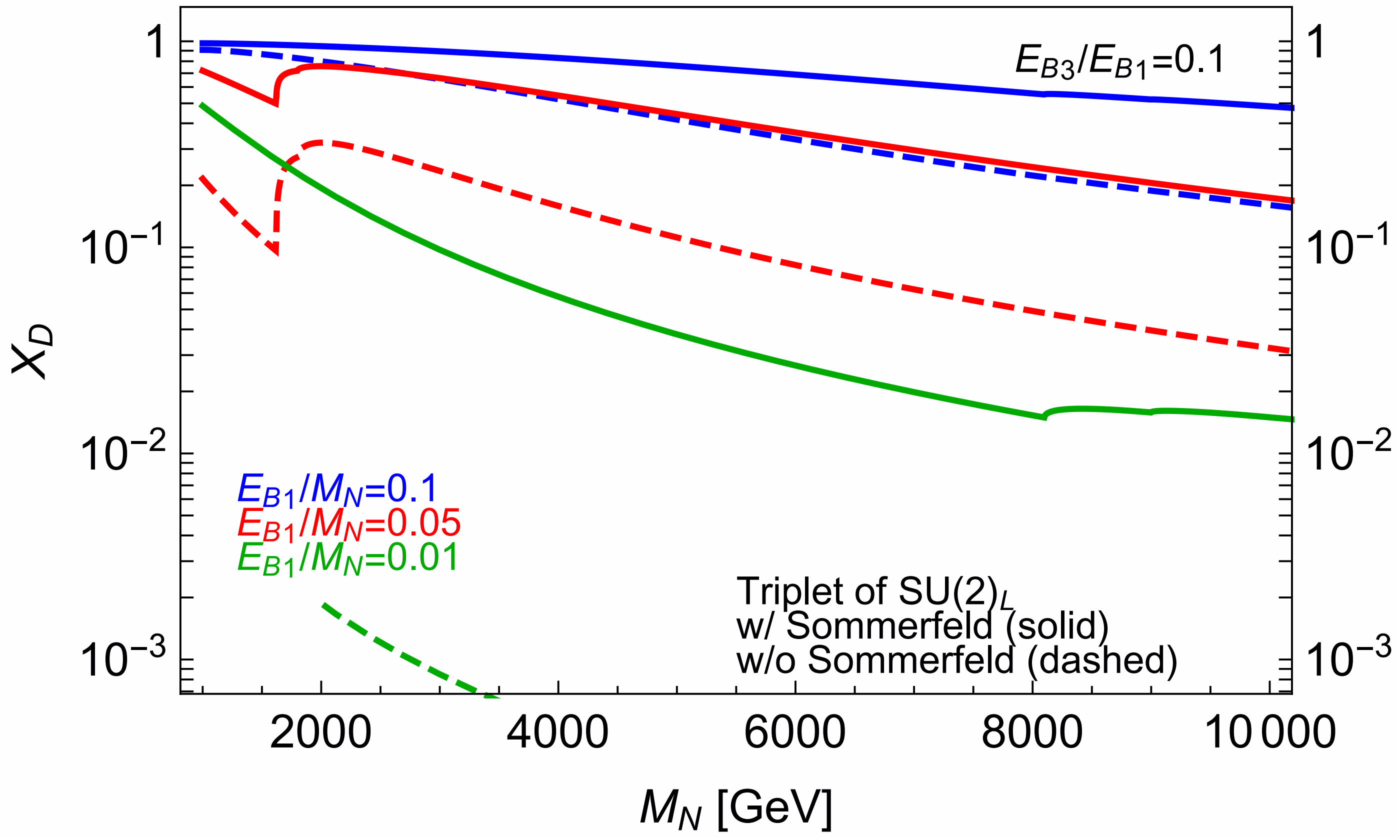
Bai, Long, Lu '18

Dark BBN

MR, Tesi '18

If DM is made of dark baryons it could undergo nucleosynthesis and produce heavier elements.





For DM in the TeV range a fraction could be in the form of dark deuterium and traces of tritium.

If DM is a singlet it could be lighter and deuterium could be formed efficiently. Elements with very large atomic number could also be formed.

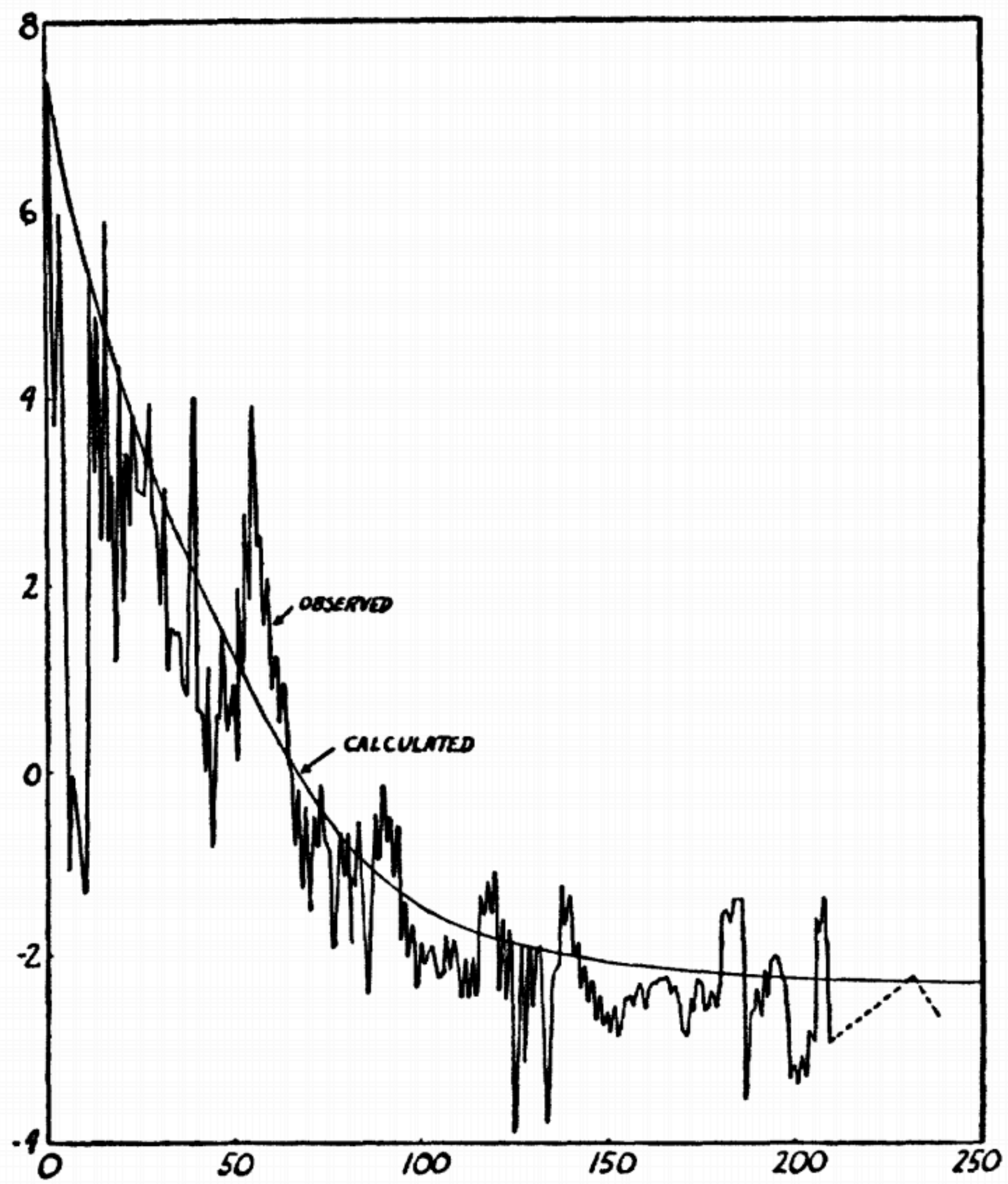


FIG. 1.

Log of relative abundance

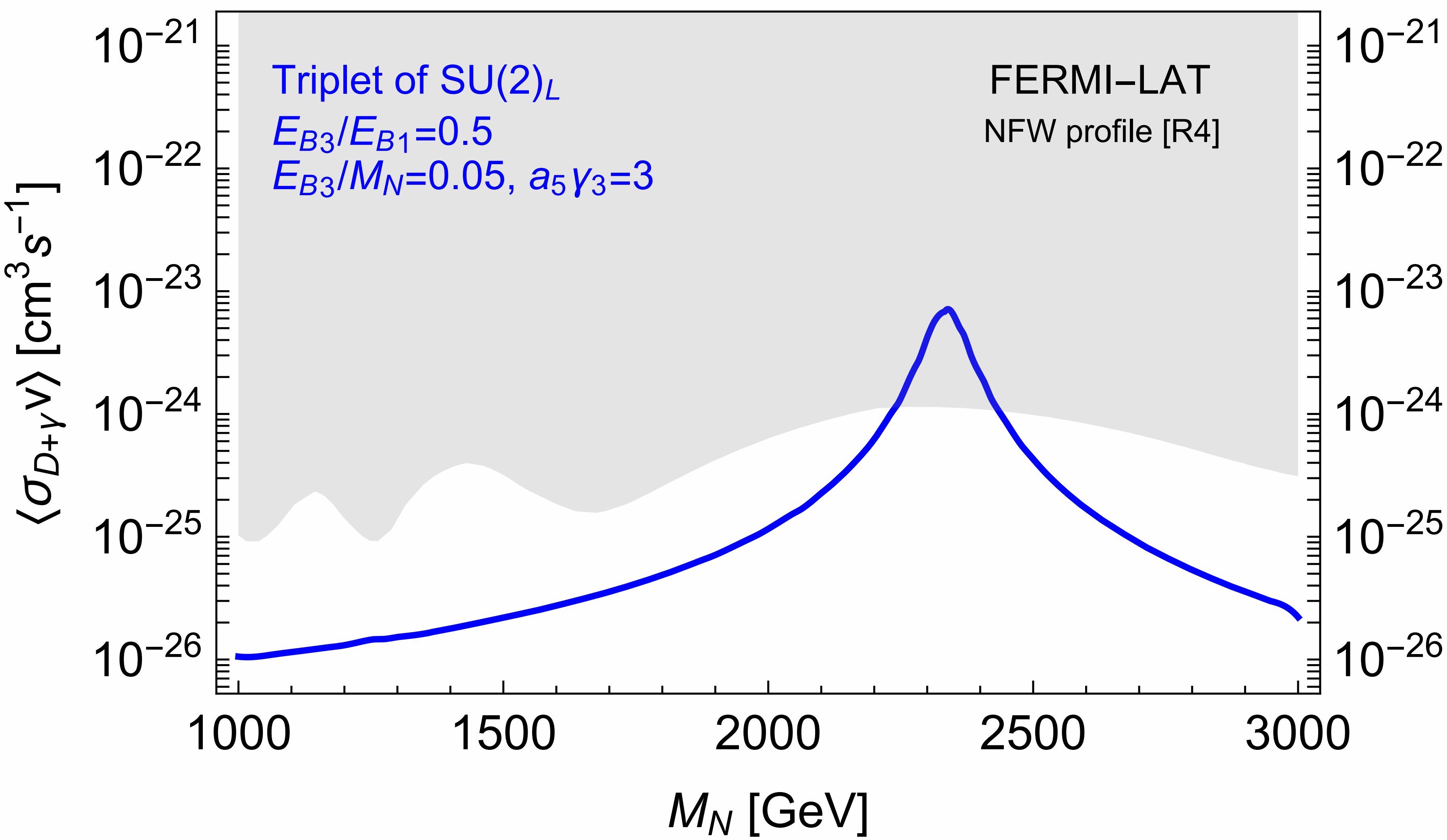
Atomic weight

Alpher, Bethe, Gamow '48

Indirect detection:

Deuterium could be formed today emitting a monochromatic photon that could be within the reach Fermi and other gamma-ray telescopes:

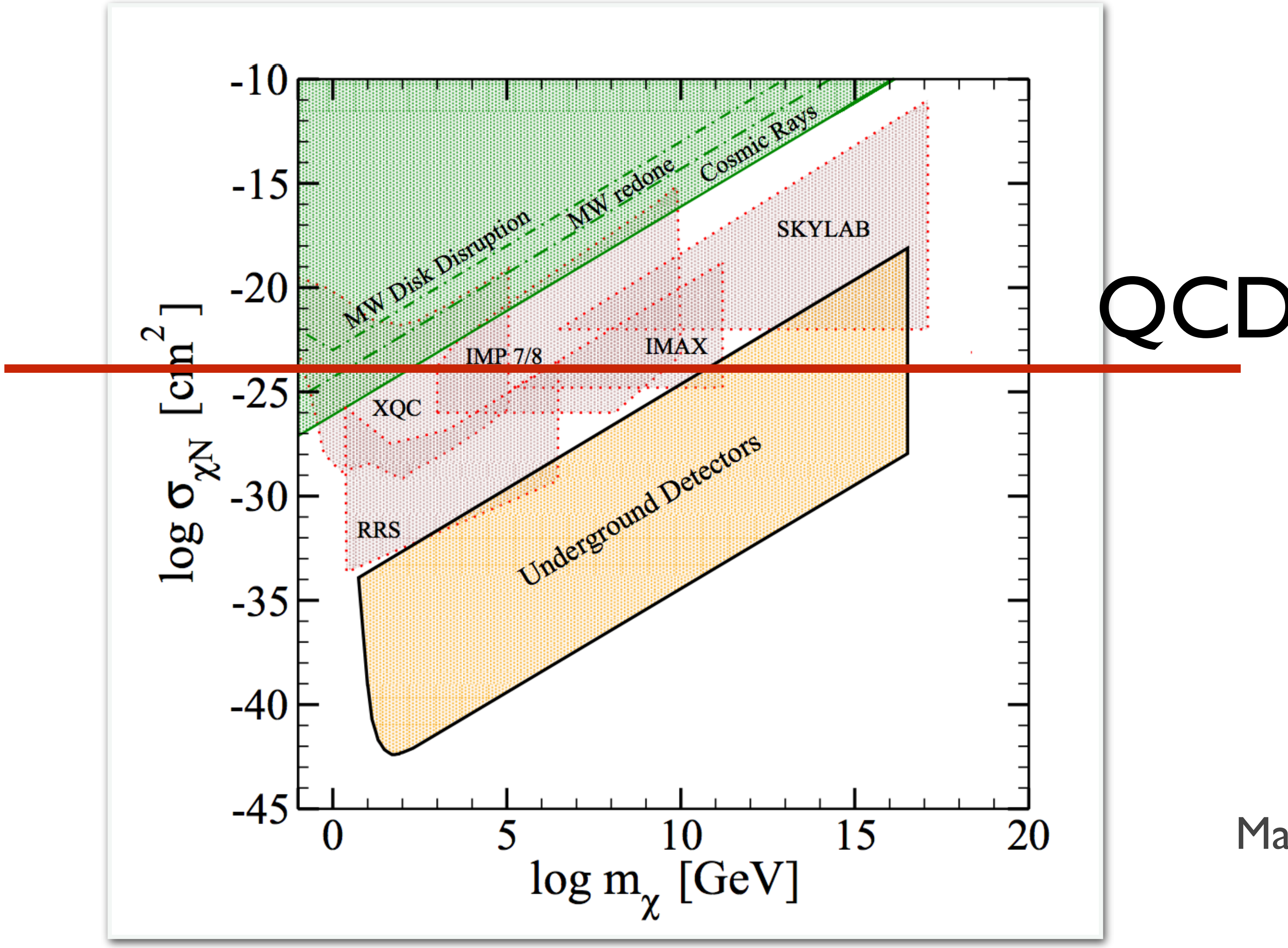
$$E_\gamma \approx E_B$$



Colored Dark Matter

- 1801.01135 with V. De Luca, A. Mitridate, J. Smirnov, A. Strumia

Dark Matter should not have charge or color.



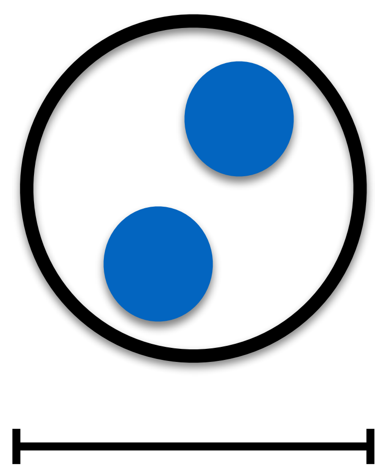
Mack, Beacom, Bertone. '07

Counter Example:

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

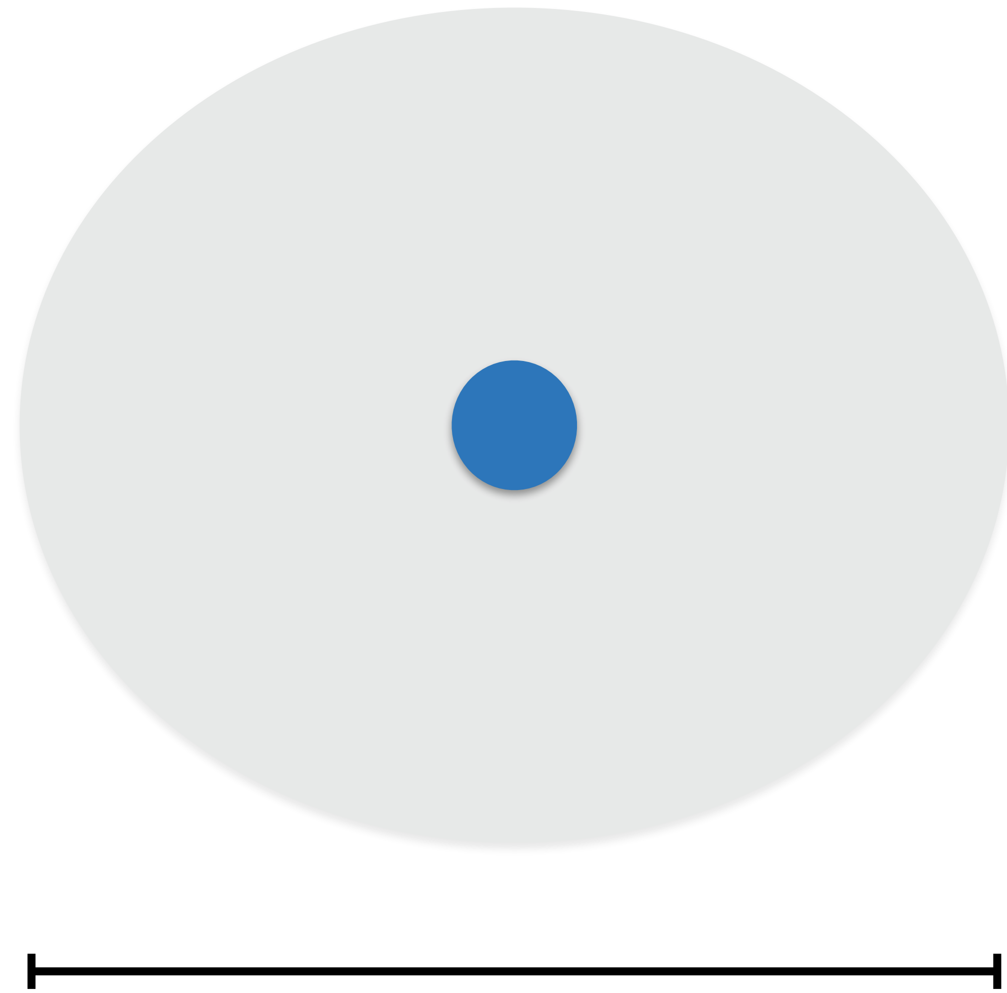
$$Q = (8,1)_0 \qquad\qquad M_Q \gg \Lambda_{QCD}$$

Stable hadrons:



$(\alpha_3 M_Q)^{-1}$

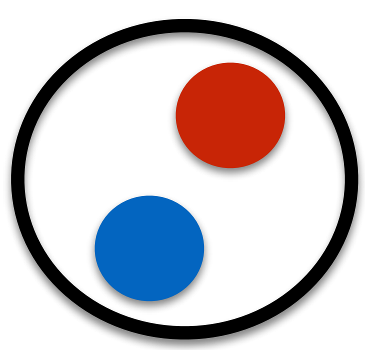
$E_B \sim \alpha_3^2 M_Q$



Λ_{QCD}^{-1}

$E_B \sim \Lambda_{QCD}$

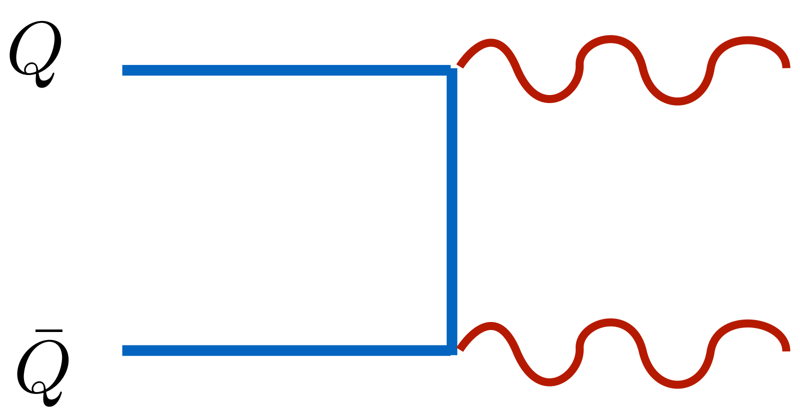
Unstable hadrons:

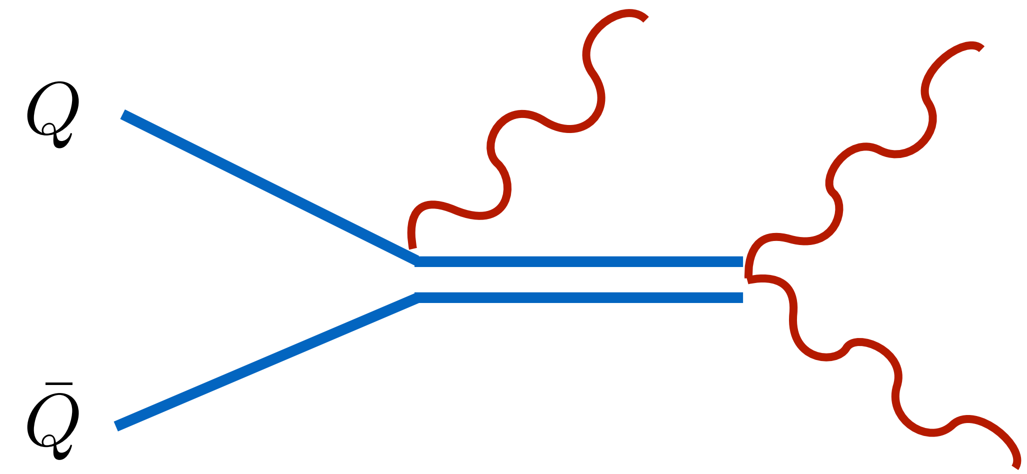


$\Gamma(Q\bar{Q} \to gg) \sim \alpha_3^5 M_Q$

Cosmological history goes through 3 stages:

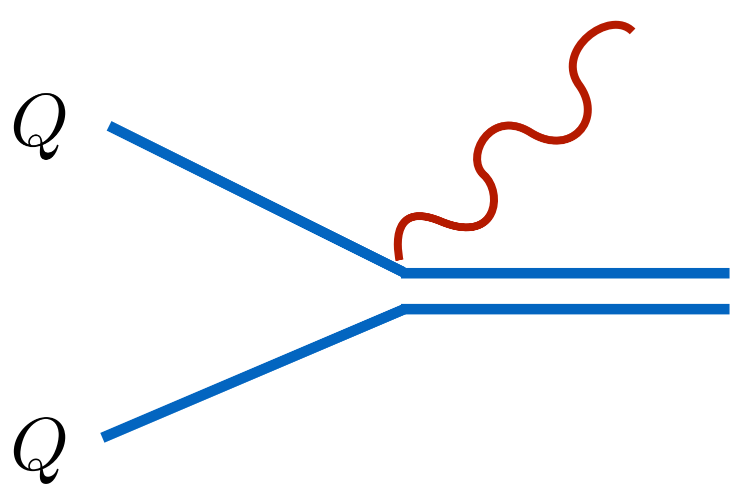
- Thermal freeze-out at T=m/25





$$\Omega_{Q+\bar{Q}} h^2 \approx 0.1 \left(\frac{M_Q}{7\,\mathrm{TeV}} \right)$$

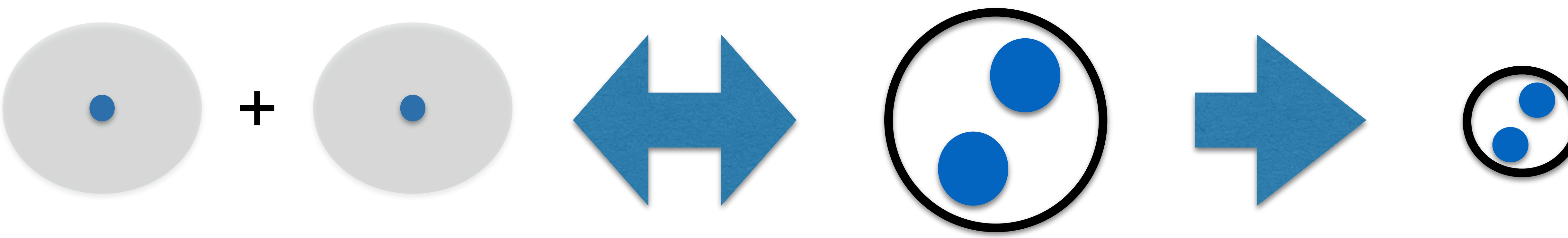
- $T < E_B$



$$\frac{\Omega_{QQ}}{\Omega_{Q+\bar{Q}}} \sim \alpha^2$$

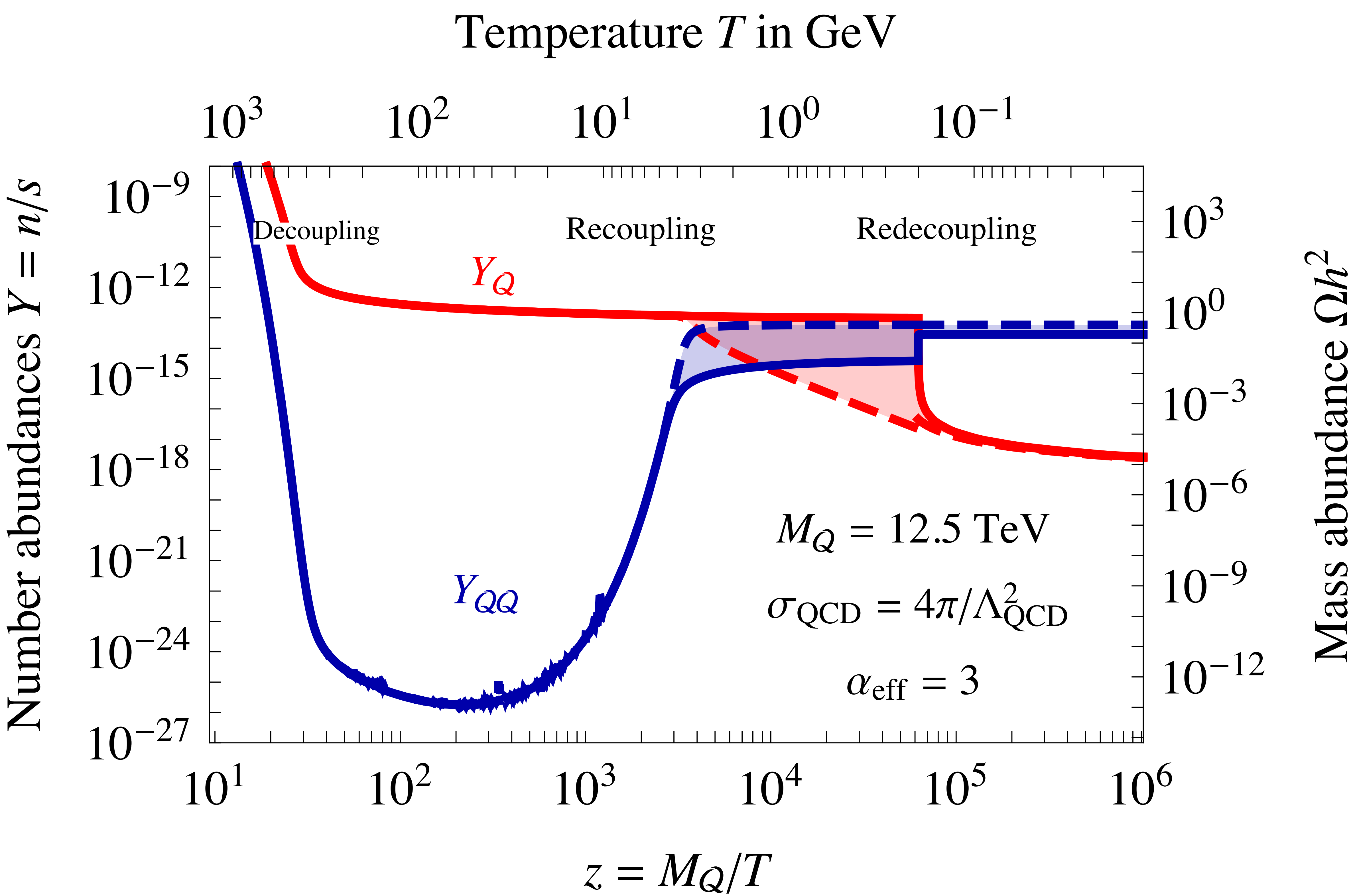
- Hadronization at T=200 MeV

- Re-coupling

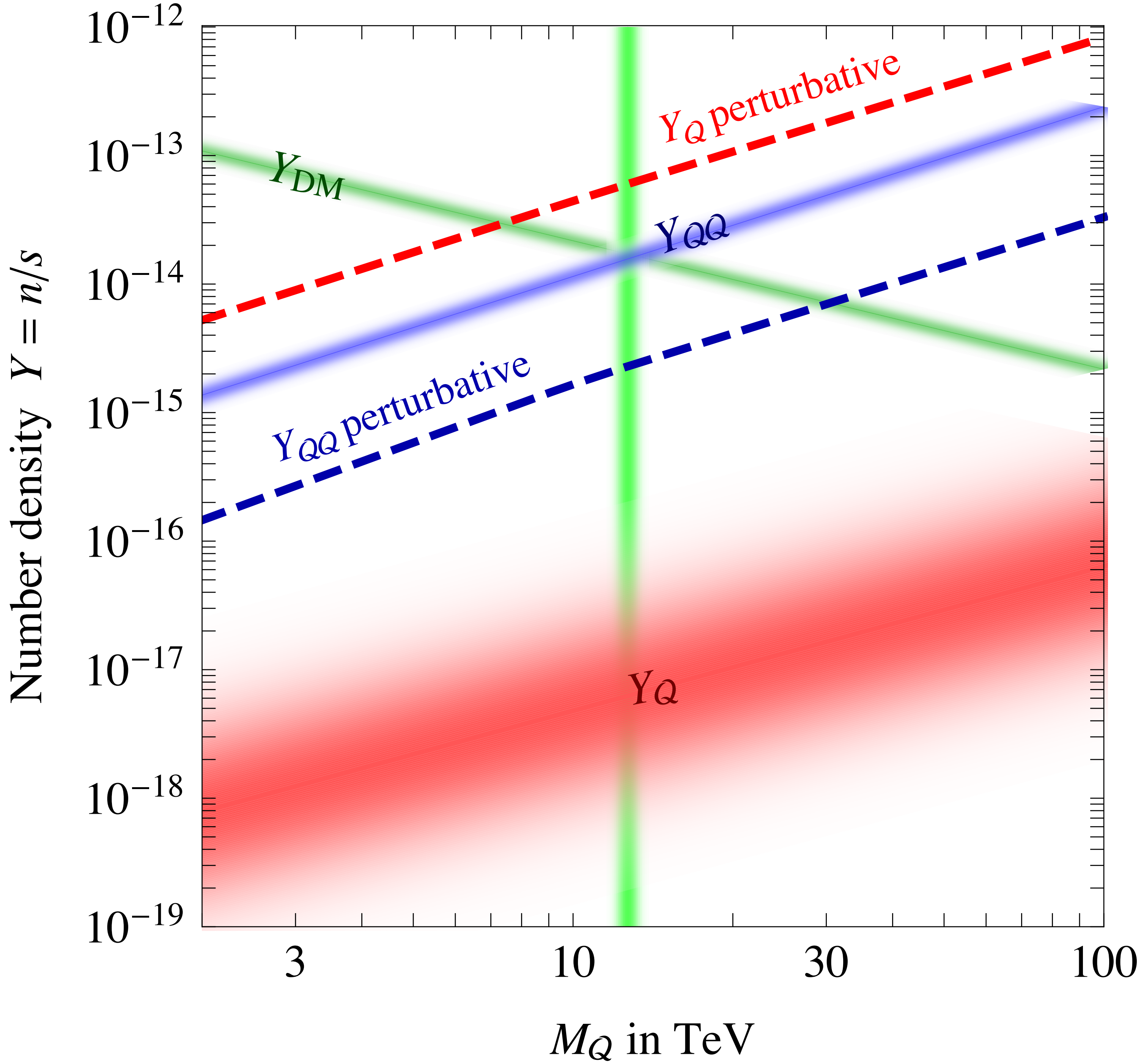


$$\sigma \sim \frac{1}{\Lambda_{QCD}^2} \longrightarrow n_Q(\Lambda_{QCD})\langle\sigma v\rangle \gg H(\Lambda_{QCD})$$

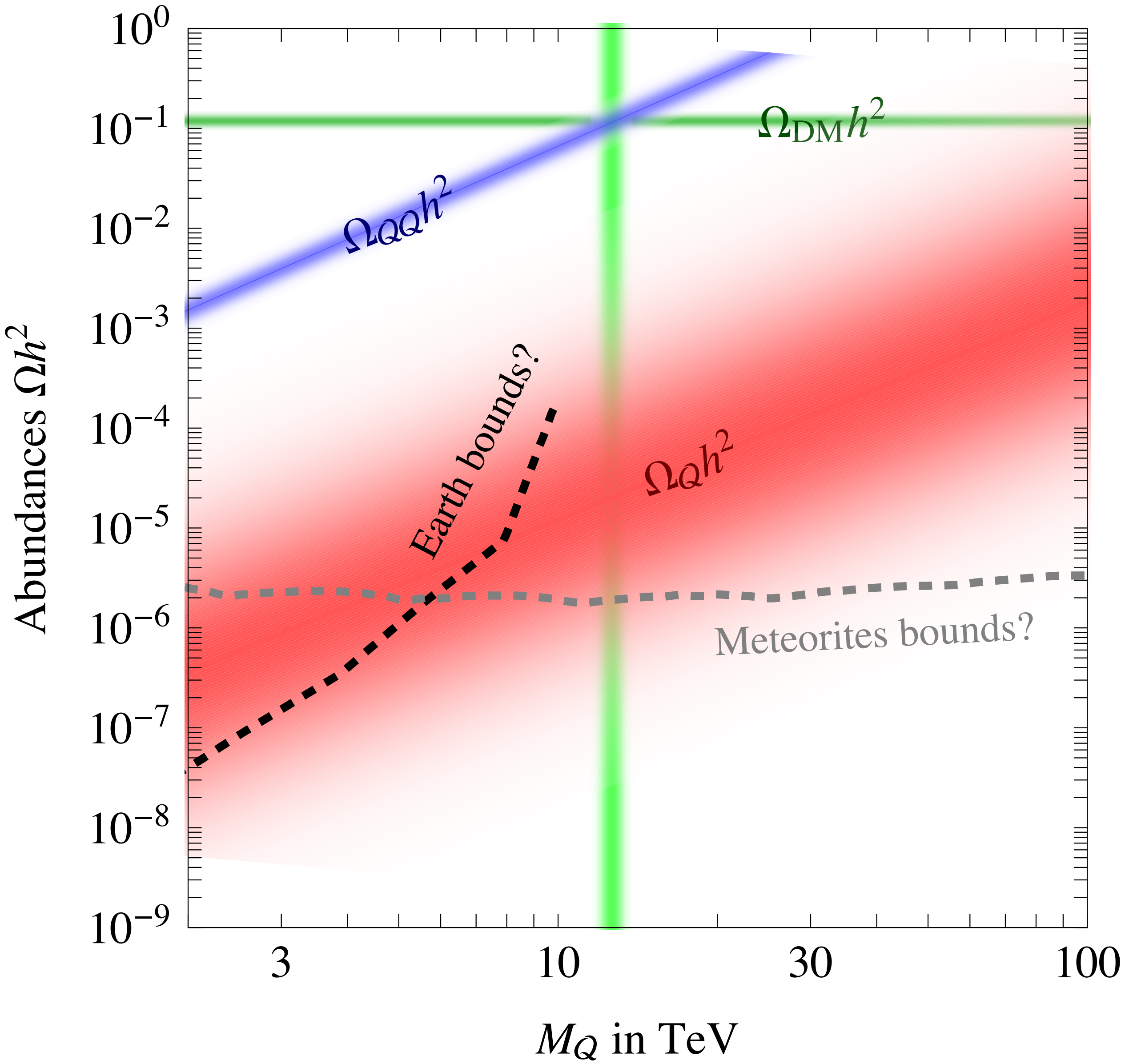
Only a small fraction of hybrids is left!
1/2 quarks is bound in stable bound states and 1/2 annihilates to SM.



Temperature T in GeV
10^3 10^2 10^1 10^0 10^{-1}
Number abundances $Y = n/s$
10^{-9} 10^{-12} 10^{-15} 10^{-18} 10^{-21} 10^{-24} 10^{-27}
Decoupling
Recoupling
Redecoupling
Y_Q
Y_{QQ}
$M_Q = 12.5$ TeV
$\sigma_{\rm QCD} = 4\pi/\Lambda^2_{\rm QCD}$
$\alpha_{\rm eff} = 3$
Mass abundance Ωh^2
10^3 10^0 10^{-3} 10^{-6} 10^{-9} 10^{-12}
10^1 10^2 10^3 10^4 10^5 10^6
$z = M_Q/T$



Critical mass: $M_Q \approx (12.5 \pm 1)\,\mathrm{TeV}$



$$\frac{\Omega_Q}{\Omega_{QQ}} \sim 10^{-4}$$

Only small fraction of DM ends in hybrid states. Bounds are relatively safe but uncertain. Octet favourable:

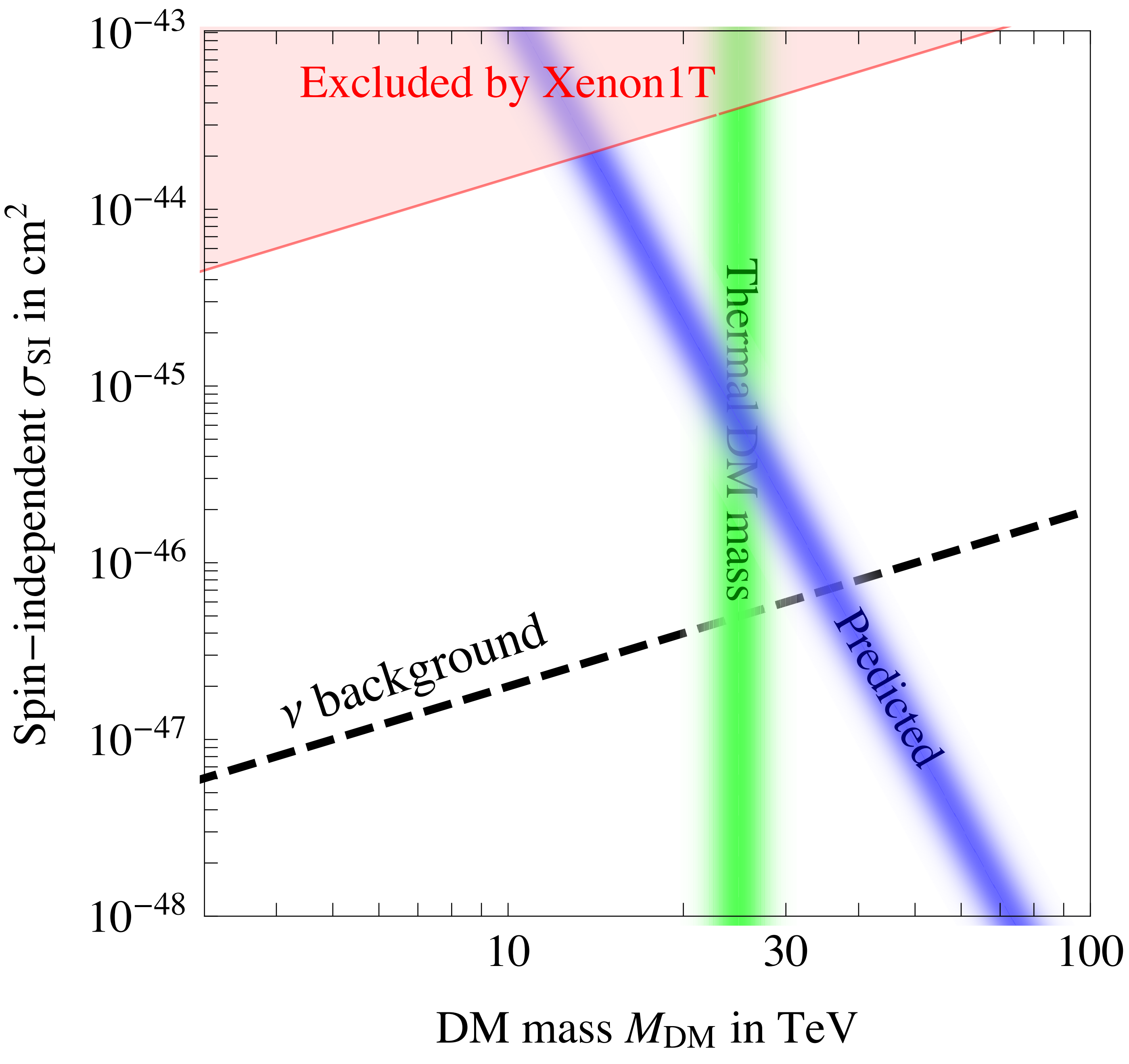
- No fractionally charged hadrons.

- (Qg) may not bind to matter

DM has “Rayleigh” interactions with gluons:

$$H_{\rm eff} = -\frac{1}{2}[c_E \vec{E}^{a2} + c_B \vec{B}^{a2}]$$

Direct detection

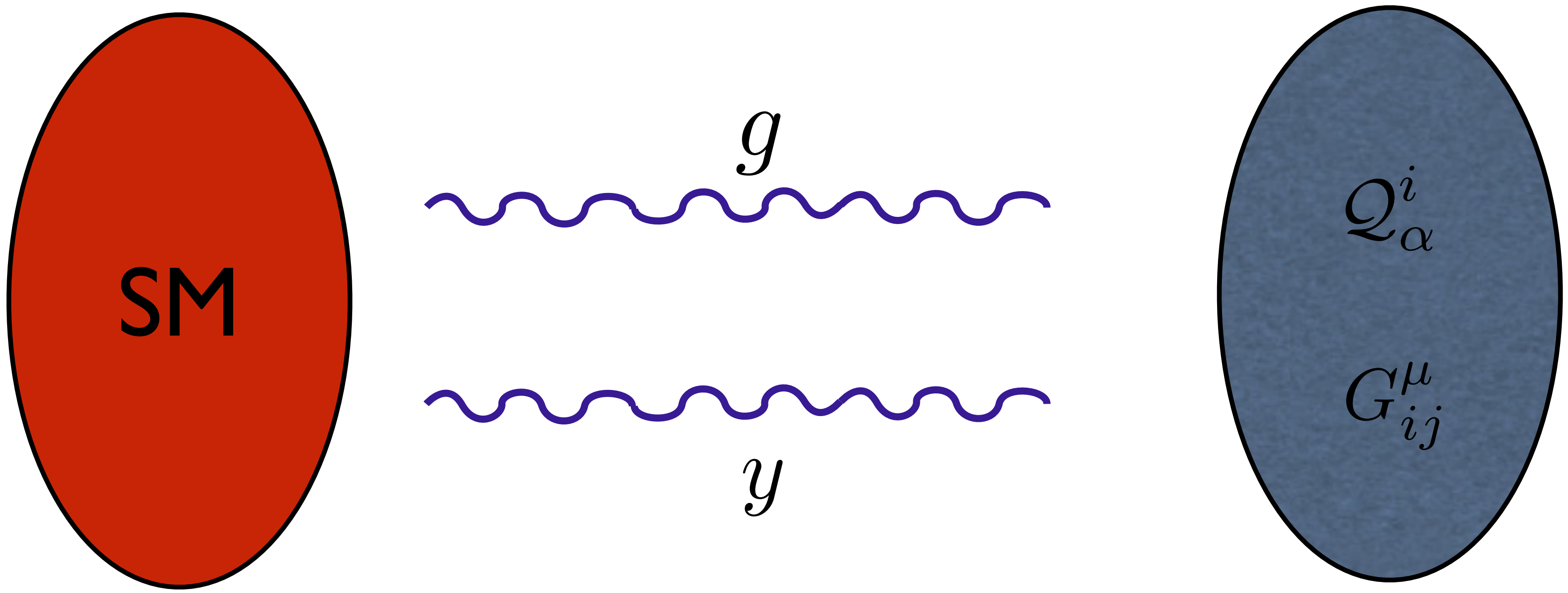


$$\sigma_{\rm SI} \approx 2.3\ 10^{-45}\,{\rm cm}^2 \times \left(\frac{20{\rm TeV}}{M_{\rm DM}}\right)^6$$

SUMMARY

- The failure to find new physics at the TeV scale likely requires a paradigm shift for particle physics. A sector with new gauge forces is a "minimal" extension of the SM compatible with current data that automatically produces viable DM candidates.
- DM could be a baryon of a new gauge force. Thermal abundance of DM is obtained for masses 1-100 TeV. Cosmological evolution can be non-standard. DM could also be a bound state of QCD itself.
- The dark sector could be accessible to a variety of experiments. Interesting signals include: resonance production, Higgs compositeness, EDMs, gravitational waves, long lived glueballs, unification…

Confining gauge theory with fermions charged under SM:



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

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

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

COLLIDER

(O. Antipin, MR, 1508.01112
De Curtis, Barducci, MR, Tesi1805.12578)

- $m_Q > \Lambda_{\rm DC}$

Mitridate, MR, Smirnov, Strumia '17

Mesons can be produced resonantly through gauge boson fusion or Drell-Yan

$$\sigma(pp \to X) = \frac{(2J_X+1)D_X}{M_X s} \sum_{\mathcal{P}} C_{\mathcal{P}\mathcal{P}} \Gamma(X \to \mathcal{P}\mathcal{P})$$

Spin-0 resonances decay to SM gauge bosons and spin-1 to fermions and scalars.

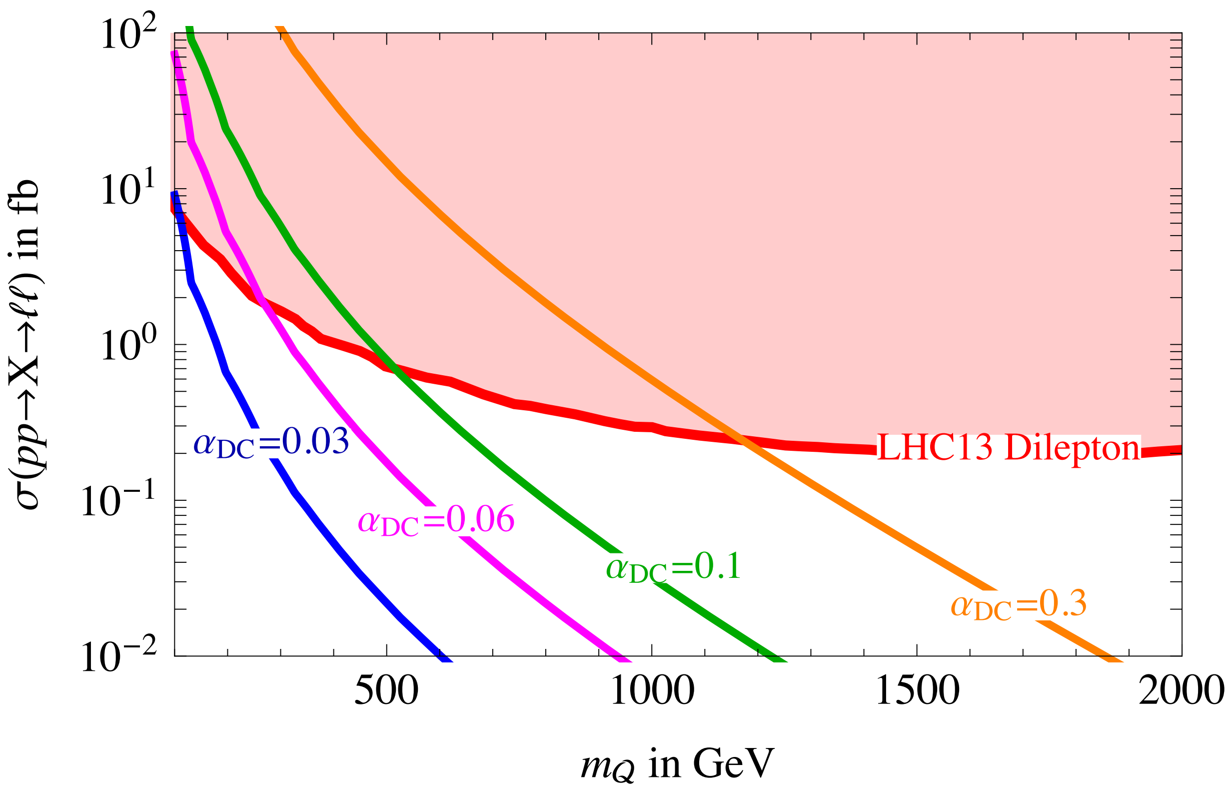
$$\Gamma(X \to SM\, SM) \sim N_{DC} \alpha_{SM}^2 \frac{|\psi(0)|^2}{m_Q^2} \qquad |\Psi(0)|^2 \sim \alpha_{DC}^3 m_Q^3$$

Open production:

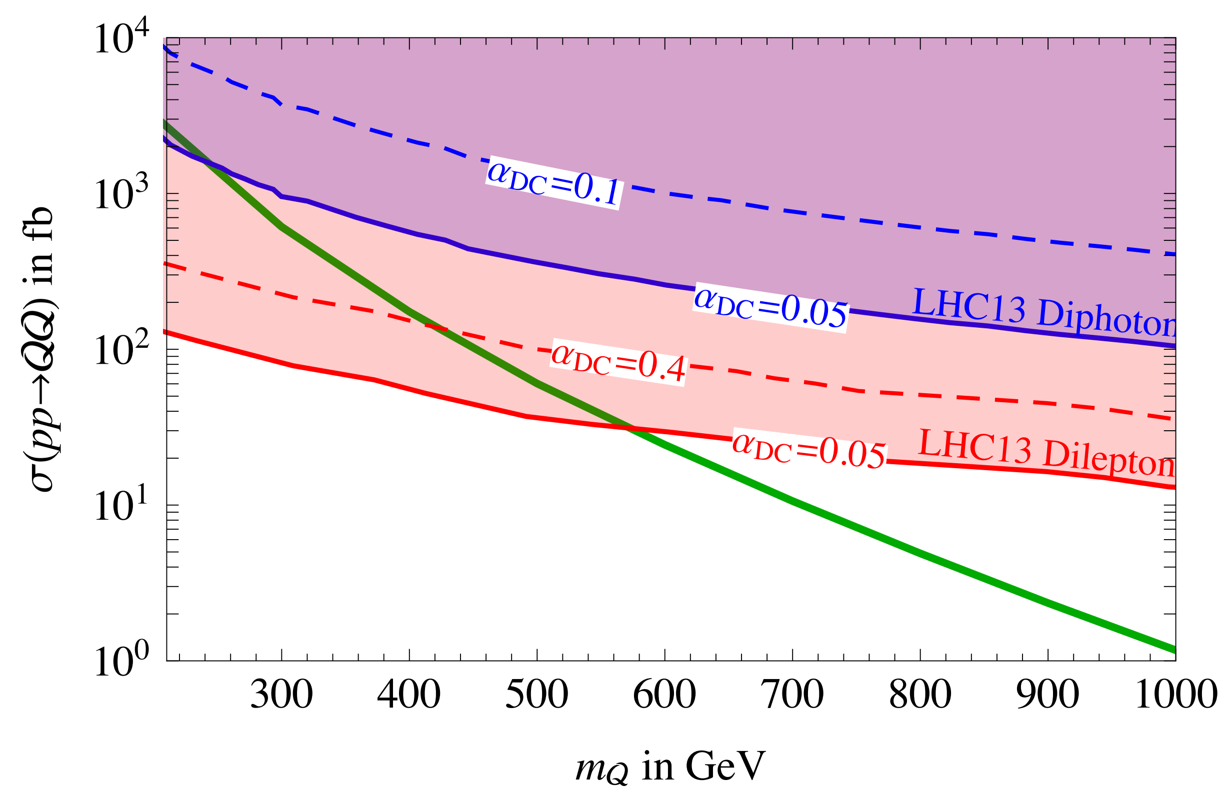
$$l_{\rm max} \sim \frac{m_Q}{\Lambda_{DC}^2} \sim 10^{-13}\,{\rm m} \left(\frac{m_Q}{\rm TeV}\right)\left(\frac{\rm GeV}{\Lambda_{DC}}\right)^2$$

Spin-0 resonances are produced from hadronization of heavy quarks and decay mostly to glueballs. Spin-1 resonances are produced from light quarks.

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



Single



Double

$\bullet\, m_Q < \Lambda_{DC}$

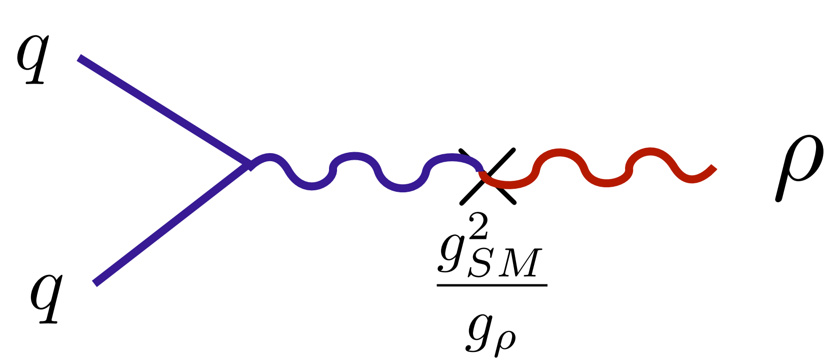
Kilic, Okui, Sundrum '09

Goldstone bosons and vector bosons with SM charges:

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

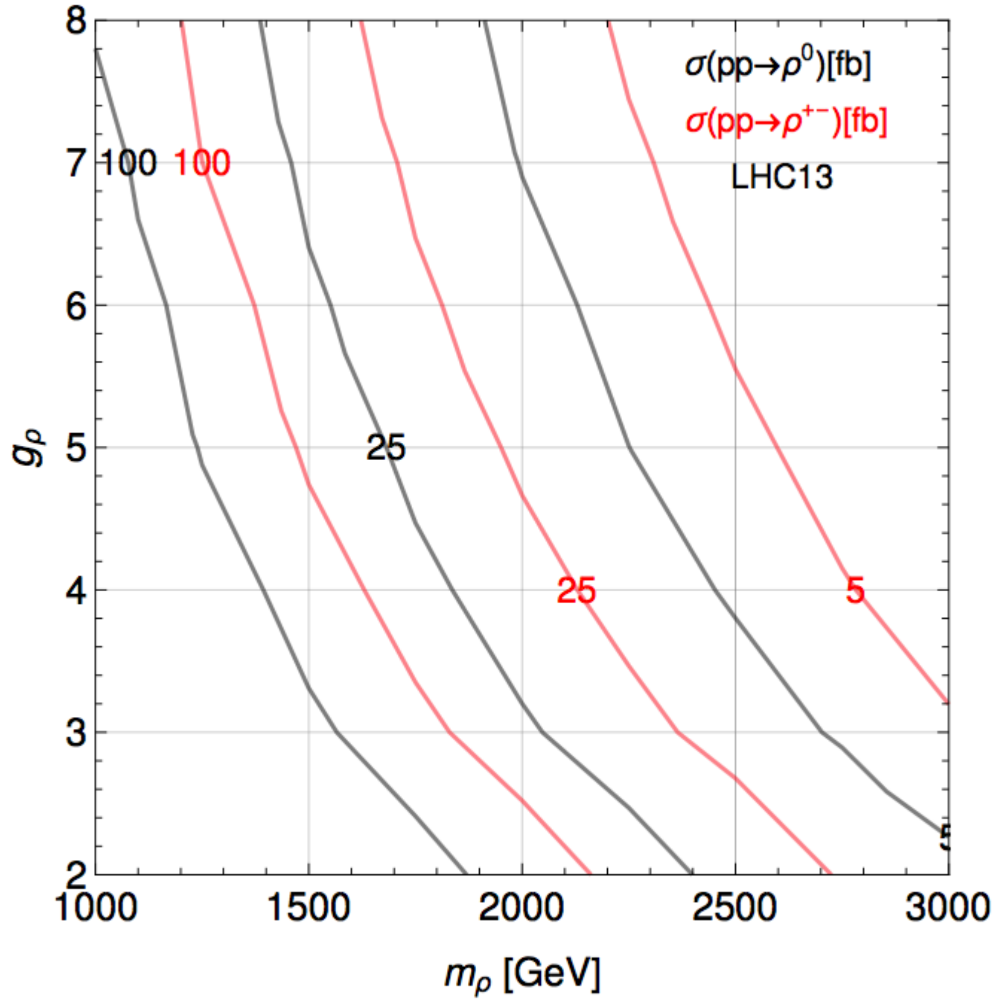
$$\langle 0|\bar{\Psi}\gamma^\mu \gamma^5 T^a \Psi|\pi^b\rangle = -i\delta^{ab}\, f\, p^\mu$$

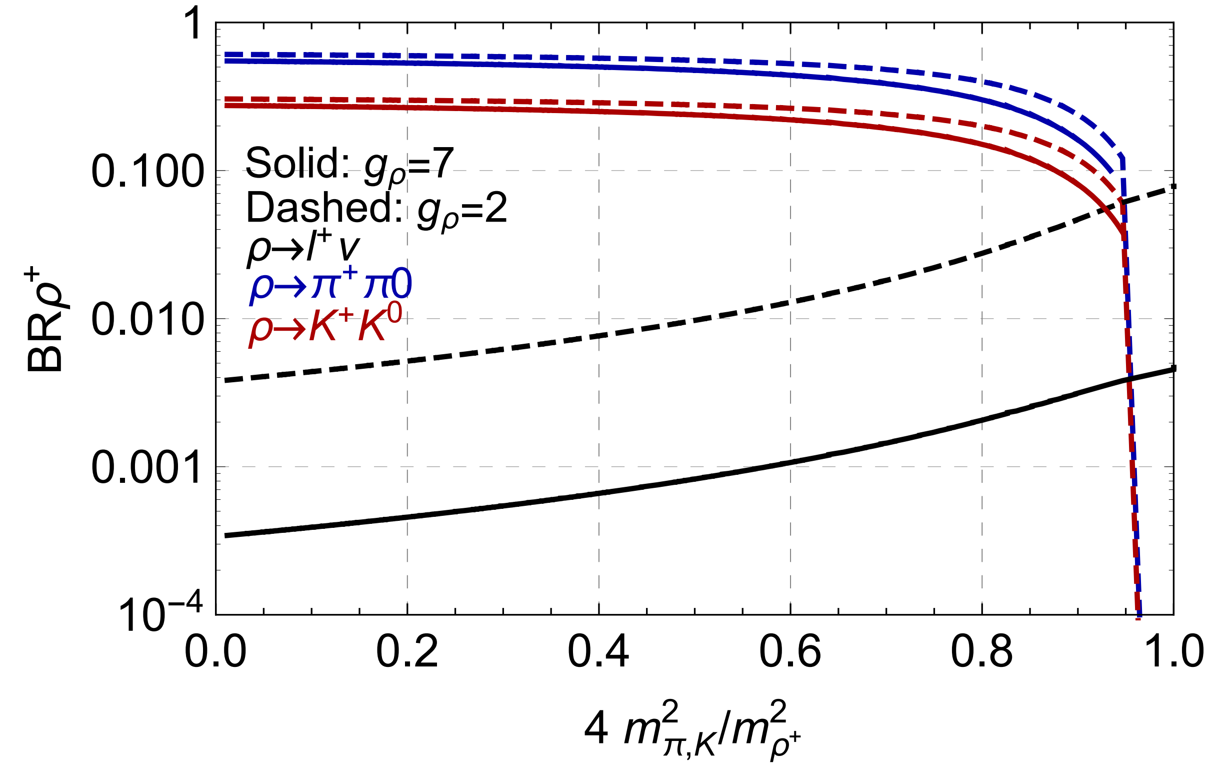
Heavy vectors mix with SM gauge bosons



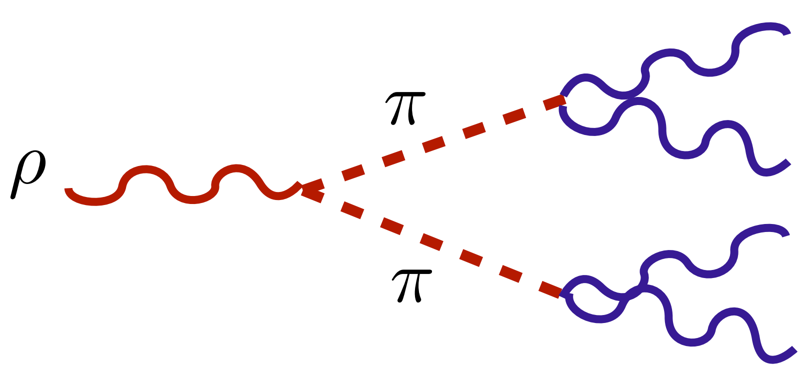
$$m_\rho \sim g_\rho f \qquad g_\rho \sim \frac{4\pi}{\sqrt{N}}$$

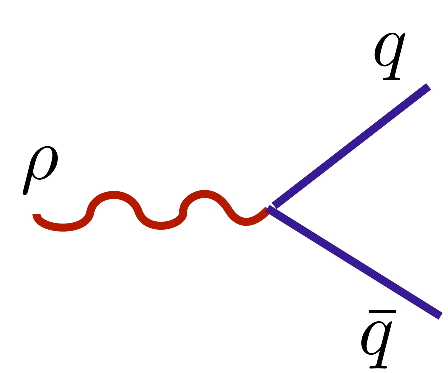
Unlike composite Higgs models fermions are elementary.





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

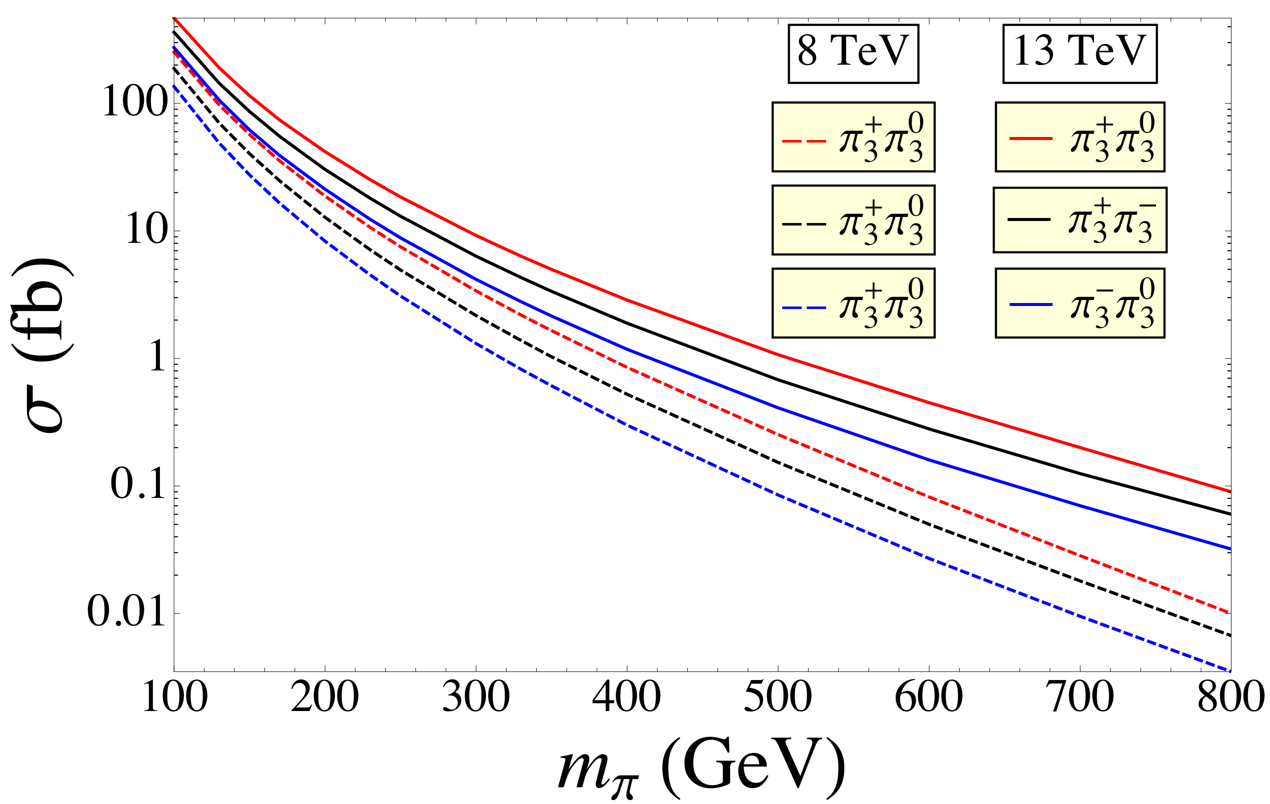


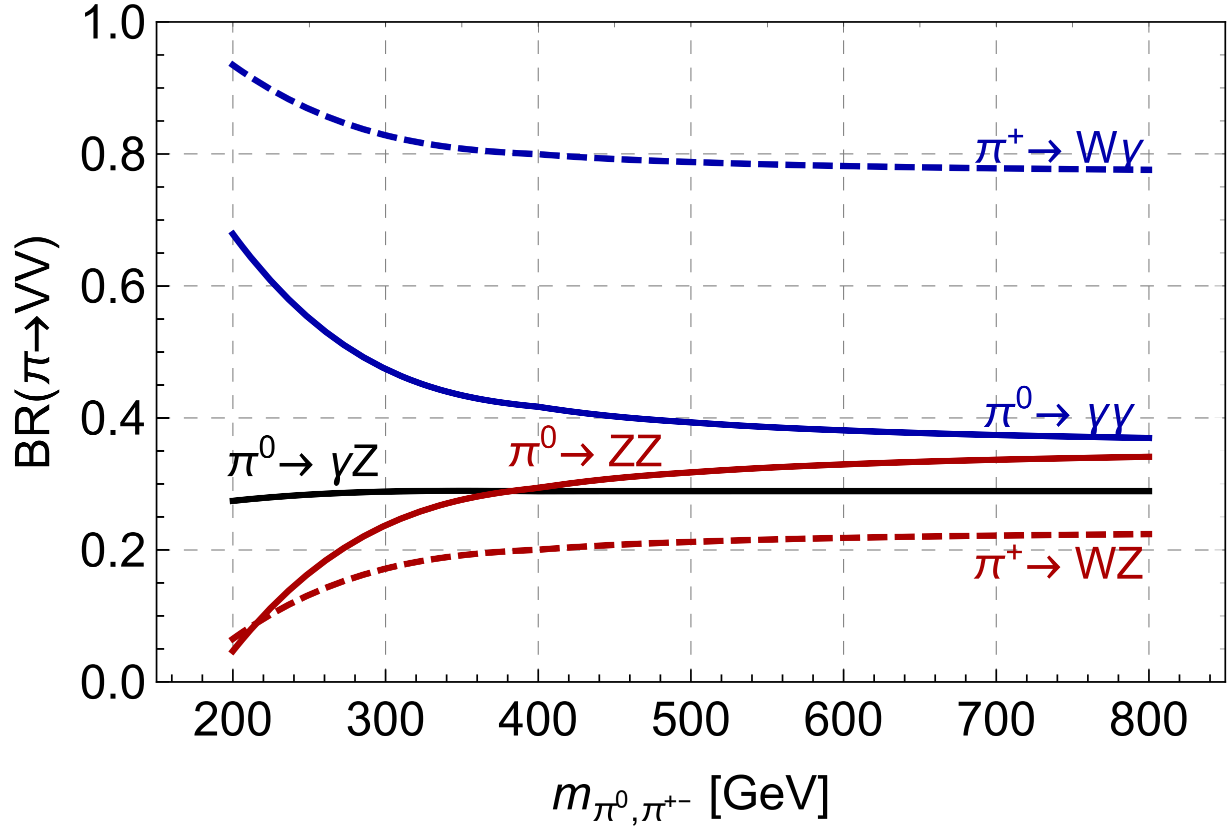


$$\mathrm{Br}(\rho \to q\bar{q}) \propto \frac{g_2^4}{g_\rho^4}$$

GBs with species number can be collider stable or long lived.

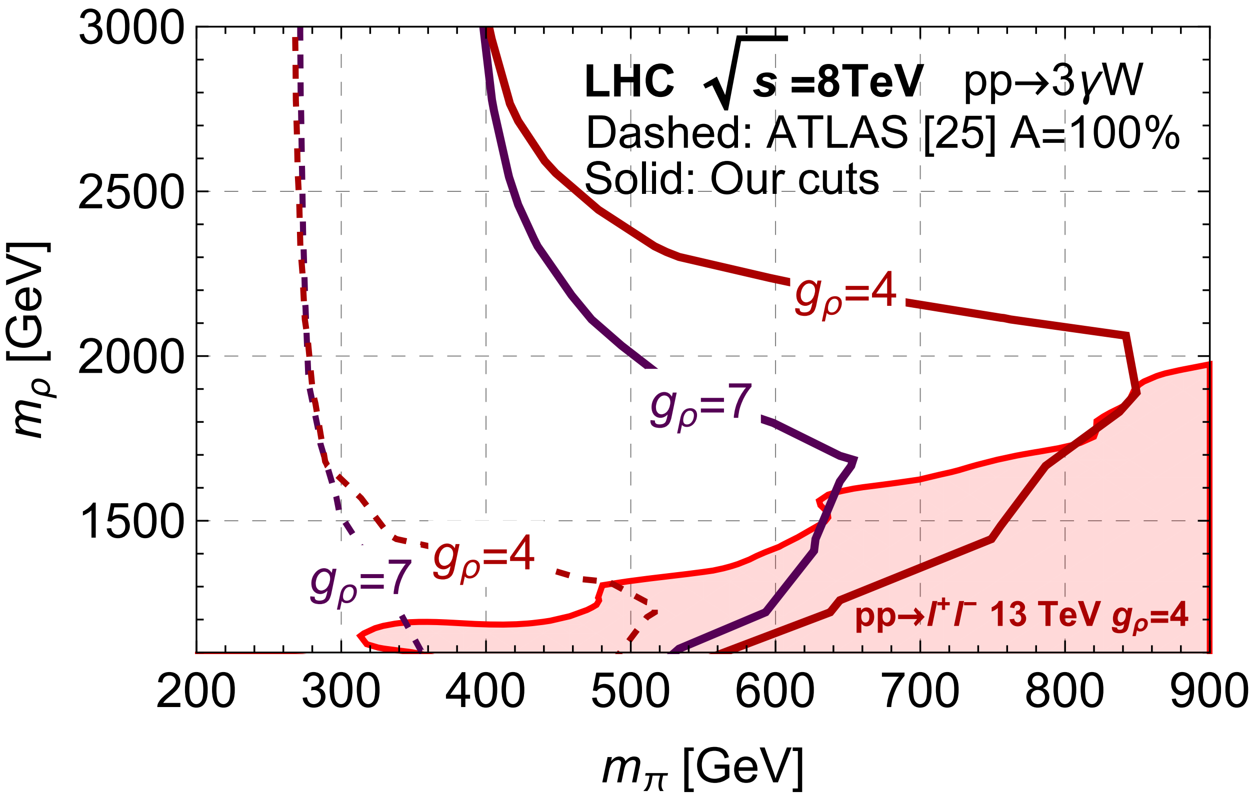
Pions triplets can also be produced through SM interactions

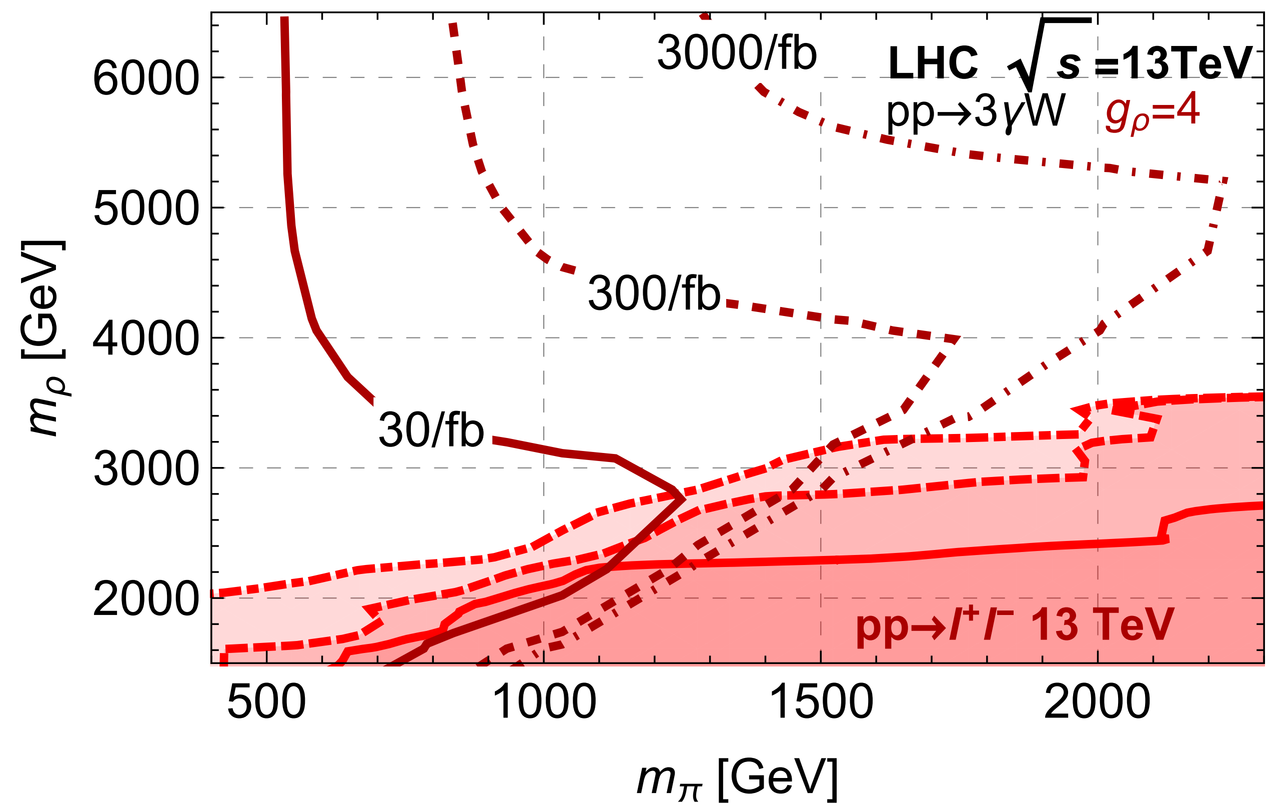




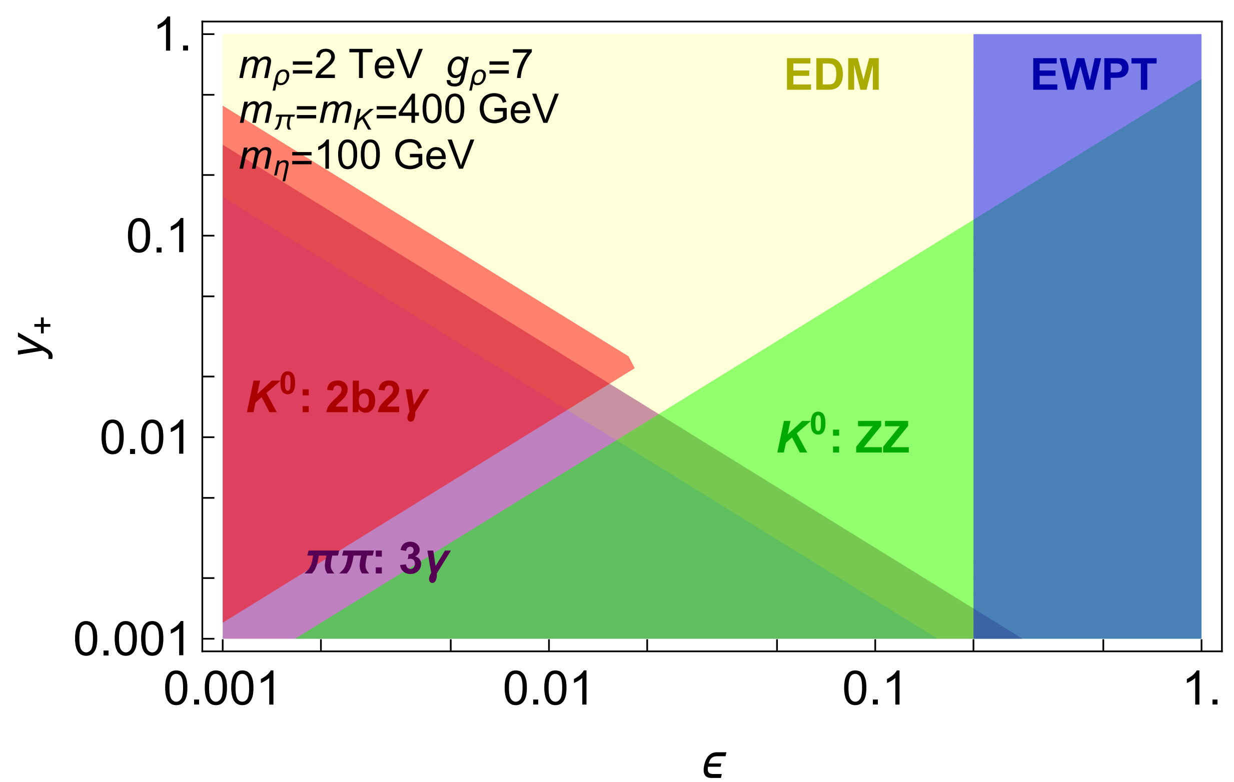
Cleanest signal:

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





Yukawa couplings allow scalars to mix with Higgs. Dominant decay to SM fermions:



PARTIALLY COMPOSITE HIGGS

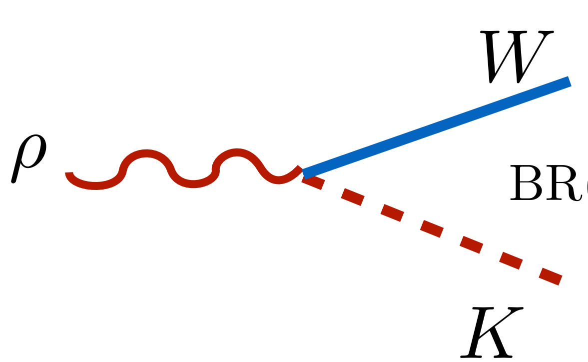
Antipin, MR '15
Barducci, De Curtis, MR, Tesi '18

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

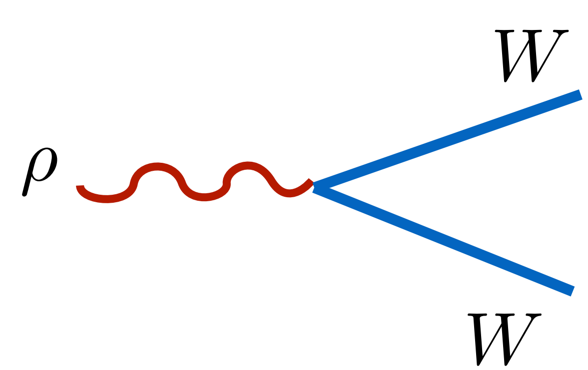
$$M^2 = \begin{pmatrix} m_H^2 & \epsilon m_K^2 \\ \epsilon^* m_K^2 & m_K^2 \end{pmatrix} \qquad \epsilon \sim (y_L - y_R)\frac{m_\rho f}{m_K^2}$$

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…

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

- Pions with species number can decay to Higgs + singlet

$$\Gamma(K \to H\eta) = \frac{|y + \tilde{y}^*|^2}{96\pi}\frac{m_\rho^2}{m_K}$$

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

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

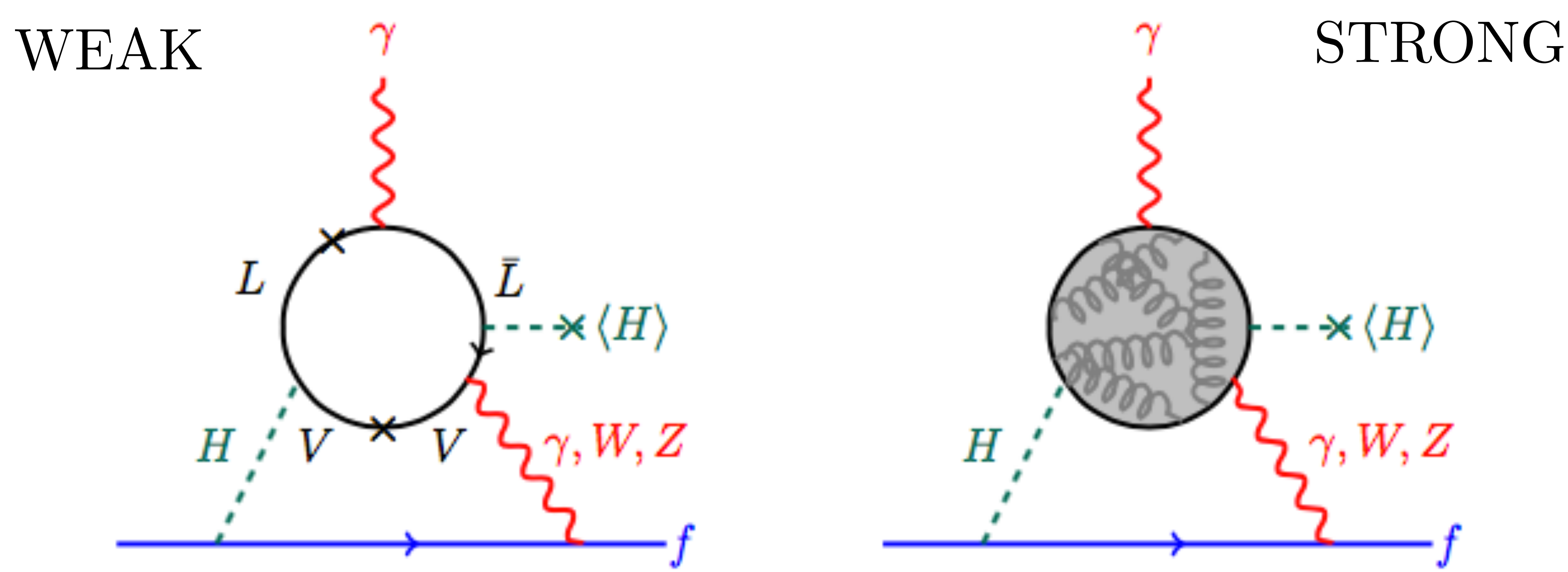
Mixing with elementary Higgs triggers electro-weak symmetry breaking.

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

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

ELECTRIC DIPOLE MOMENTS

EDM for SM particles generated with complex Yukawas:



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

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

UNIFICATION

Incomplete SU(5) reps modify SM running

SU(5)	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	charge	name	Δb_3	Δb_2	Δb_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

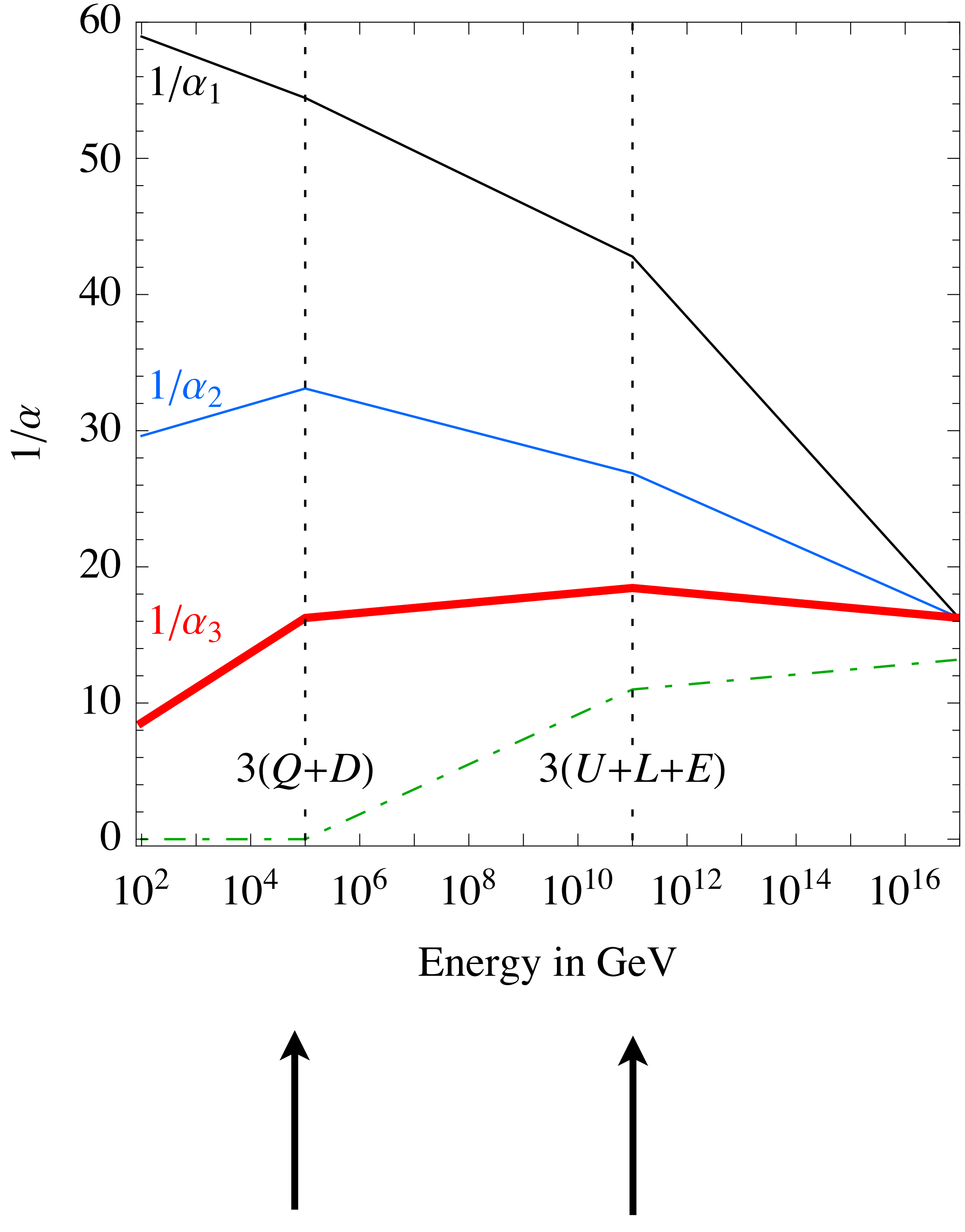
$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{\rm GUT}} + \frac{b_i^{\rm SM}}{2\pi}\log\frac{M_{\rm GUT}}{M_Z} + \frac{\Delta b_i}{2\pi}\log\frac{M_X}{\Lambda_{\rm TC}} + \frac{\Delta b}{2\pi}\log\frac{M_{\rm GUT}}{M_X}$$

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

Ex:

$Q + \tilde{D}$

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



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

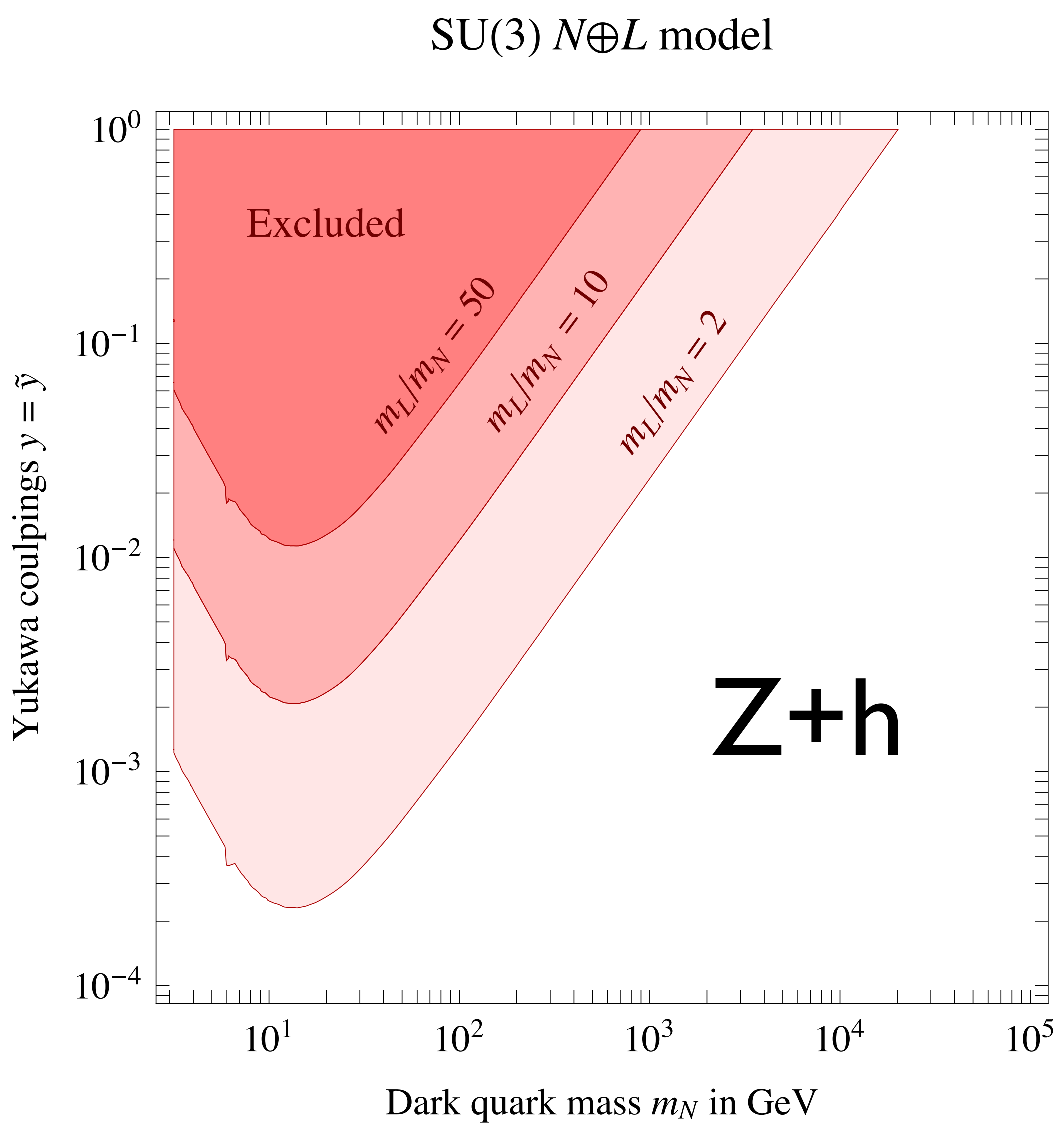
$M_{\mathrm{GUT}} \approx 2 \times 10^{17}\,\mathrm{GeV}$

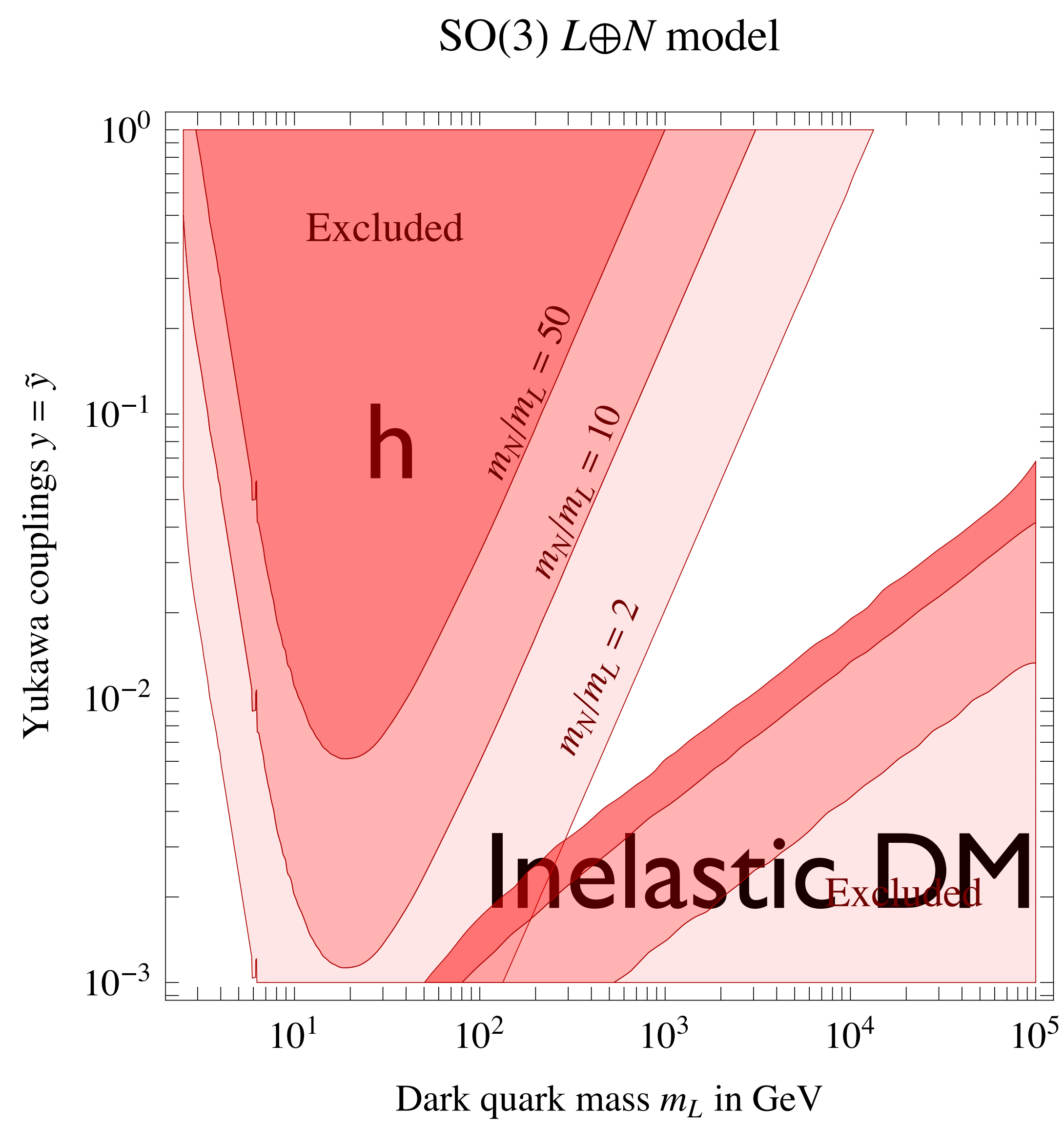
$\Lambda_{DC} = 100\,\mathrm{TeV}$ $\quad M_X \approx 2 \times 10^{11}\ \mathrm{GeV}$

Direct detection:

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

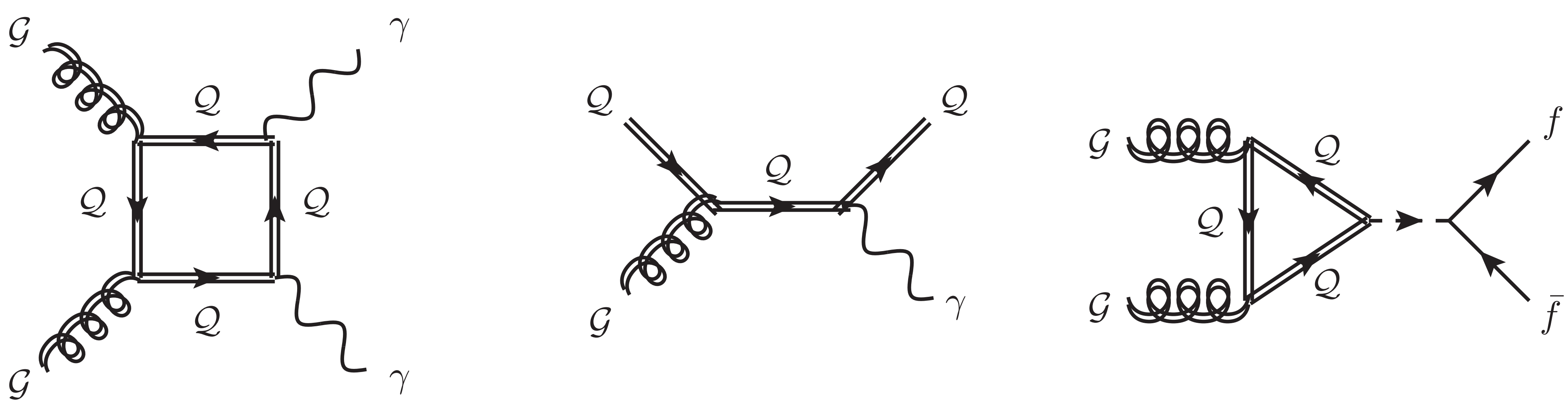
- **SO(N):** Higgs SI x-sec and Z inelastic transitions.





Glueballs:

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



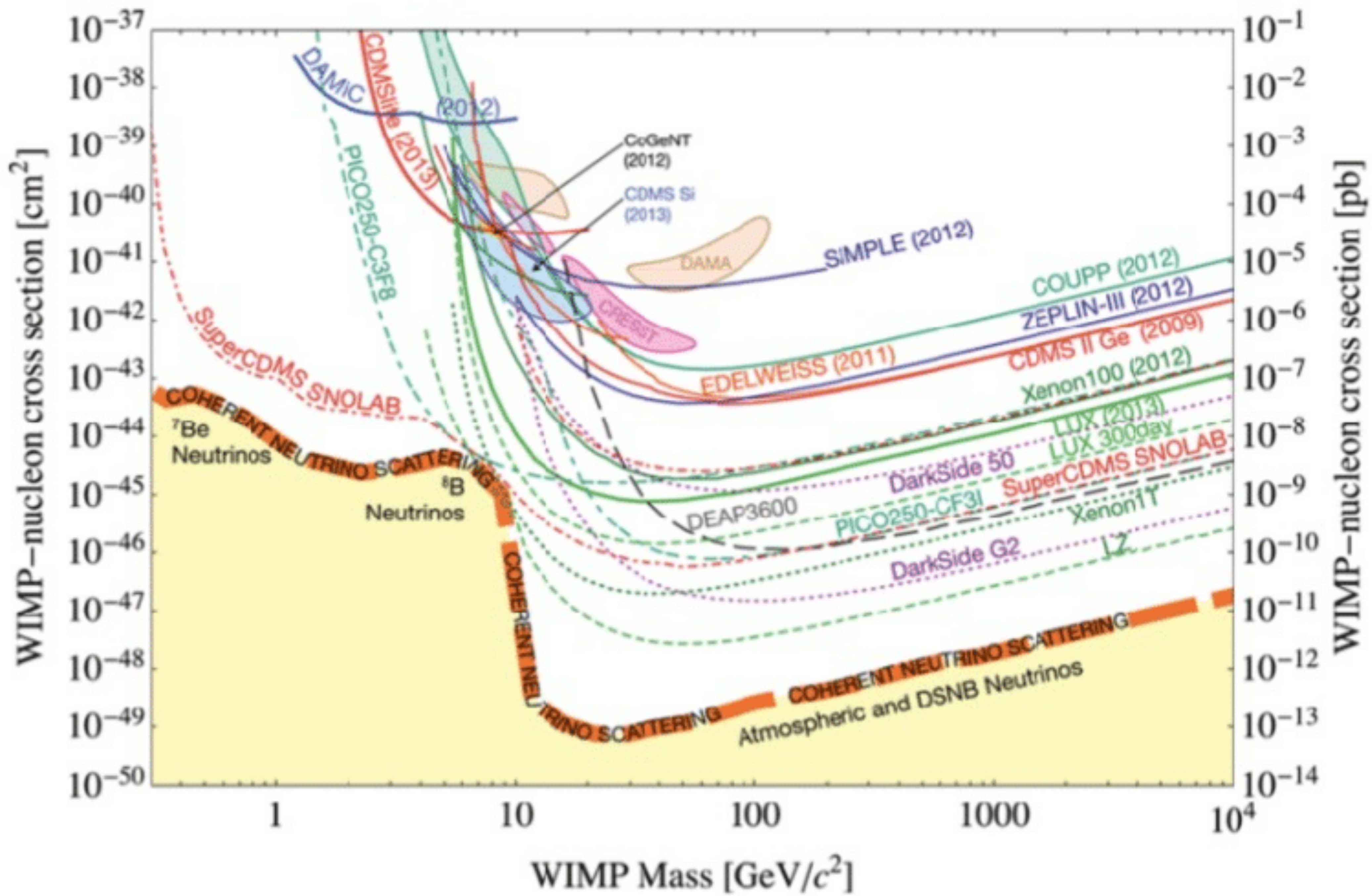
$$\tau_{\rm DG}^{\gamma\gamma} \sim 10{\rm sec}\left(\frac{10\,{\rm GeV}}{m_{\rm DG}}\right)^9\left(\frac{m_Q}{\rm TeV}\right)^8$$

Glueballs need to decay before BBN:

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

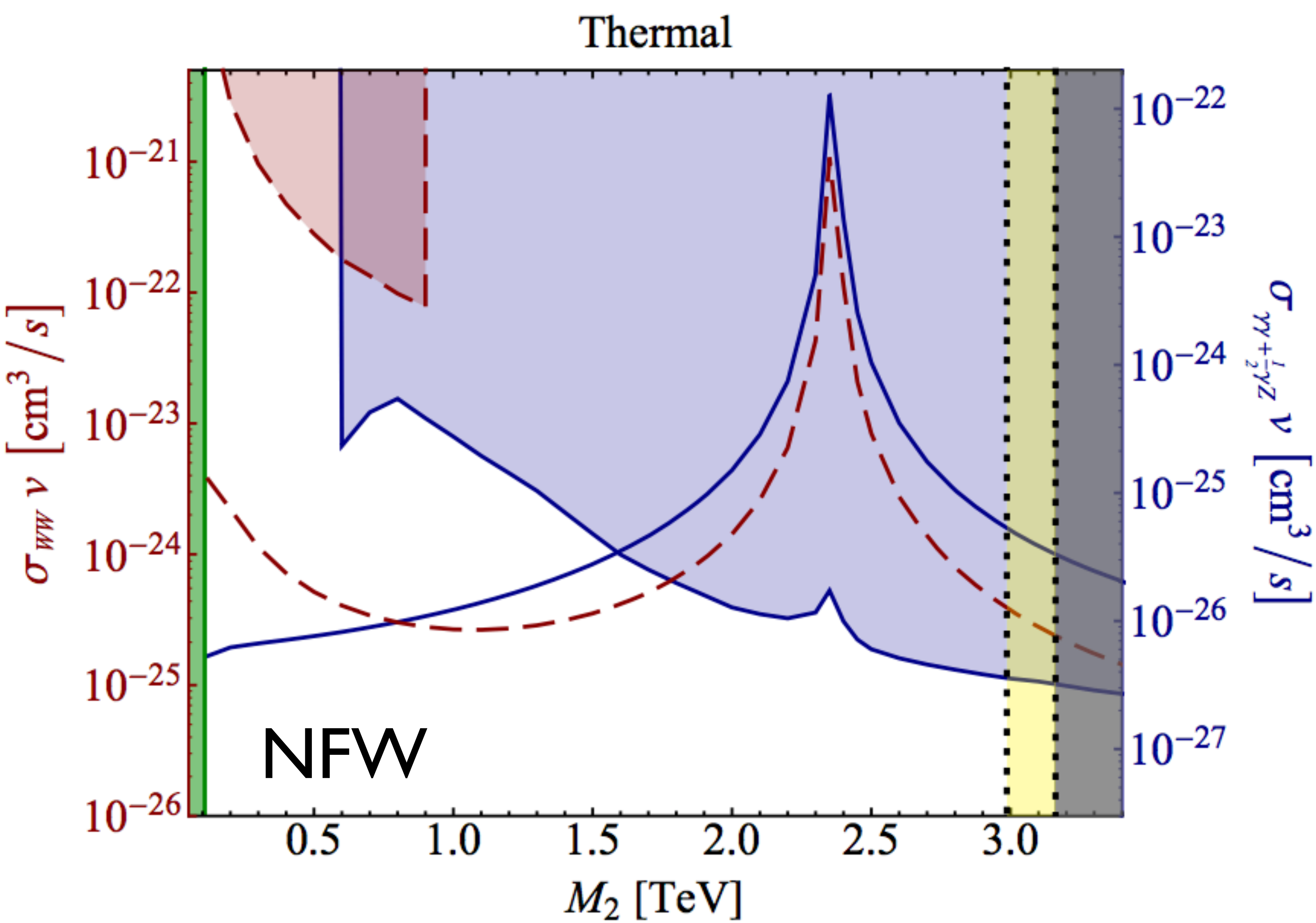
WIMPs will live beyond LHC but will be tested.

Direct Detection:



Indirect Detection:

$$\tilde{W}_0 \tilde{W}_0 \to \gamma + X$$



Cohen et al.'13

Non-standard cosmologies:

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

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

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

Late time decays of glueballs further dilute abundance.