Dark Nuclear Matter

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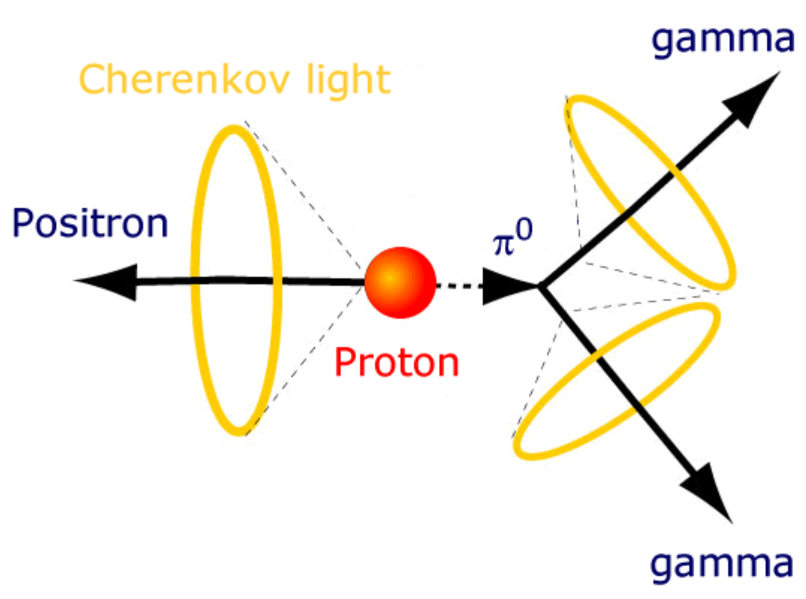
Based on: arxiv 1503.08749 + 1812.08784 +1908.00538
+ work in progress

Cortona - October 10, 2019

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:

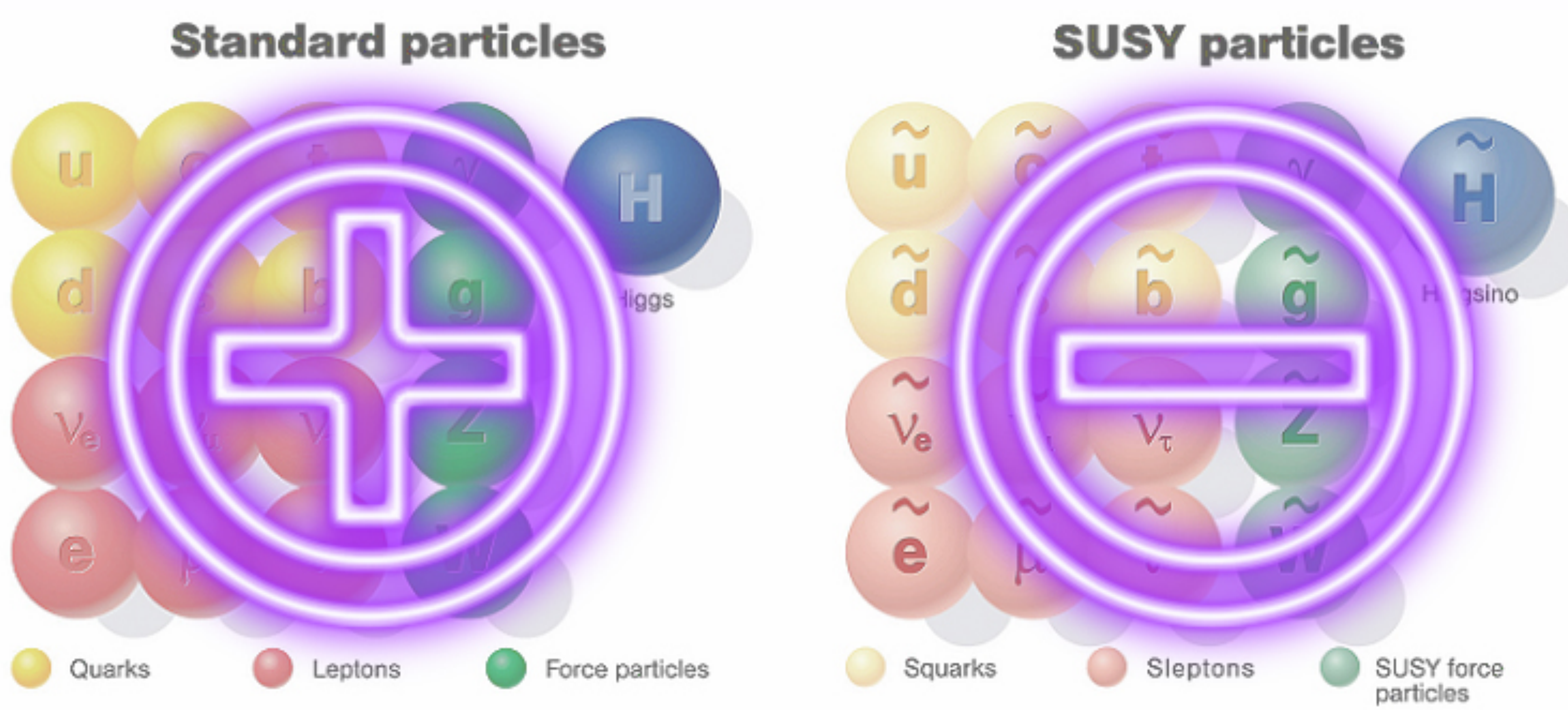
$$U(1)_B \qquad q \to e^{i\alpha} q$$

Violation:

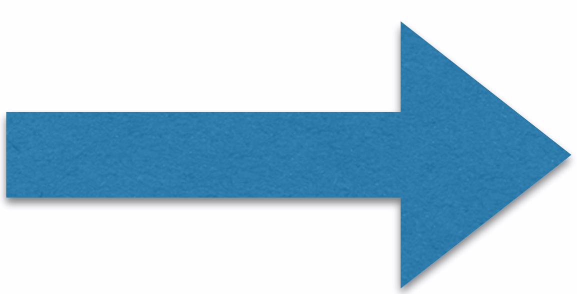
$$\frac{qqql}{\Lambda^2} \longrightarrow \tau_p \sim \frac{8\pi\Lambda^4}{m_p^5} = 3\times 10^{34}\,\mathrm{y}\left(\frac{\Lambda}{10^{16}\,\mathrm{GeV}}\right)^4$$

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

R-parity:

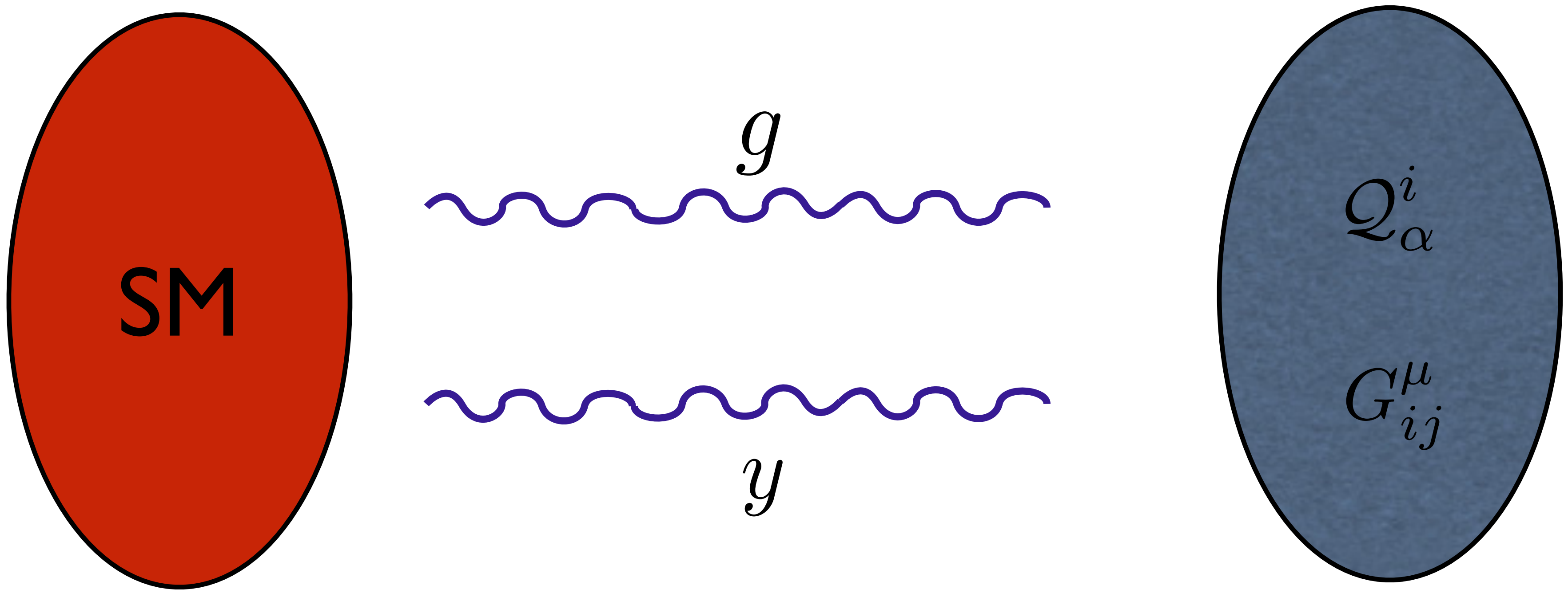


Can DM be accidentally stable as the proton?



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:

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

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

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:

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

Models

- Q-complex (SU(N) fundamental)

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

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

- Q-real (SO(N) fundamental)

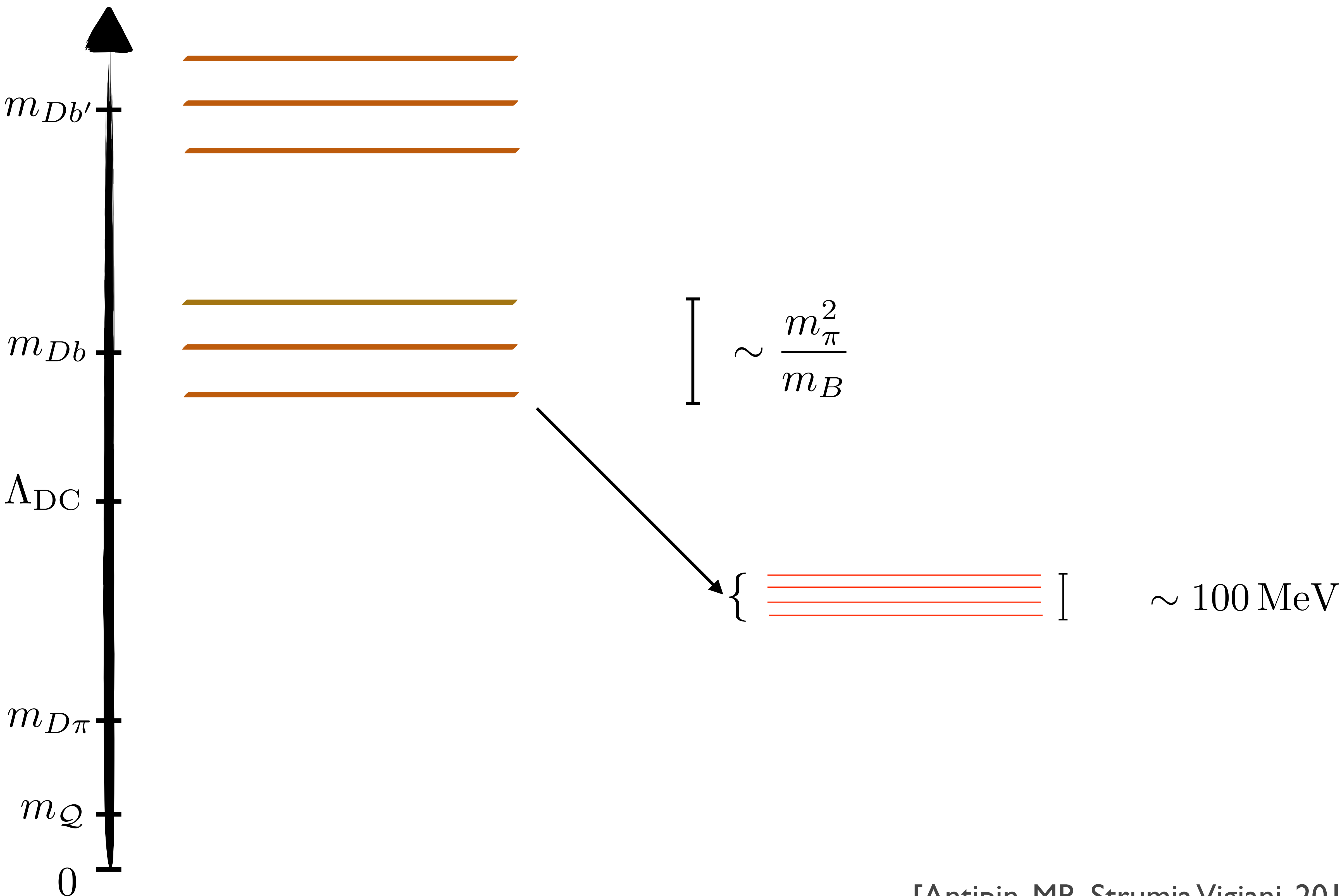
Baryon and anti-baryons are the same particle so 2 DM particles can annihilate. DM cannot be asymmetric.

- Q-adjoint

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

[Contino, Mitridate, Podo, MR, 2018]

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



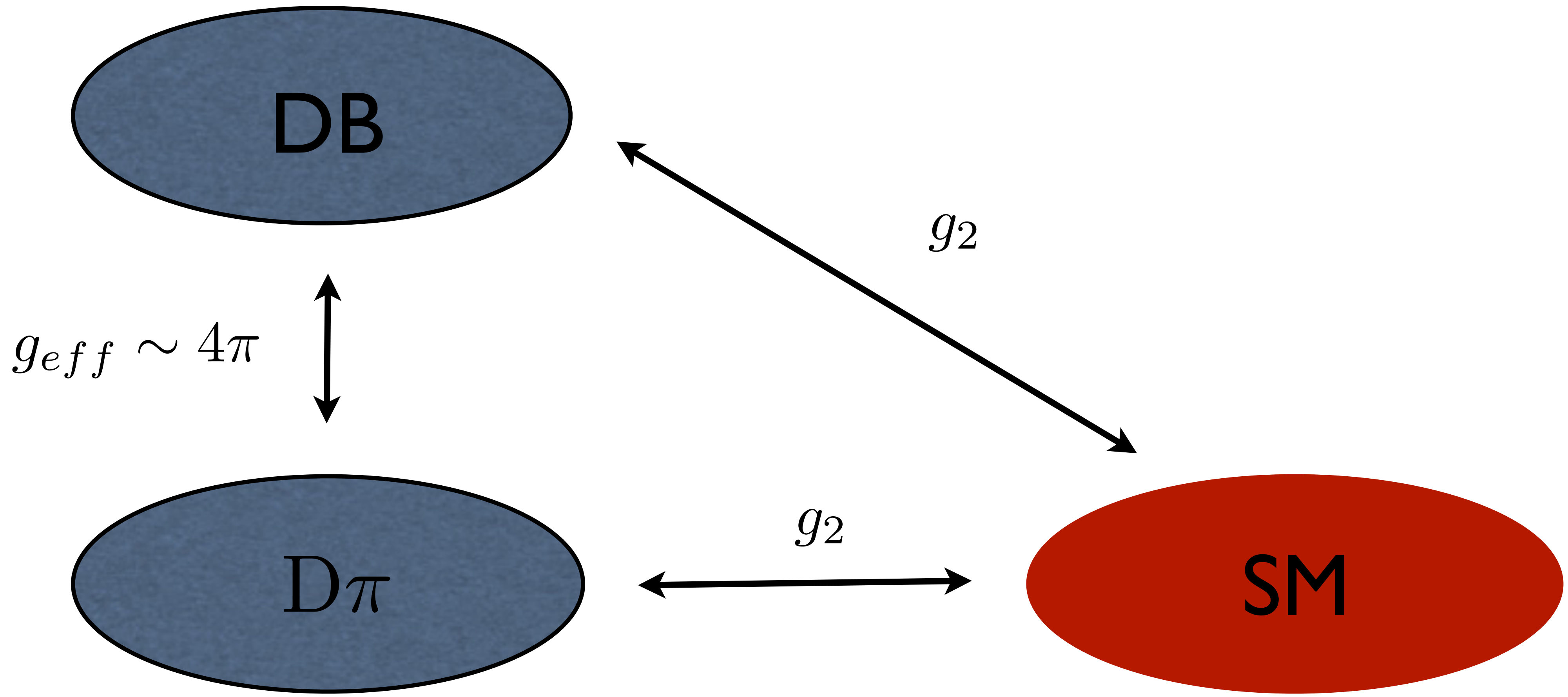
[Antipin, MR, Strumia Vigiani, 2015]

SU(N) classification:

SU(N) techni-color. Techni-quarks	Yukawa couplings	Allowed N	Techni-pions	Techni-baryons	under
$N_{\rm TF}=3$			8	$8, \bar{6}, \ldots$ 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:

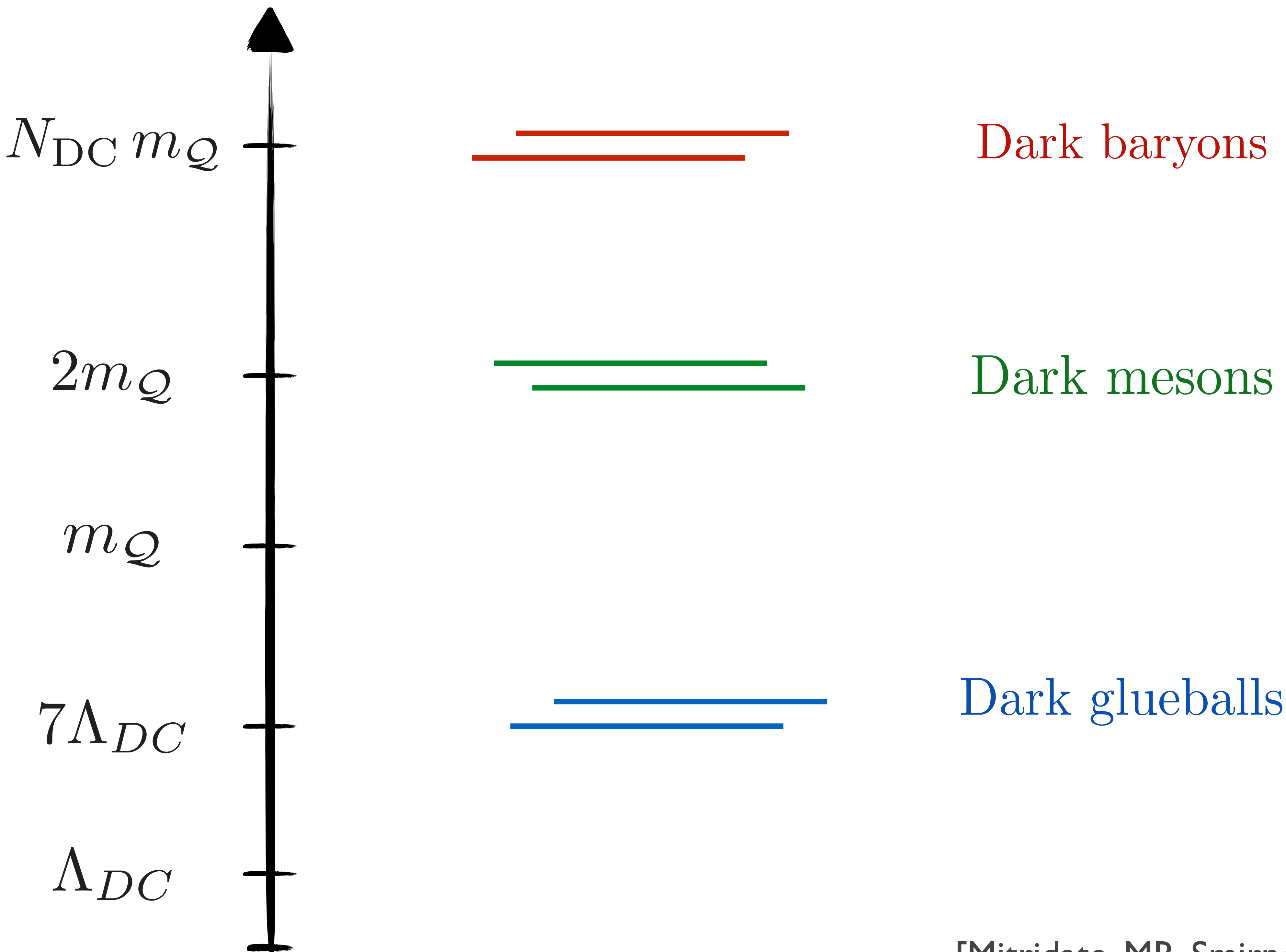


$$\langle \sigma v_{\rm rel} \rangle_{\rm ann} \sim \frac{4\pi}{M_B^2} \longrightarrow m_B \sim 100\,\mathrm{TeV}$$

DM could also be asymmetric with lower mass.

- Heavy Dark Quarks:

$(m_Q > \Lambda_{DC})$

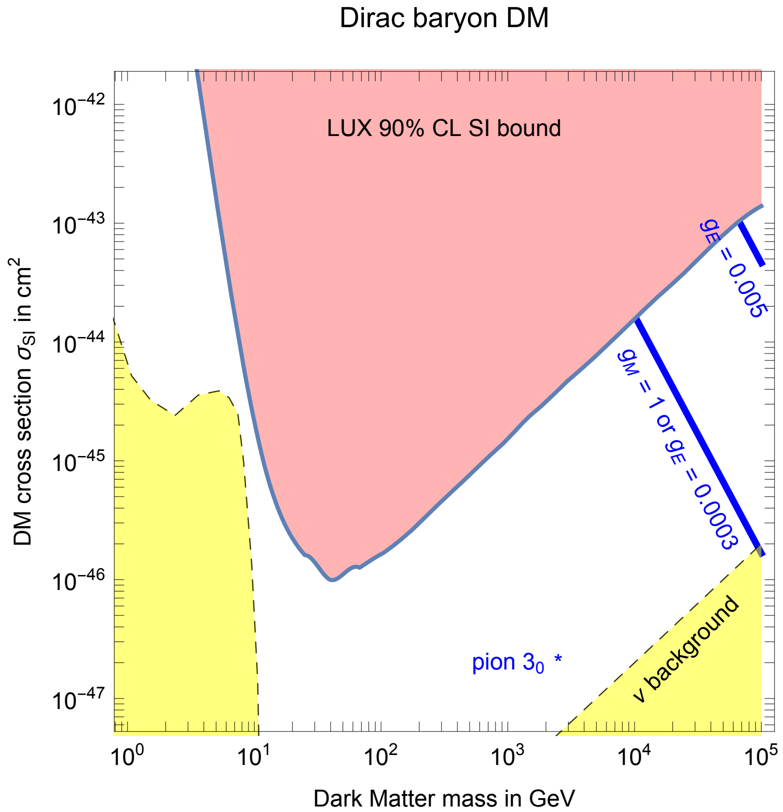


[Mitridate, MR, Smirnov, Strumia, 2017]
[Contino, Mitridate, Podo, MR, 2018]

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

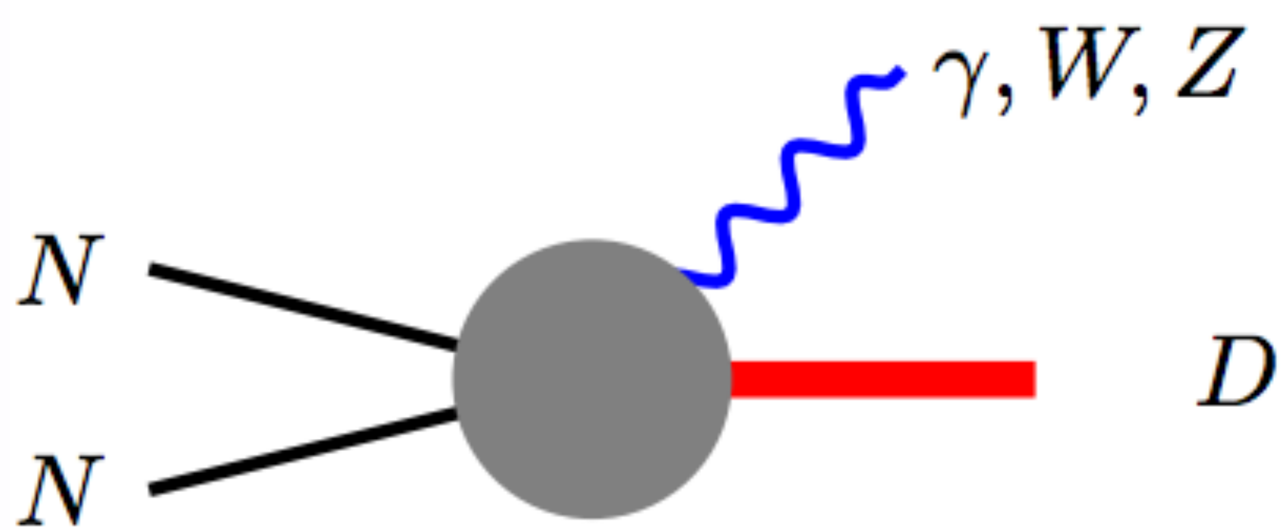


- Annihilation cross-section

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

Dark Nuclei

If DM is made of dark SU(N) baryons, heavier stable nuclei likely exist and can be produced.
Dark deuterium:



- Dark Nucleo-synthesis [MR, Tesi, 2018]

- Indirect Detection Signals [Mahbubani, MR, Tesi, 2019]

Dark Nucleosynthesis can be computed by solving equations analogous to BBN. Focusing on asymmetric DM:

$$D: \quad N + N \rightleftarrows D + X$$

$$T: \quad D + N \rightleftarrows T + X\,, \; D + D \rightleftarrows T + N$$

$$\dots$$

$$\dot{n}_D + 3Hn_D = \langle \sigma_D v \rangle \left[n_N^2 - \frac{(n_N^{\rm eq})^2}{n_D^{\rm eq}} n_D \right]$$

Deuterium starts forming at **T~EB/20**:

$$X_D = 5\% \left(\frac{3\mathrm{TeV}}{M}\right)^2 \left(\frac{E_B/M_N}{0.05}\right) \left(\frac{\langle \sigma_D v \rangle}{\alpha/M_N^2}\right) \left(\frac{g_\star}{106.75}\right)^{1/2} \left(\frac{25}{z_f}\right)$$

Need cross-sections...

We can compute the x-sec from "first principles":

$$\frac{E_B}{M_\pi} \ll 1 \quad \xrightarrow{E \ll M_\pi} \quad \text{Effective theory of nucleons}$$

PHYSICAL REVIEW VOLUME 76, NUMBER 1 JULY 1, 1949

Theory of the Effective Range in Nuclear Scattering

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(Received February 28, 1949)

The scattering of neutrons up to about 10 or 20 Mev by protons can be described by two parameters, the scattering length at zero energy, a, and the effective range, r_0. A formula (16), expressing the phase shift in terms of a and r_0 is derived; it is identical with one previously derived by Schwinger but the derivation is very much simpler. Reasons are given why the deviations from the simple formula are very small, as shown by the explicit calculations by Blatt and Jackson.

The theory is then applied to proton-proton scattering, with a similarly simple result. Moreover, a method is developed to compare proton-proton and proton-neutron scattering without explicit calculation of a nuclear potential.

The most recent experimental results are evaluated on the basis of the theory, and accurate values for the effective ranges are obtained for the triplet scattering of neutrons, and for proton-proton scattering. The nuclear force between two protons is found to differ by a slight amount, but beyond doubt, from that between neutron and proton in the singlet state. All actual results agree with those obtained by Breit and collaborators, and by Blatt and Jackson.

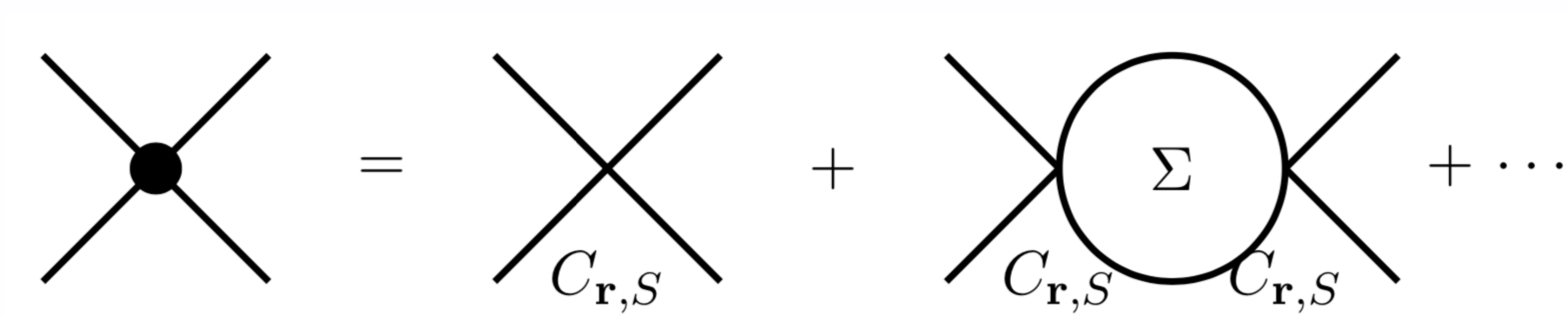
Pion-less EFT:

[Kaplan, Savage, Wise, nucl-th/9801034]

$$\mathcal{L} = N^\dagger \left(iD_t + \frac{\vec{D}^2}{2M_N} + \frac{D_t^2}{2M_N} \right) N + \mathcal{L}_4 + \frac{\kappa}{M_N} g_2 N^\dagger J^a (\vec{\sigma} \cdot \vec{B}_a) N$$

$$\mathcal{L}_4 = -\sum_{\mathbf{r},S} \frac{C_{\mathbf{r},S}}{4} \left(N P^i_{\mathbf{r},S} N \right)^\dagger \left(N P^i_{\mathbf{r},S} N \right) + \ldots$$

Coefficients are fixed to reproduce elastic scattering:

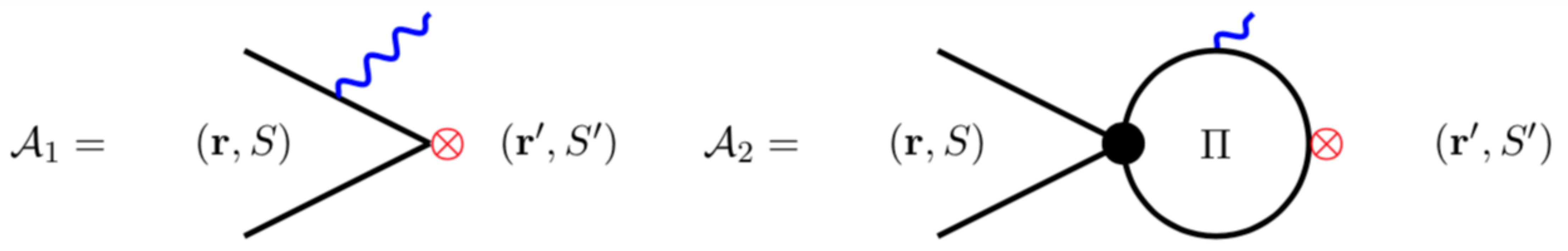


$$\mathcal{A}_{\mathbf{r},\mathbf{S}} = \frac{4\pi}{M_N} \frac{1}{p \cot \delta_{\mathbf{r},\mathbf{S}} - ip} \qquad p \cot \delta_{\mathbf{r},S} = -\frac{1}{a_{\mathbf{r},\mathbf{S}}} + \frac{r_0}{2} p^2 + \ldots$$

$$\frac{1}{a_{\mathbf{r},S}} \approx \sqrt{M_N E_B}$$

This theory also describes deuterium!

Magnetic transition:

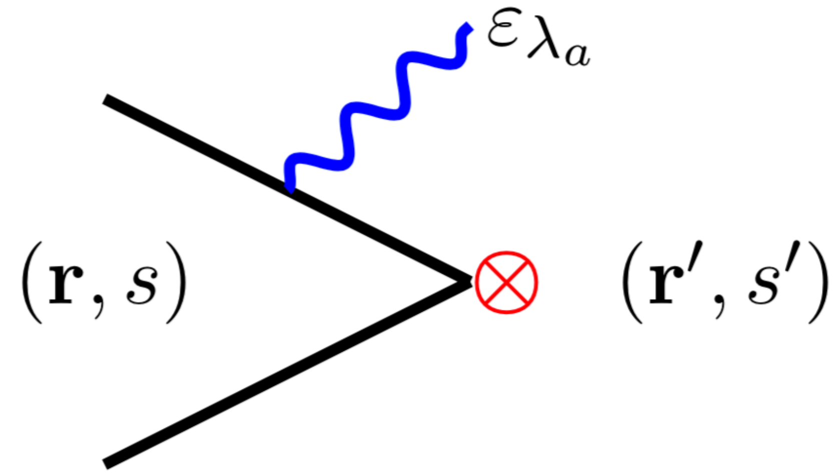


$$\Delta S = 1 \qquad \Delta L = 0$$

$$\sigma v_{\rm rel}\big|_{\rm magnetic} = K_M \frac{\pi \kappa^2 \alpha}{M_N^2} \left(\frac{E_B}{M_N}\right)^{\frac{3}{2}} \left(1 - \frac{a_{\rm initial}}{a_{\rm final}}\right)^2$$

Electric transition:

$\mathcal{A} =$



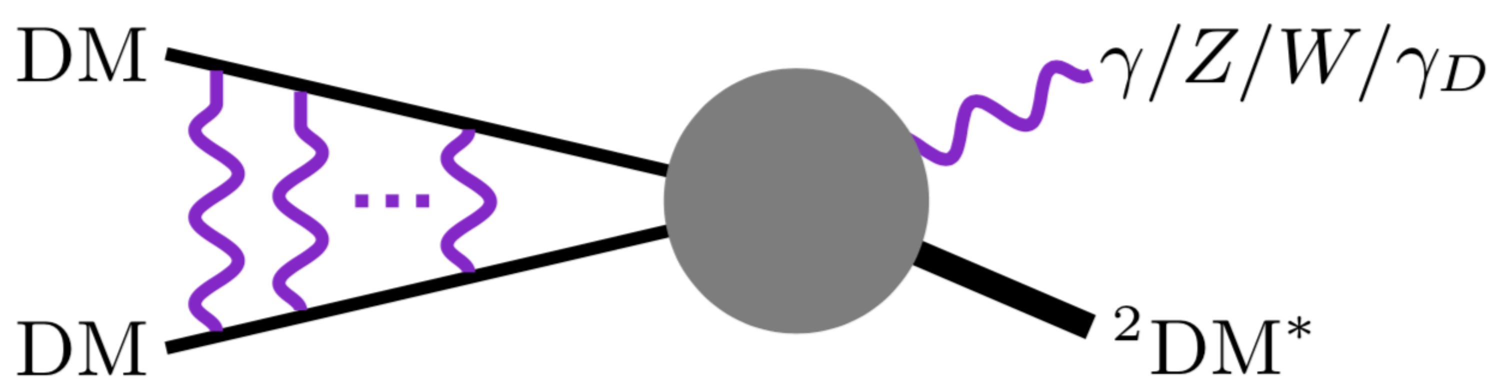
$\Delta S = 0$ $\Delta L = 1$

Initial p-wave state:

$$\sigma v_{\rm rel}\Big|_{\rm electric} = K_E \frac{\pi\alpha}{M_N^2}\left(\frac{M_N}{E_B}\right)^{\frac{1}{2}} v_{\rm rel}^2$$

In the SM LO computations agree to 10% with exp.

Contrary to SM we also have to include long distance effects due to weak interactions:



This leads to the Sommerfeld enhancement:

$$\sigma_{\text{tot}} = \text{SE} \times \sigma_{\text{short}}$$

For MV=0:

$$\text{SE}_{s-\text{wave}} = \frac{2\pi\alpha_{\text{eff}}/v_{\text{rel}}}{1 - e^{-2\pi\alpha_{\text{eff}}/v_{\text{rel}}}} \approx \frac{2\pi\alpha_{\text{eff}}}{v_{\text{rel}}}$$

$$\text{SE}_{p-\text{wave}} = \left[1 + \left(\frac{\alpha_{\text{eff}}}{v_{\text{rel}}}\right)^2\right] \frac{2\pi\alpha_{\text{eff}}/v_{\text{rel}}}{1 - e^{-2\pi\alpha_{\text{eff}}/v_{\text{rel}}}} \approx 2\pi \left(\frac{\alpha_{\text{eff}}}{v_{\text{rel}}}\right)^3$$

Triplet model:

$$SU(3)_D \otimes SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \qquad Q = (3\,,1\,,3)_0$$

Dynamics same as QCD with 3 degenerate flavours.
Lightest states are dark pions:

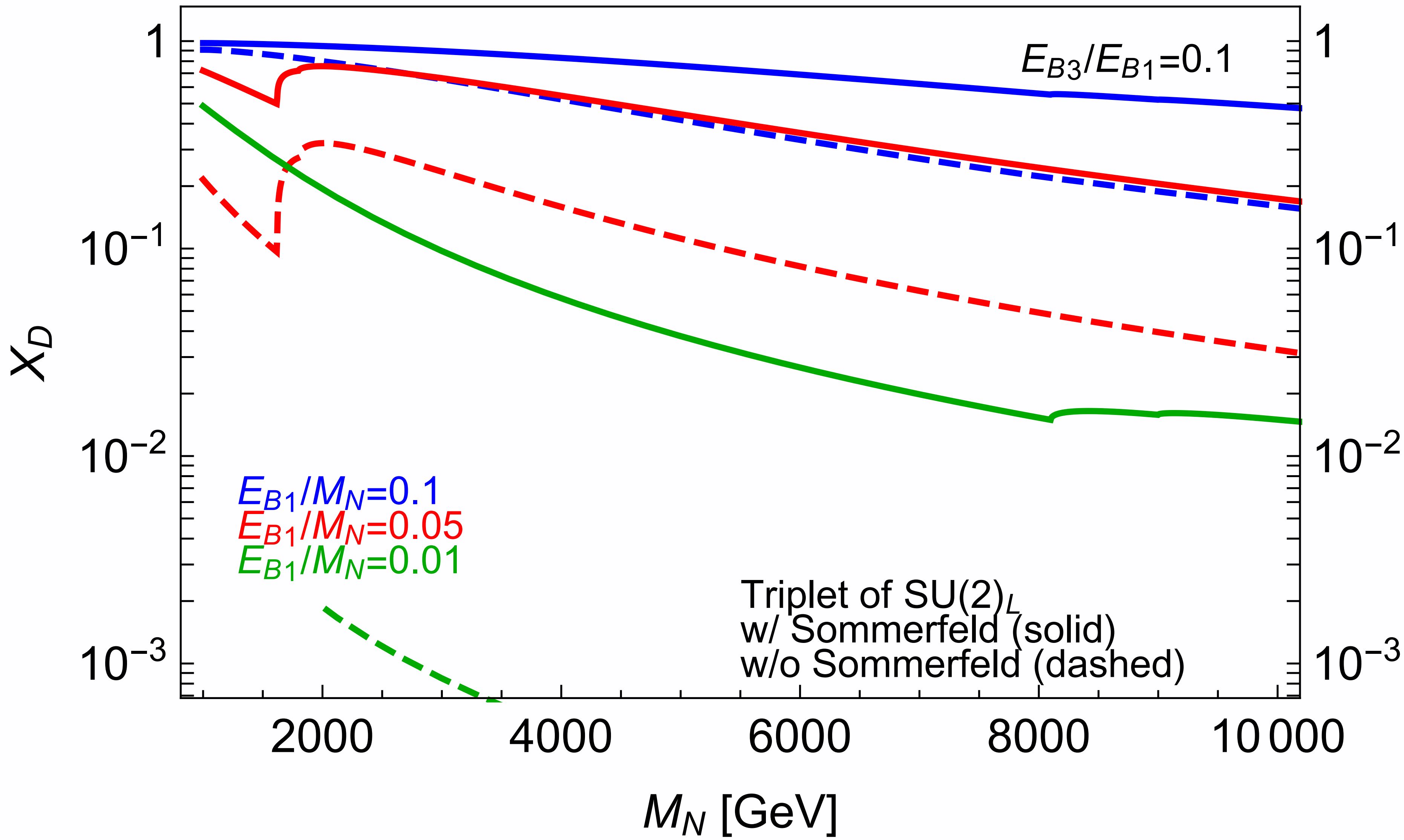
$$8 = 3 + 5$$

Dark matter is the neutral component of dark baryon in a triplet rep V. Lightest deuterium isotopes are VxV:

Name	$SU(2)$	Spin
D_1	1	0
D_3	3	1
D_5	5	0

[see Beane et al. 2019]

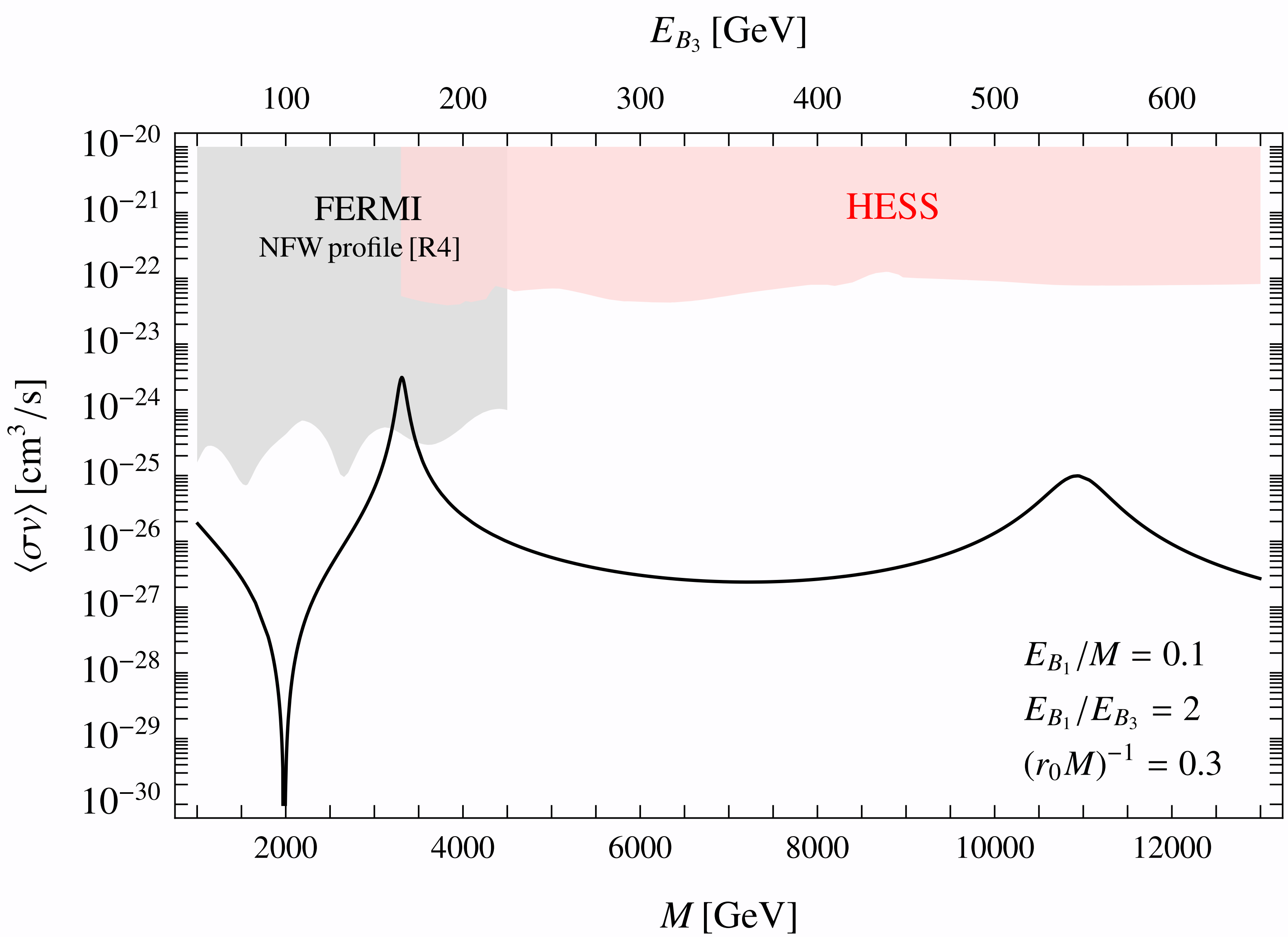
[MR, Tesi, 1812.08784]



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

Indirect detection:

Deuterium could be formed today through emission of a monochromatic photon detectable with gamma-ray telescopes.



$$V_0 V_0 \Longrightarrow D_3^0 + \gamma$$

$$E_\gamma \approx E_{B_3}$$

Secondary line:

$$E_{\gamma'} \approx E_{B_1} - E_{B_3}$$

At low DM velocities factorisation can fail due to finite size effects and shift of zero energy bound states:

$$\mathrm{SE} \approx \frac{V_0}{E_{B_i}(M) + M_N v_{\rm rel}^2}$$

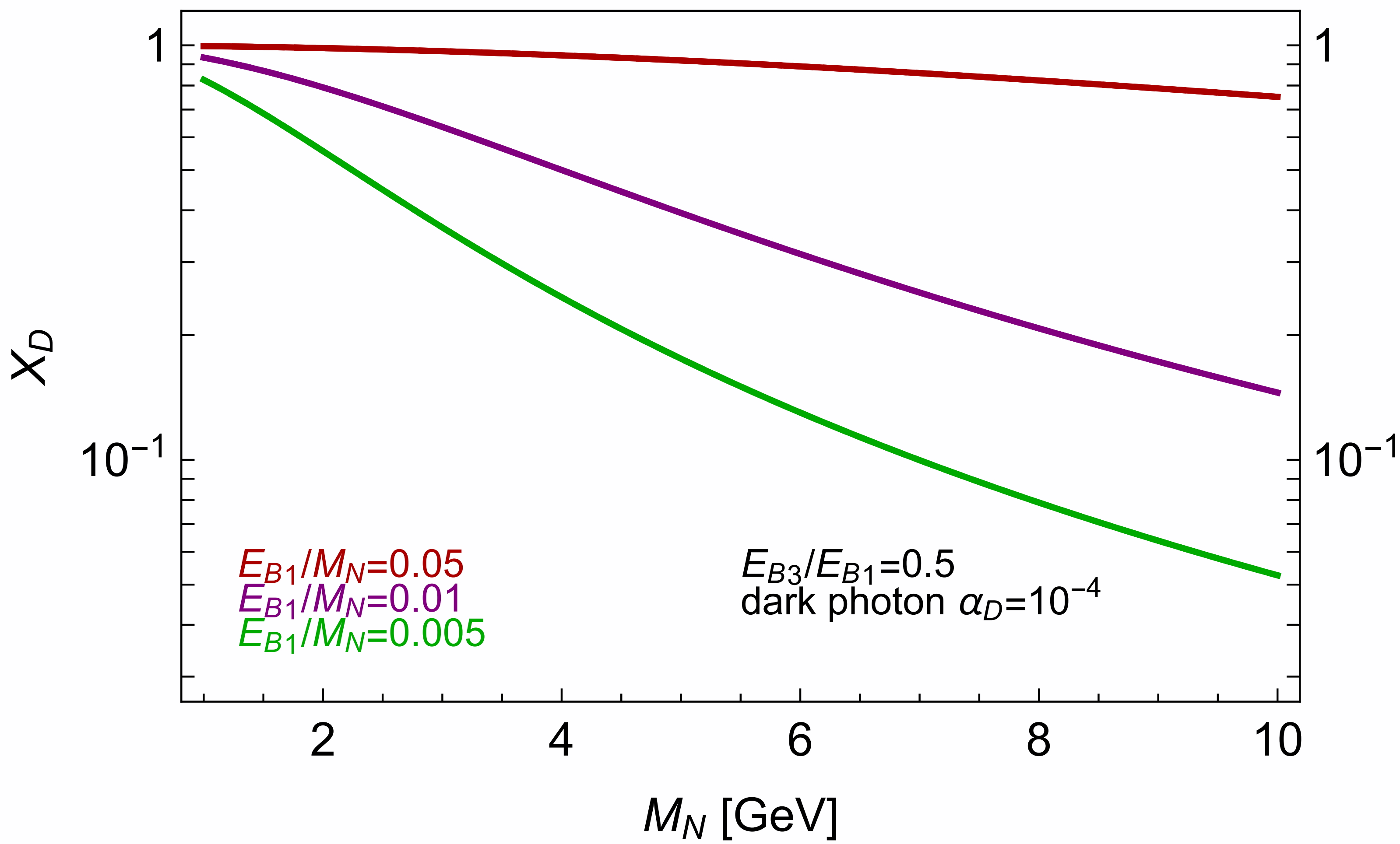
A safe way to proceed is to compute the cross-section in QM using the wave-functions of initial and final states including long and short distance potentials:

$$\sigma v_{\rm rel}\big|_{\rm mag} \propto \left| \int dr\, u_f^* u_i \right|^2 \qquad -\frac{u_l''}{M_N} + \left[V + \frac{l(l+1)}{M_N r^2} \right] u_l = E u_l$$

For shallow nuclear bound states the result depends weakly on the choice of the potential:

$$V_N(r) = -V_I \theta(r_0 - r)$$

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



[Alpher, Bethe, Gamow, 1948]

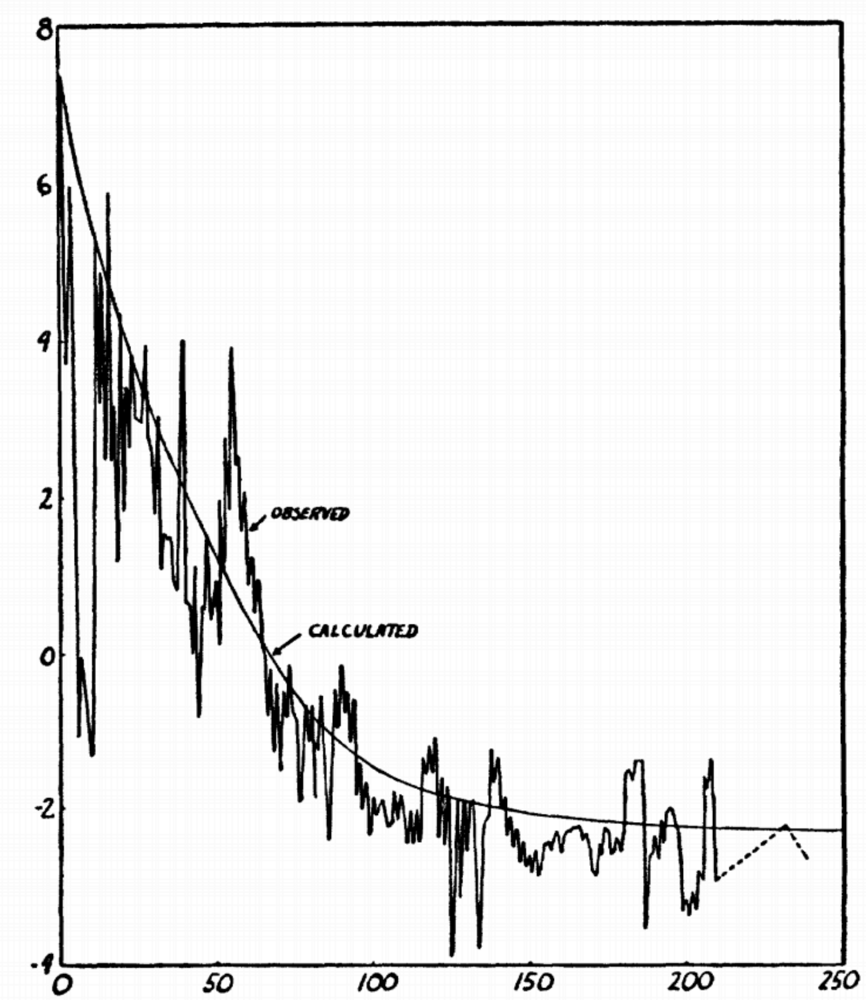


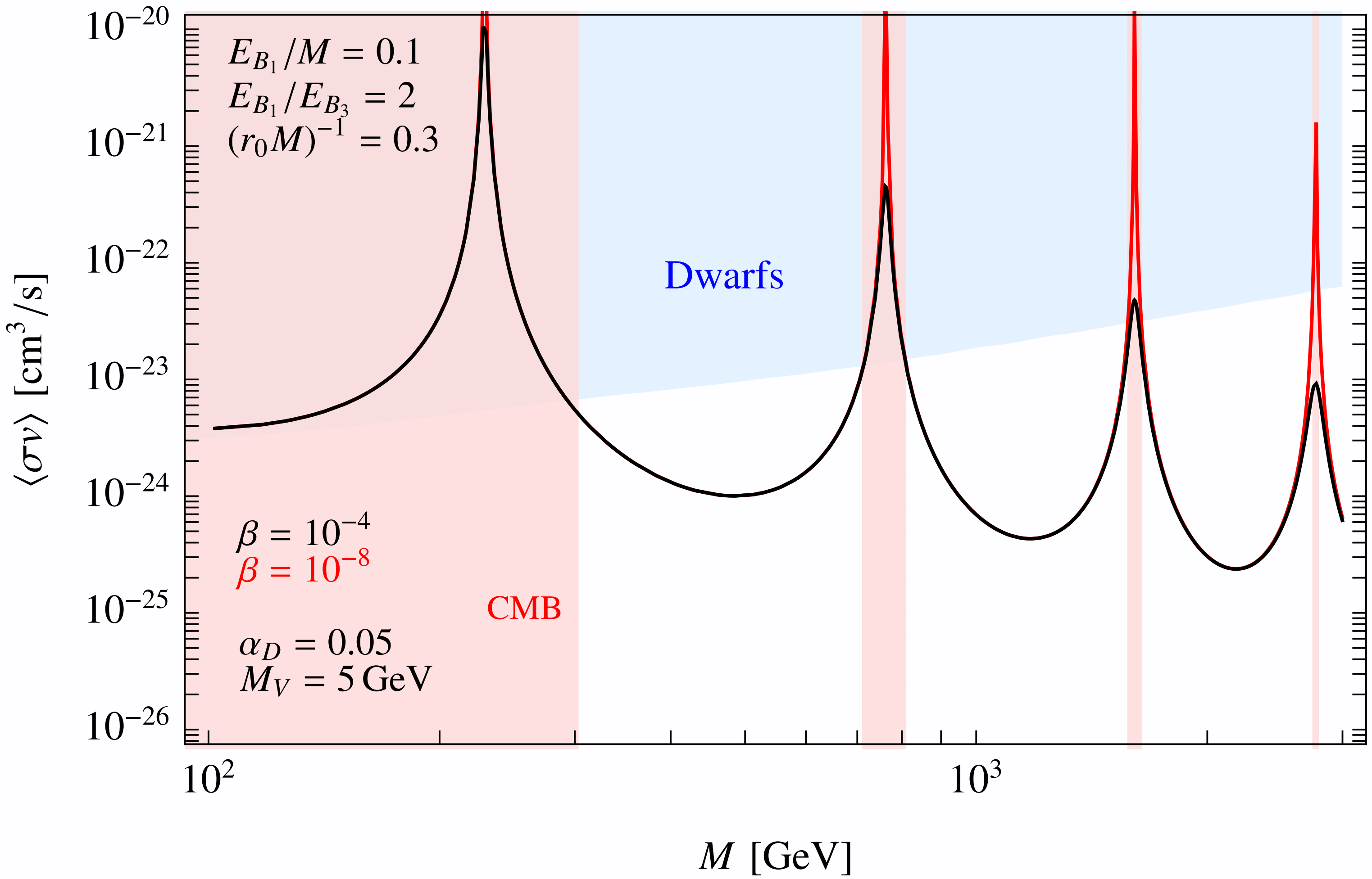
FIG. 1.

Log of relative abundance

Atomic weight

Dark nucleosynthesis can only start if a light quantum can be emitted. Simple option is a dark photon:

$$\mathcal{L}_D = -\frac{1}{4} F_{D\,\mu\nu} F_D^{\mu\nu} - \frac{1}{2} M_V^2 V_\mu V^\mu - \frac{\epsilon}{2c_W} F_{D\,\mu\nu} B^{\mu\nu}$$



Dark photon emission produces a diffuse photon flux constrained by Dwarf Galaxies. Energy injected strongly constrained by CMB.

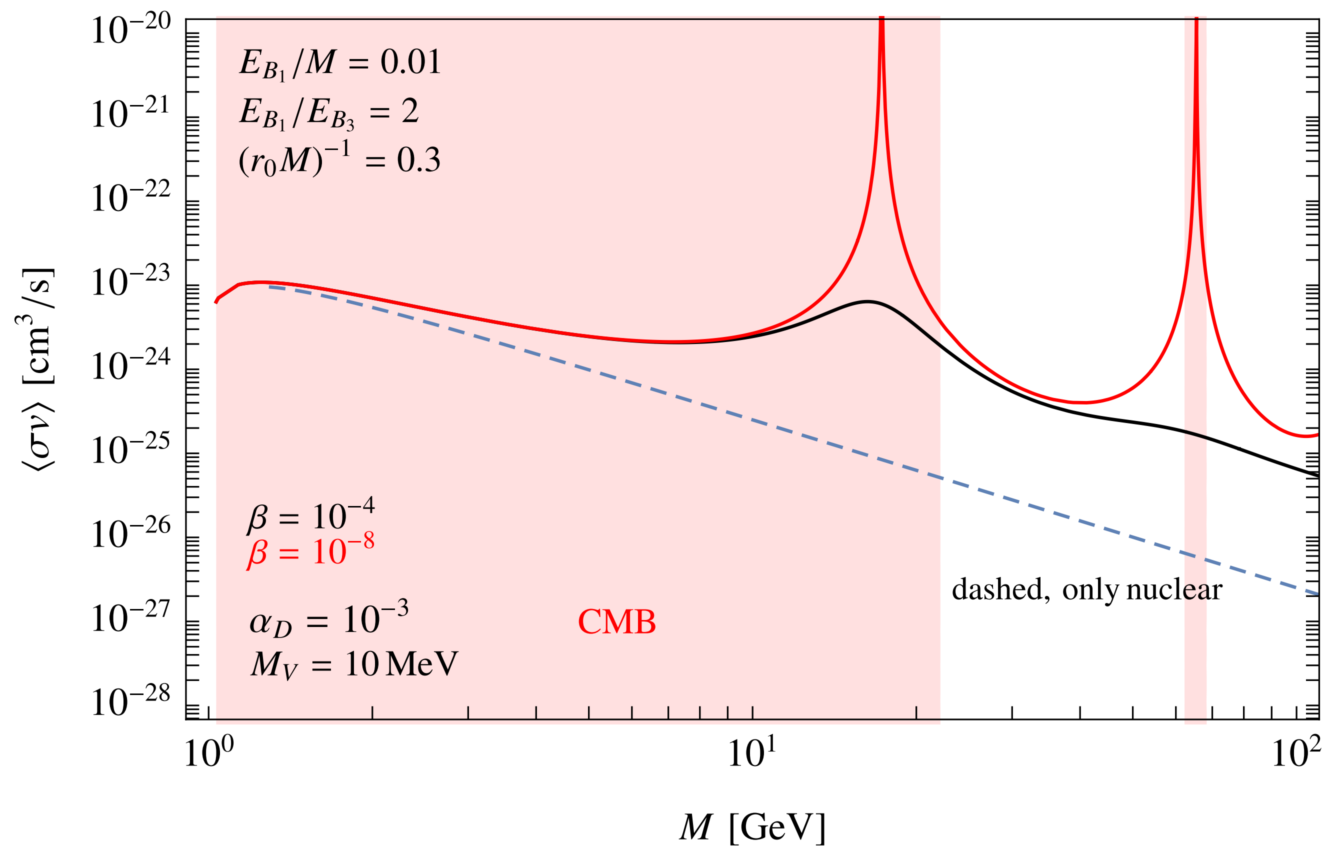
SUMMARY

- Composite dark matter, especially a baryon of a dark gauge group, is a strongly motivated and viable scenario. Many models are possible with distinctive phenomenology.

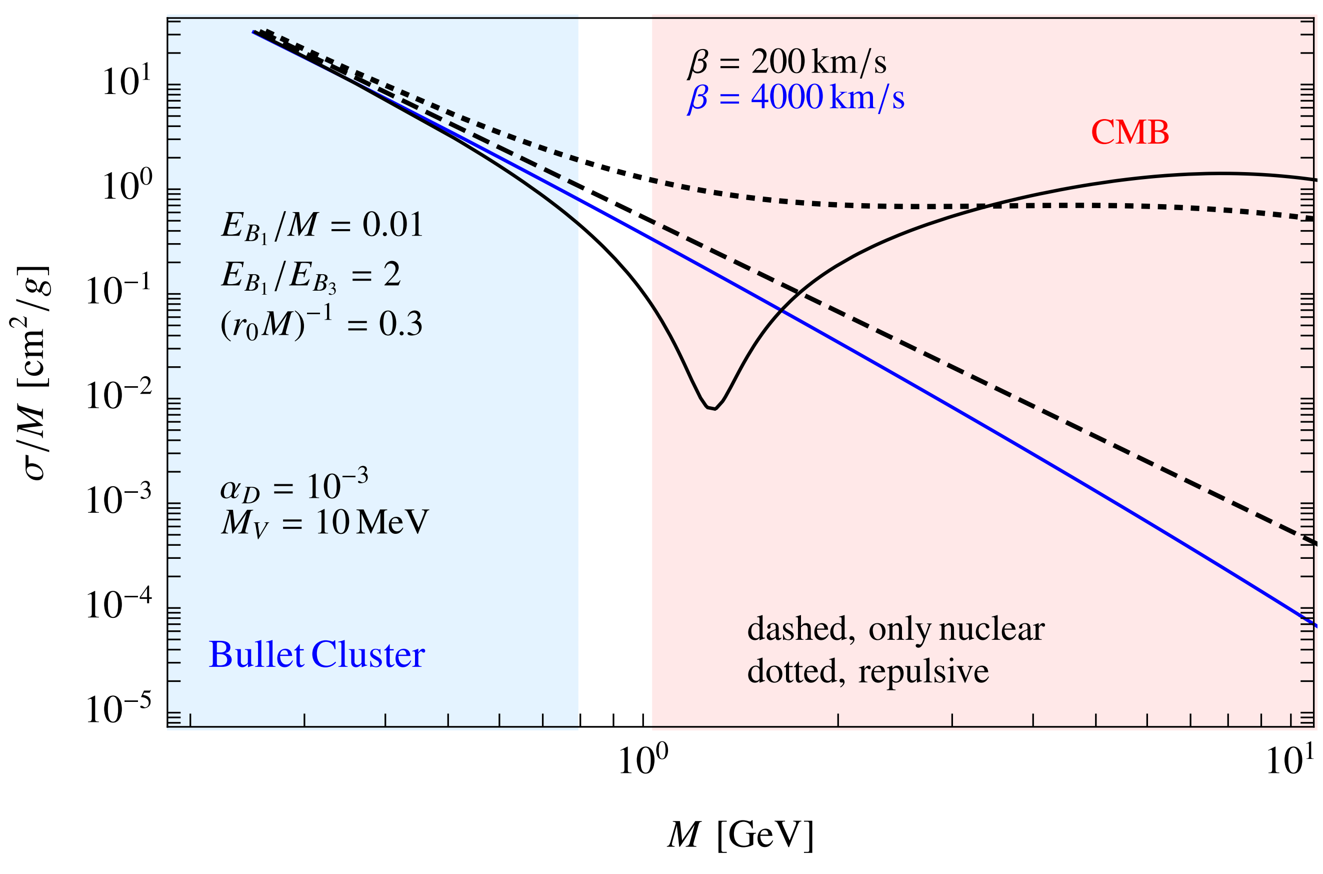
- The dark sector contains many other resonances. Nuclei could be formed in the cosmological history or in the present universe, giving rise to striking signatures in indirect detection experiments.

- A detailed study requires a DARK MANHATTAN PROJECT: determine the spectrum and interactions of hadrons and nuclei in QCD-like theories. Dark nucleosynthesis can be computed quantitatively with just few inputs.

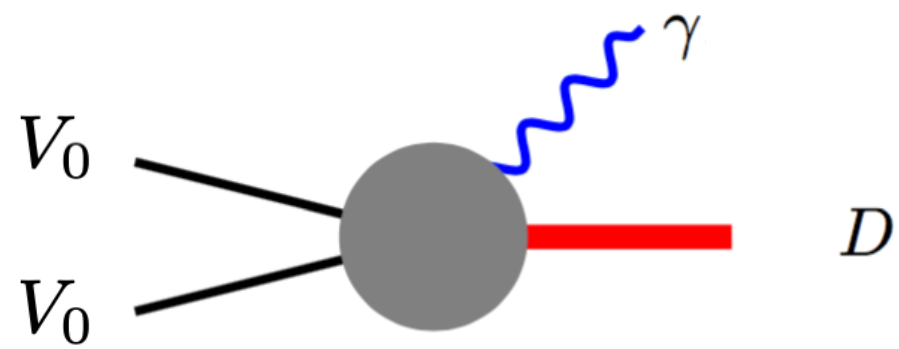
Light singlet:



Elastic x-sec:

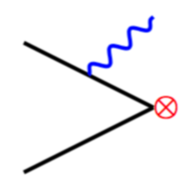


contributions of different origin

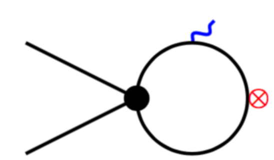


for a ‘composite dirac wino’ we expect **two effects** better seen in EFT

$$(V_0 V_0) \to (V^+ V^-)^* \to D^0_{I=1} + \gamma$$

$\mathcal{A}^{\rm SE}_{00\to+-} \times$  present also in wino annihilation

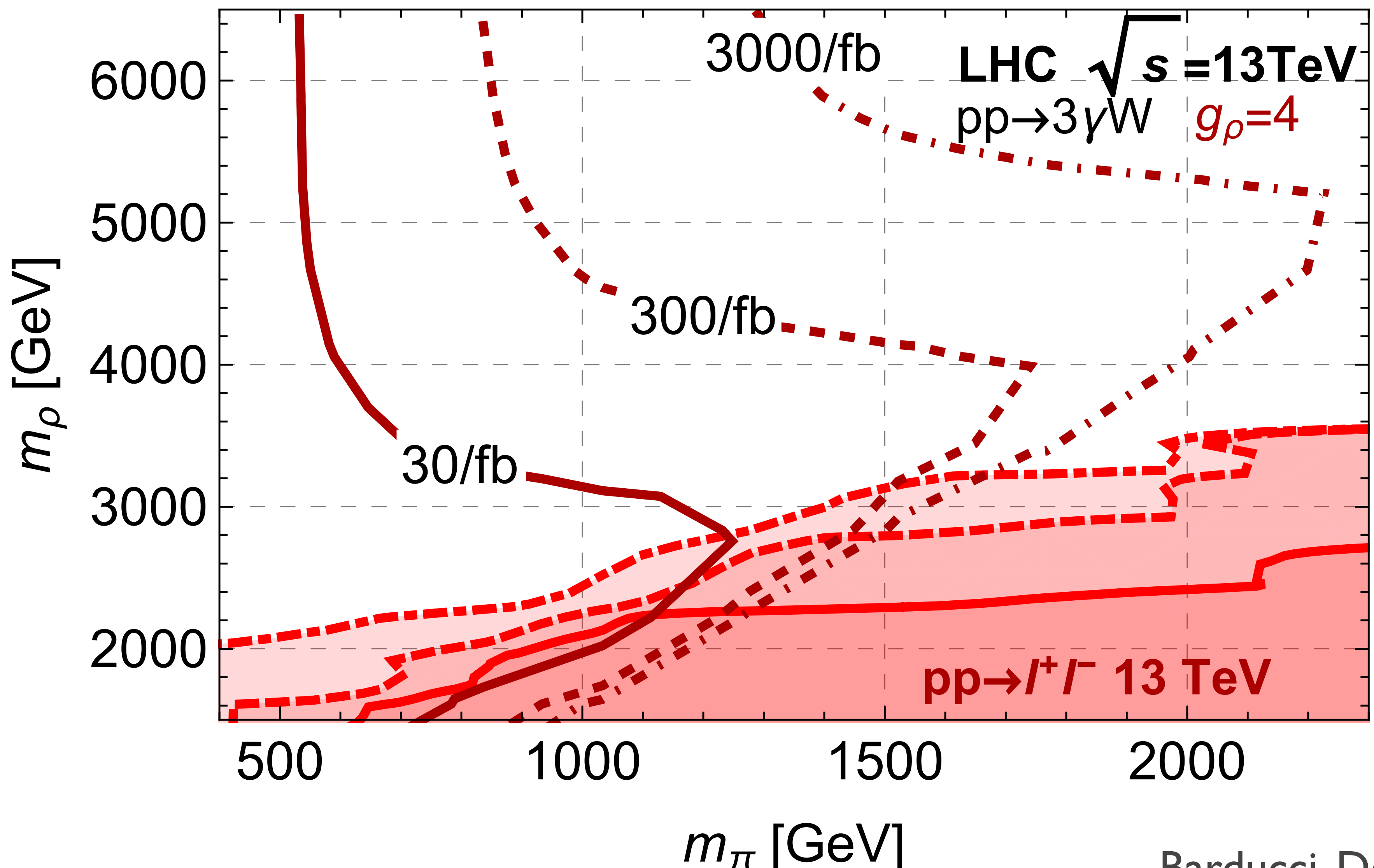
$$(V_0 V_0) \to (V_0 V_0)^* \to D^0_{I=1} + \gamma$$

$\mathcal{A}^{\rm SE}_{00\to 00} \times$ 

they can interfere (destructively)

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