Dark Matter Bound States

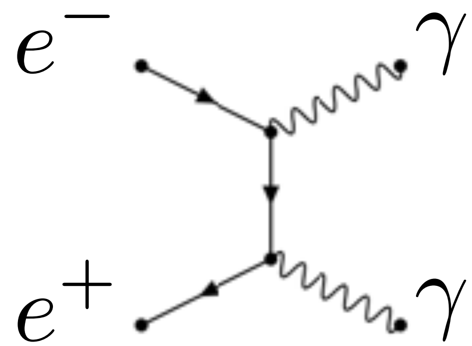
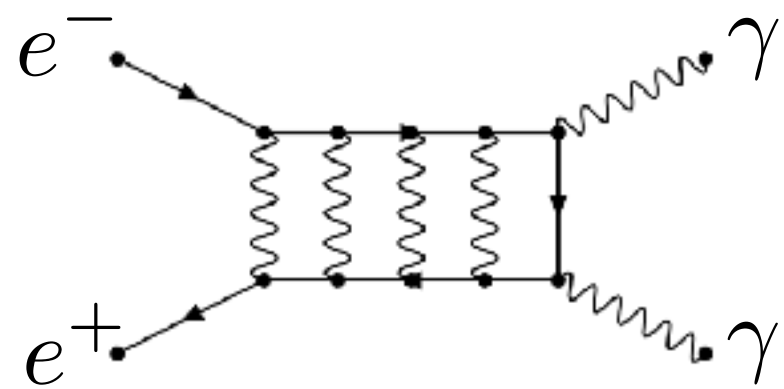
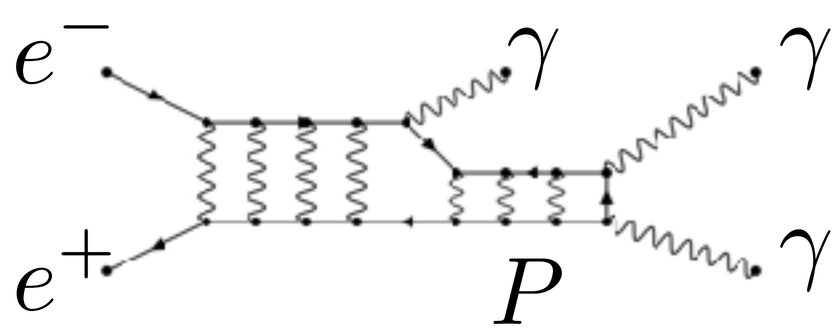
Juri Smirnov

CP3-Origins, University of Southern Denmark

Talk at CoDyCE workshop, Lyon 30.08.2018

In collaboration with: A. Mitridate, G.M. Pelaggi, A.D. Plascencia, M. Redi, A. Salvio, F. Sannino and A. Strumia

The Effect of Unstable Bound States of Dark Matter

Process	Diagram	Cross-Section area	
I) $e^+ e^- \to \gamma\gamma$			
II) $e^+ e^- \to P^* \to \gamma\gamma$			
III) $e^+ e^- \to P^* \to P\,\gamma$ $P \to \gamma\gamma$			

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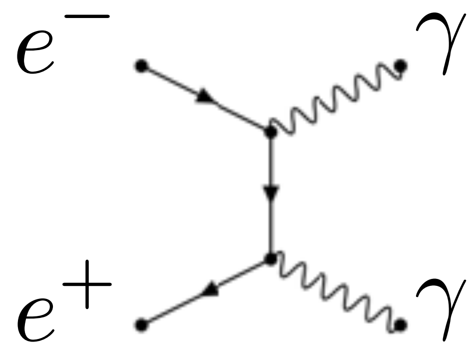
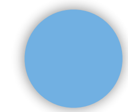
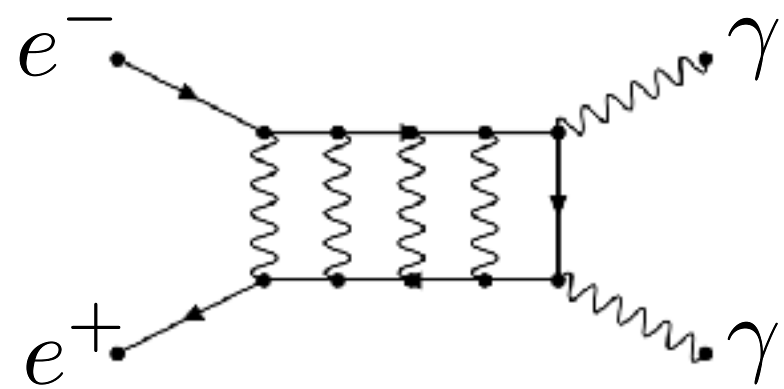
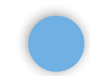
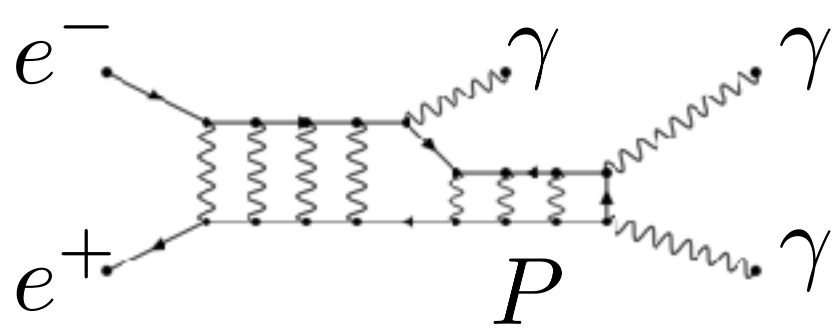
I) $e^+ e^- \to \gamma\gamma$		large velocity 	
II) $e^+ e^- \to P^* \to \gamma\gamma$			
III) $e^+ e^- \to P^* \to P\,\gamma$ $P \to \gamma\gamma$			

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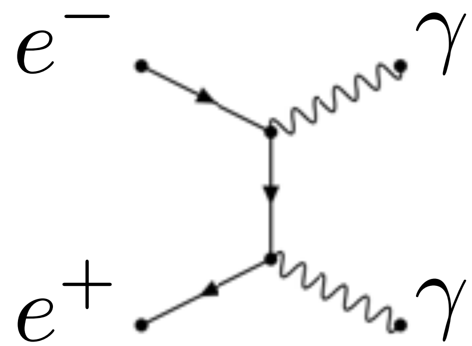
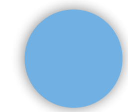
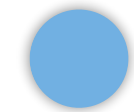
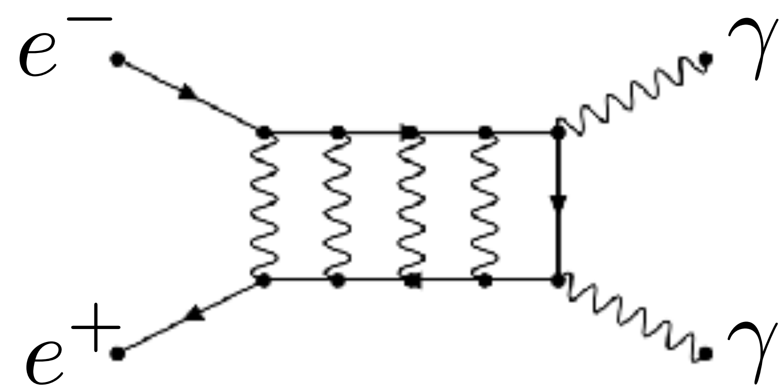
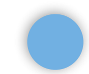
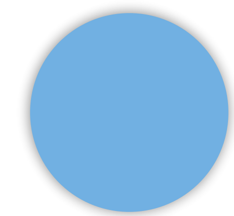
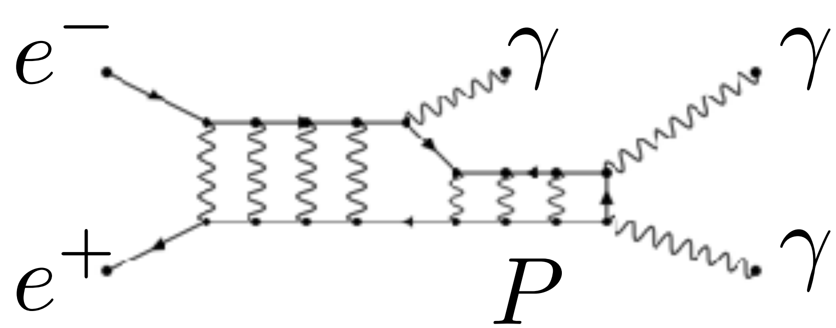
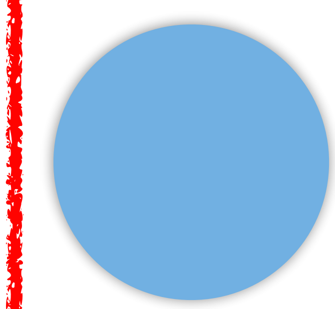
		large velocity	small velocity
I) $e^+ e^- \rightarrow \gamma\gamma$			
II) $e^+ e^- \rightarrow P^* \rightarrow \gamma\gamma$			
III) $e^+ e^- \rightarrow P^* \rightarrow P\,\gamma$ $P \rightarrow \gamma\gamma$			

Non perturbative Effects

$$M_V < \alpha_{\text{eff}}\, M_\chi$$
$$R_{\text{Bohr}} < R_{\text{Yukawa}}$$

$$V(r) = -\alpha_{\text{eff}} \frac{e^{-M_V r}}{r} \approx -\alpha_{\text{eff}} \left(\frac{1}{r} - M_V\right)$$

$$E_{n\ell} \simeq \frac{\alpha_{\text{eff}}^2 M_\chi}{4n^2} - \alpha_{\text{eff}} M_V + \mathcal{O}(M_V^2).$$

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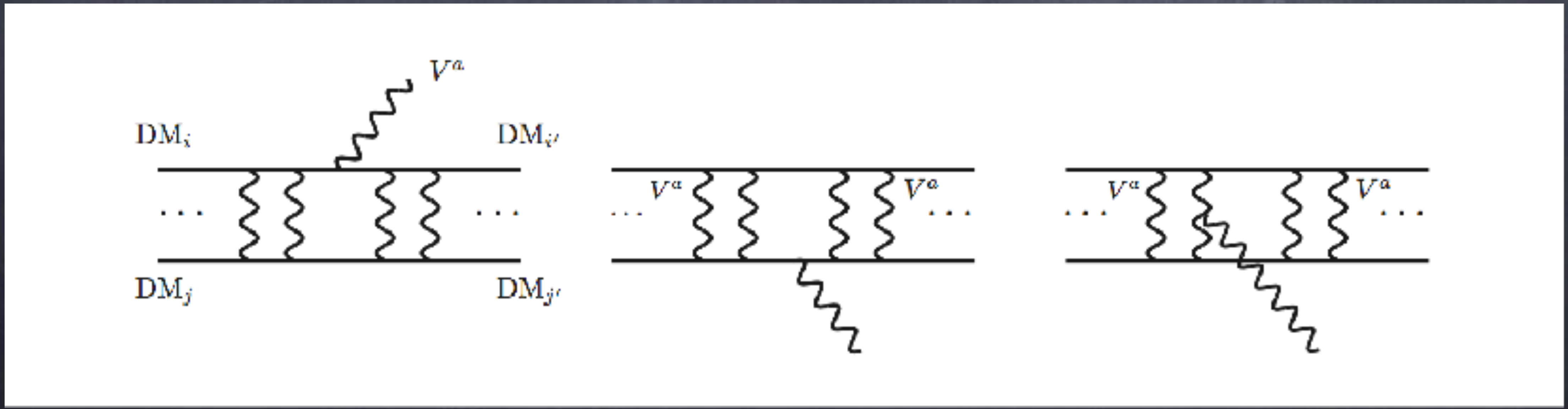
Bound State Selection Rules

- The Group theory structure
- The wave function symmetry
- Angular momentum conservation $\Delta L = 1$
- Energy conservation



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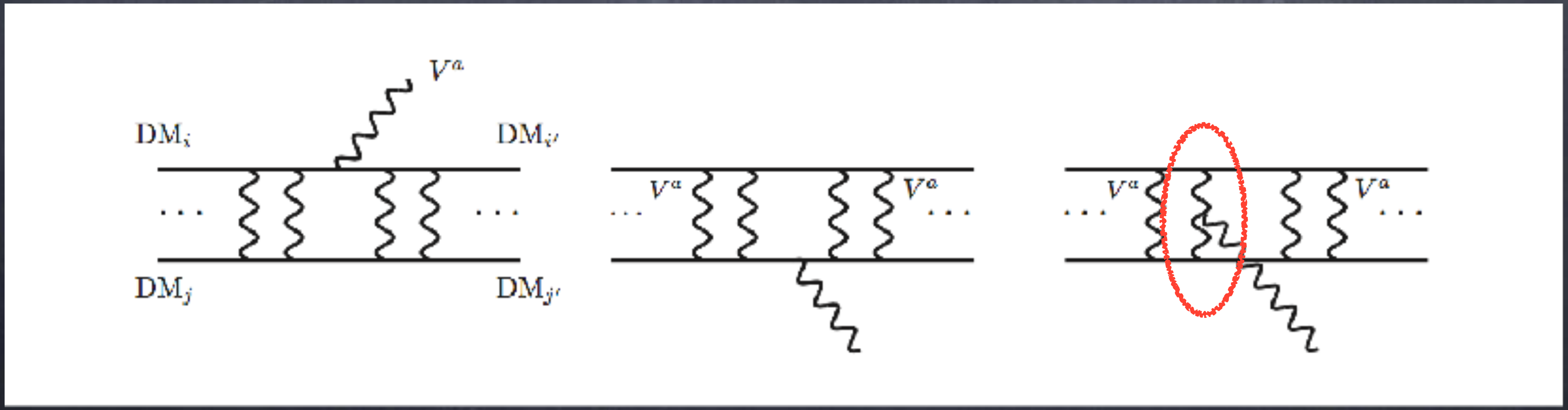

Cosmological Impact

$$\frac{dY_{DM}}{dz} = -\frac{\langle\sigma v\rangle_{\rm ann}}{z^2}\left(Y_{DM}^2 - Y_{eq.}^2\right) - \sum_i \frac{\langle\sigma v\rangle_{\rm bsf}}{z^2}\left(Y_{DM}^2 - Y_{B_i}\frac{Y_{eq.}^2}{Y_{eq.}^{B_i}}\right)$$

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$$\langle\sigma v\rangle_{bsf}\, \text{BR}(\text{B} \to \text{SM})$$

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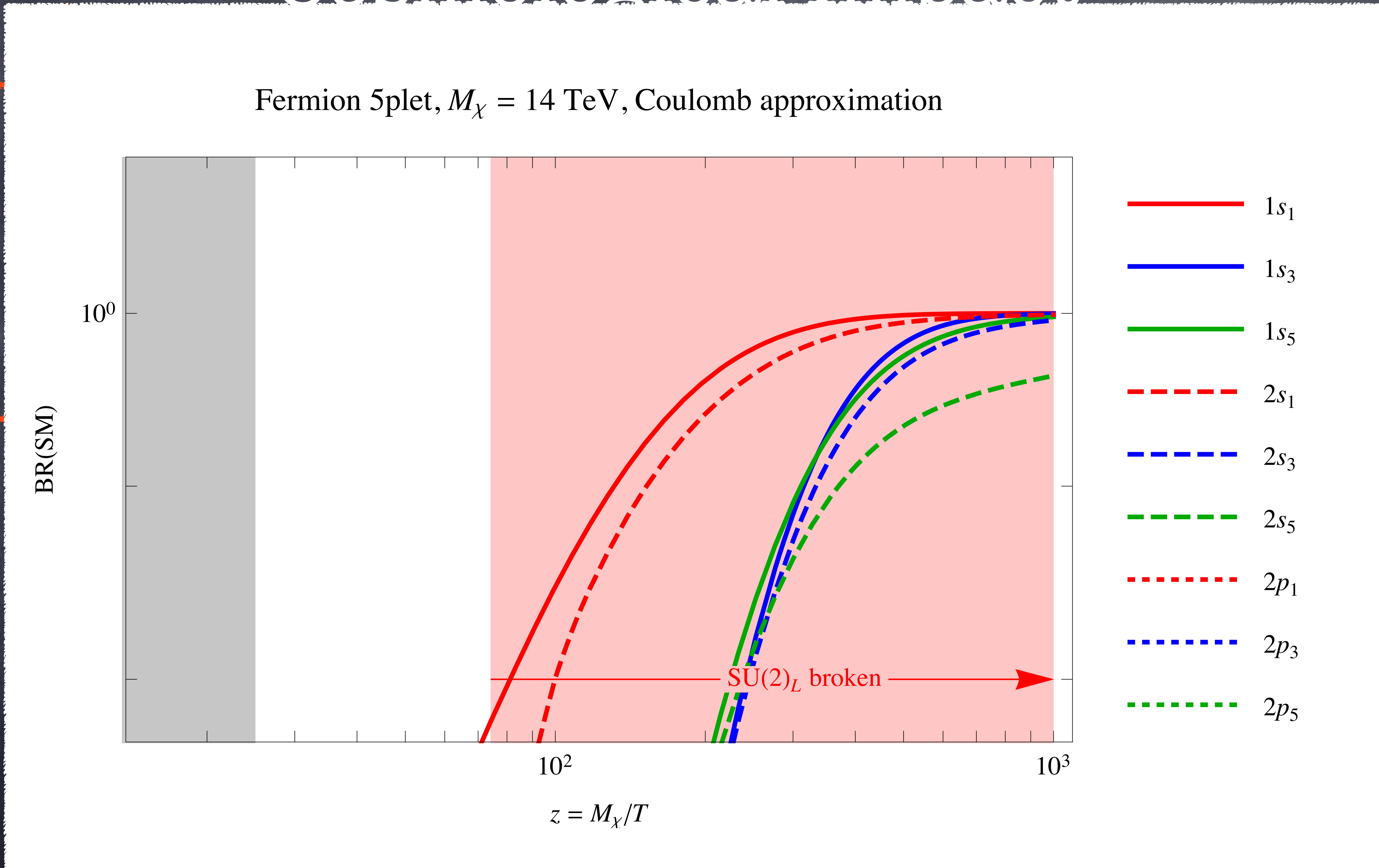
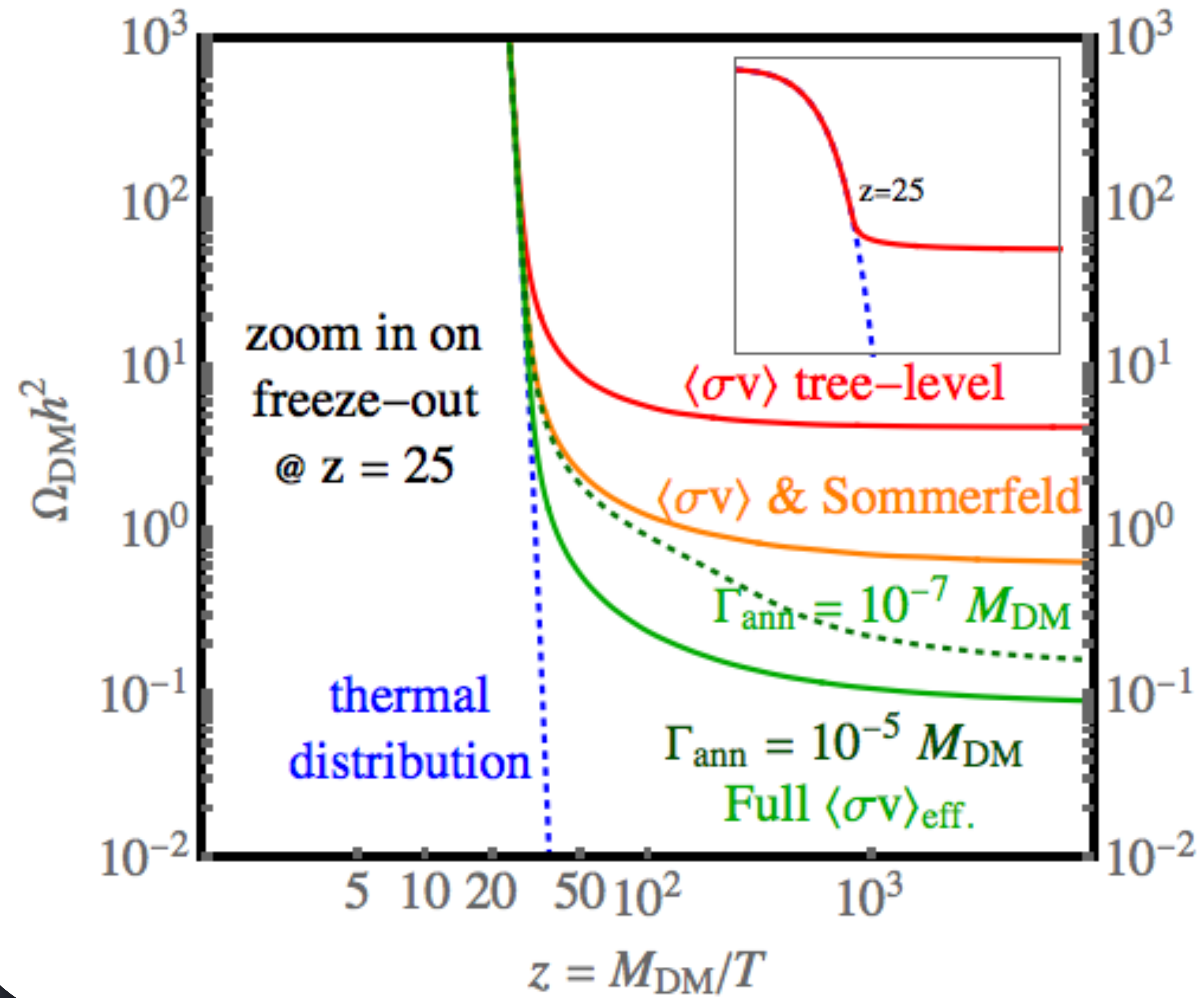


$$\langle \sigma v \rangle_{bsf}\, \mathrm{BR(B \to SM)}$$

Toy System



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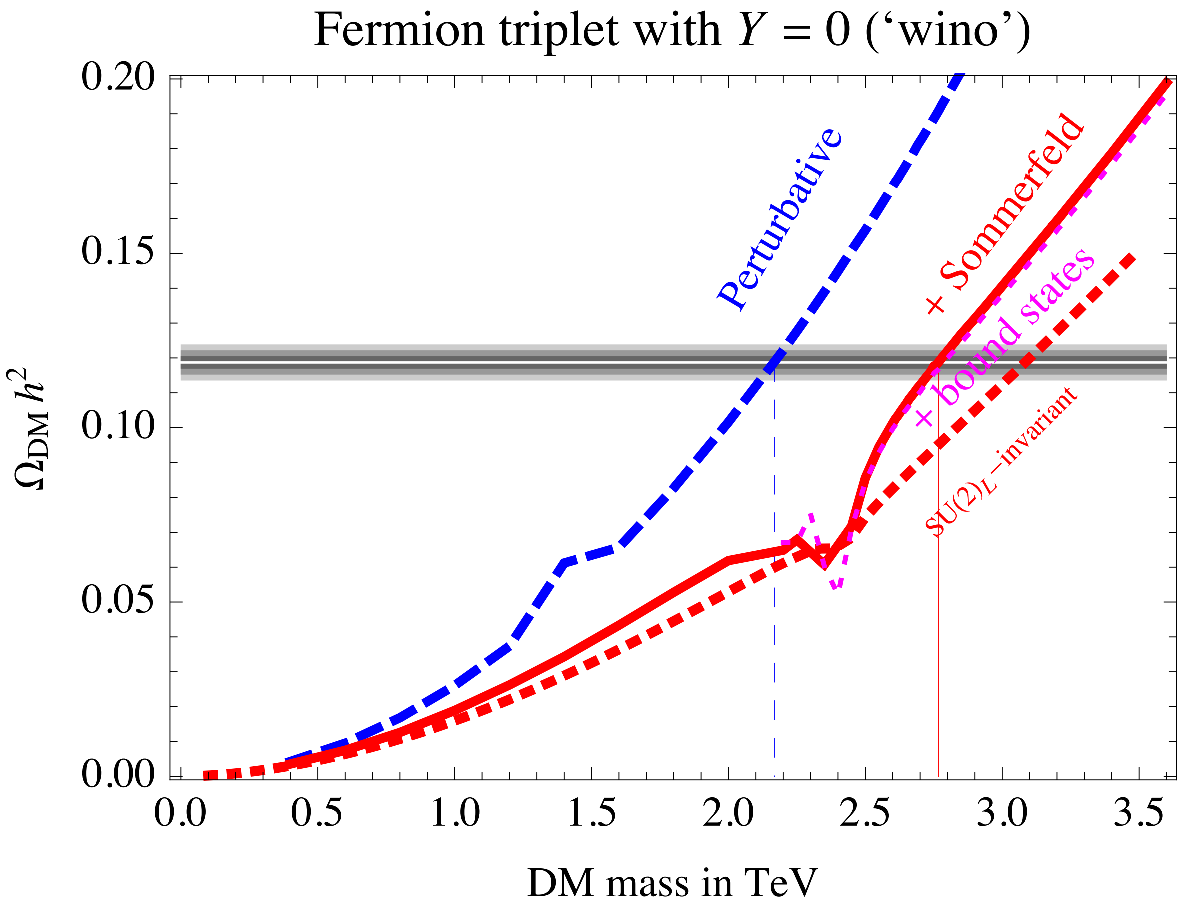
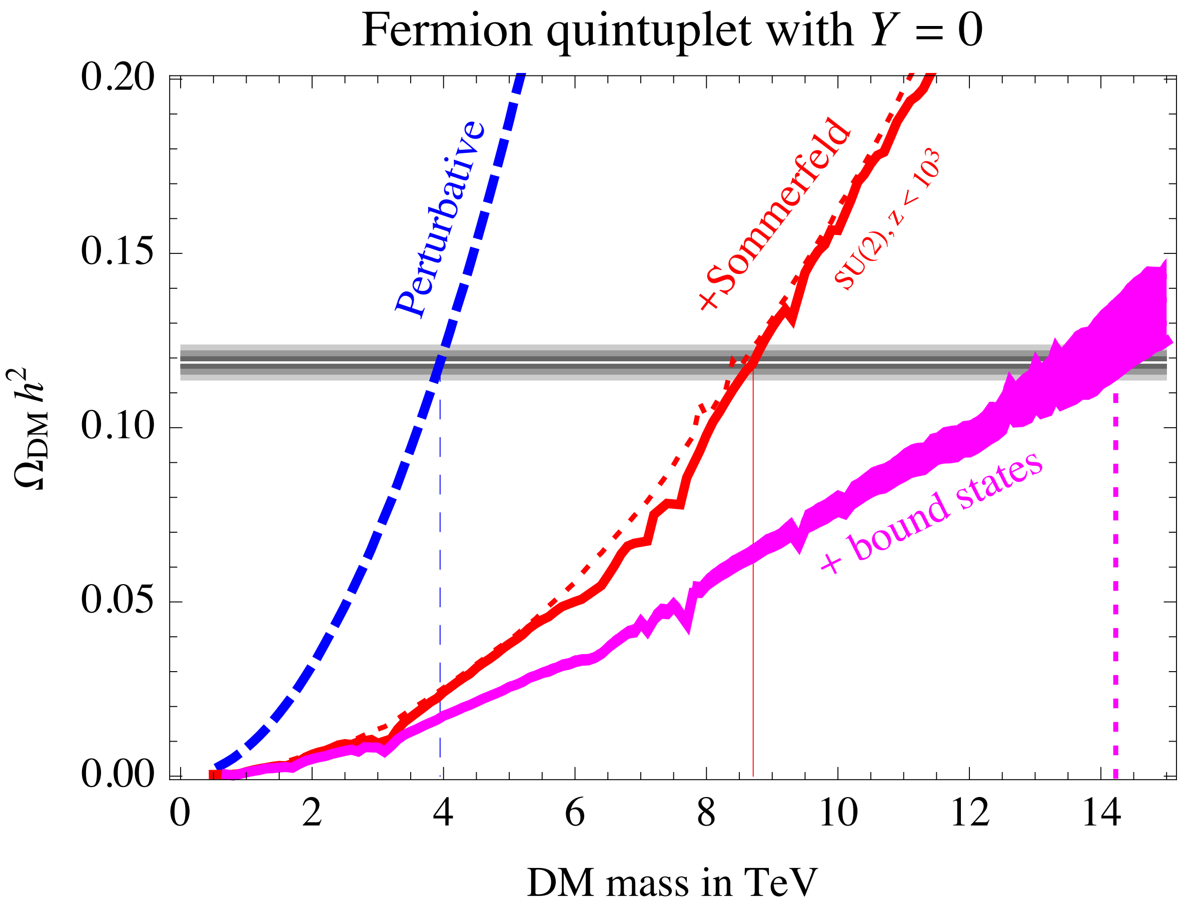
Application I: The gauge portal





The Triplet (Wino)

The Quintuplet (Minimal Dark Matter)

Summary I

- Bound State formation is an additional Non-perturbative effect which affects the DM annihilation cross section
- In models with sizeable gauge coupling and heavy dark matter candidates it can be the dominant effect setting the relic density
- Today bsf can lead to observable capture photon signals and give precision information about dark matter

Details in: JCAP 1705 (2017) no.05, 006
arXiv:1702.01141

Stable Bound States of Dark Matter

Dark Matter stability

$$SU(N)_{\rm DC} \times SU(3)_c \times SU(2)_L \times U(1)_{\rm em}$$

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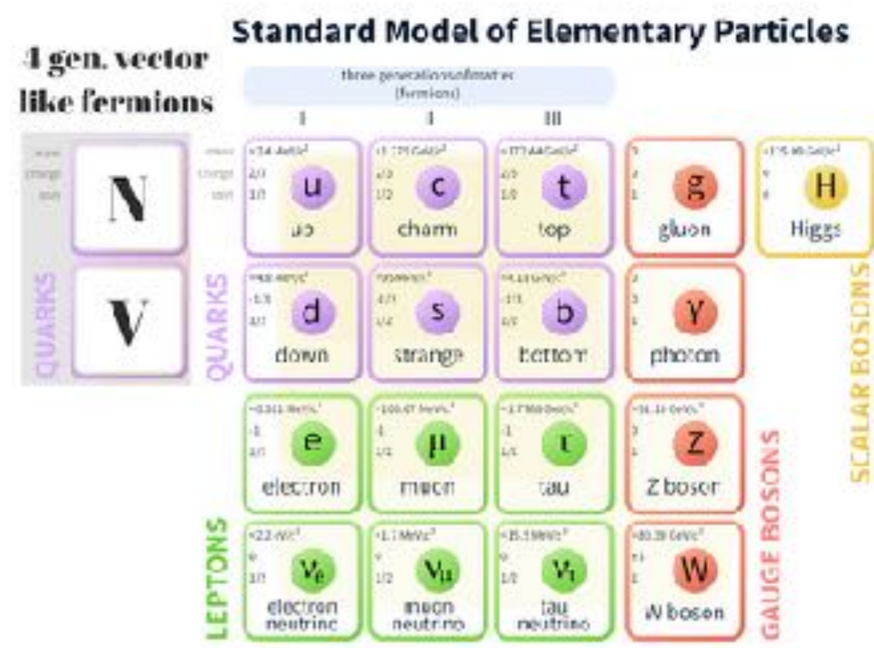

1503.08749

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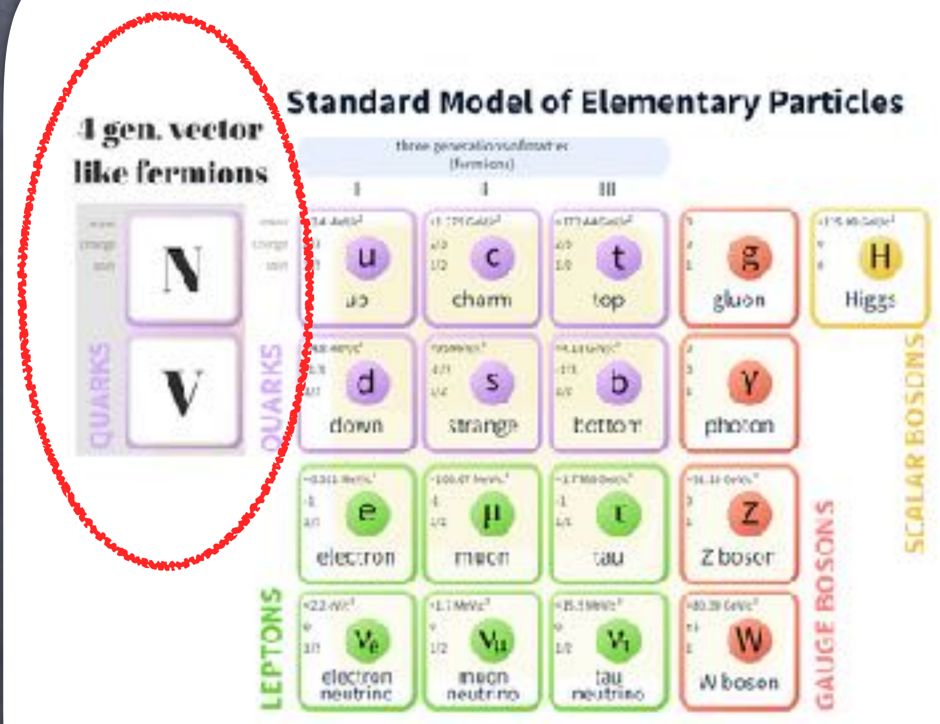
New Baryon Number → DM candidate



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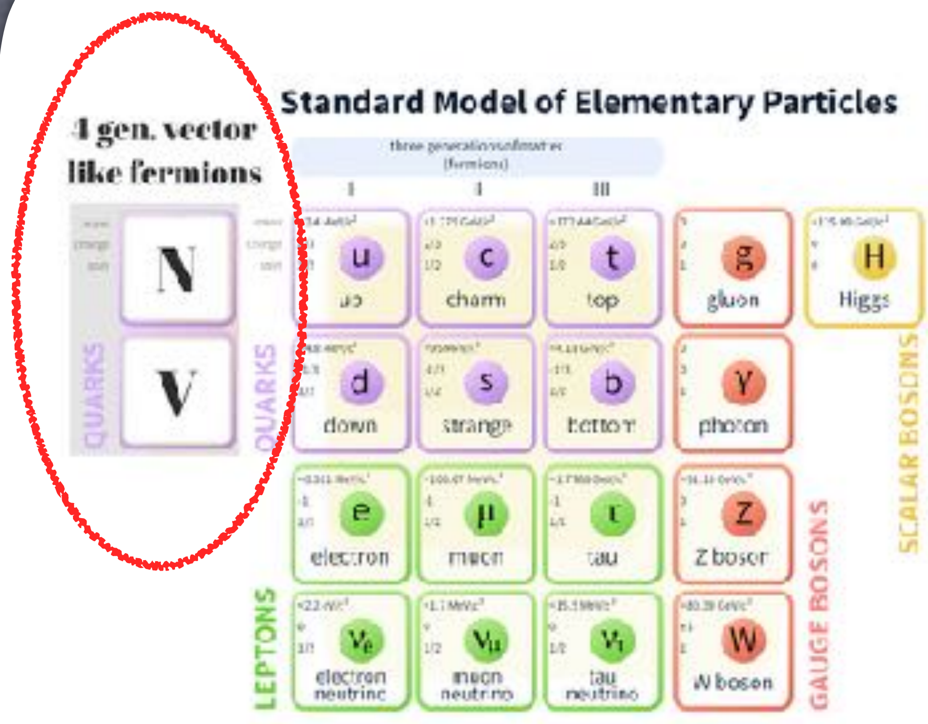
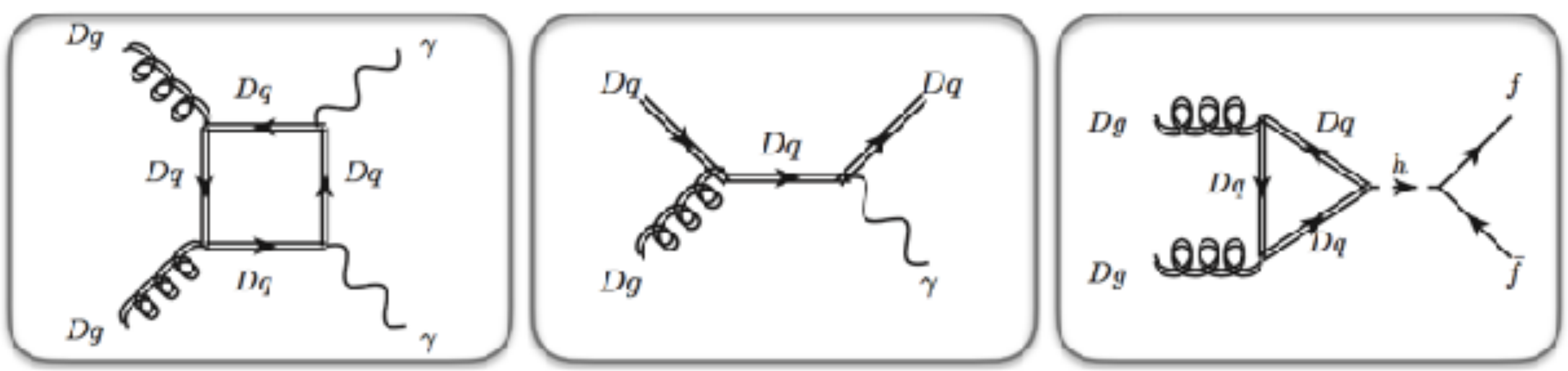


New Baryon Number → DM candidate

Thermal contact with the SM sector

1503.08749



Dark Matter stability II

New Baryon Number → DM candidate

Dark Matter stability II

Dim 5 Operators, lifetime too short

New Baryon Number → DM candidate

Dark Matter stability II

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Dim 6 Operators, acceptable if…

New Baryon Number → DM candidate

Dark Matter stability II

Dim 5 Operators, lifetime too short

Dim 6 Operators, acceptable if…

$$\mathcal{O}_6 \propto \frac{1}{\Lambda^2} QQQN_R$$

$$\Lambda > 10^{17}\ \text{GeV}$$

$$\tau > 10^{18}\ \text{sec}$$

New Baryon Number → DM candidate

The cut-off scale has to be close to the Plank scale

Consequences of Dark Color

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{\mathcal{G}^{A2}_{\mu\nu}}{4g^2_{DC}} + \frac{\theta_{DC}}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^A_{\mu\nu}$$
$$+\bar{Q}_i(i\not{D} - m_i)Q_i + y_{ij}HQ_iQ^c_j + h.c.$$

Consequences of Dark Color

- Structure formation implies no massless force mediator

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Consequences of Dark Color

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- Q in fund. rep. of SU(N): stable particle is Q^N

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Composite WINO

Simple example Model-V:

$$SU(3)_{DC} \otimes SU(3)_c \otimes SU(2)_L \times U(1)_Y$$

$$V = (3, 1, 3, 0)$$

$$DC_b = (V, V, V) : (1, 1, 3, 0) \oplus (1, 1, 5, 0)$$

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$$a_0 \approx \frac{2}{\alpha_{eff} m_Q}$$
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$$\Lambda_{DC} \sim m_Q \exp\left[-\frac{6\pi}{33\,\alpha_{DC}(m_Q)}\right]$$

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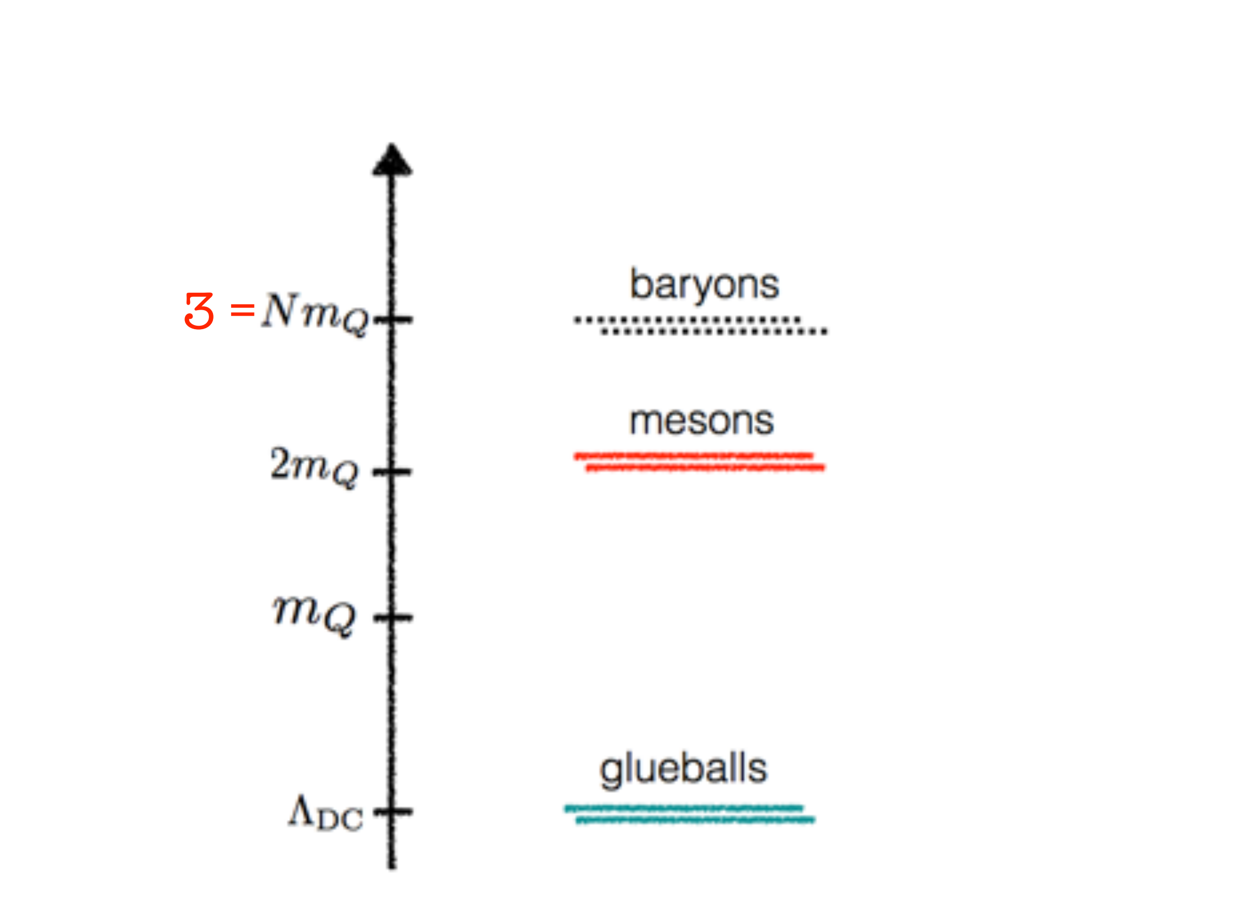

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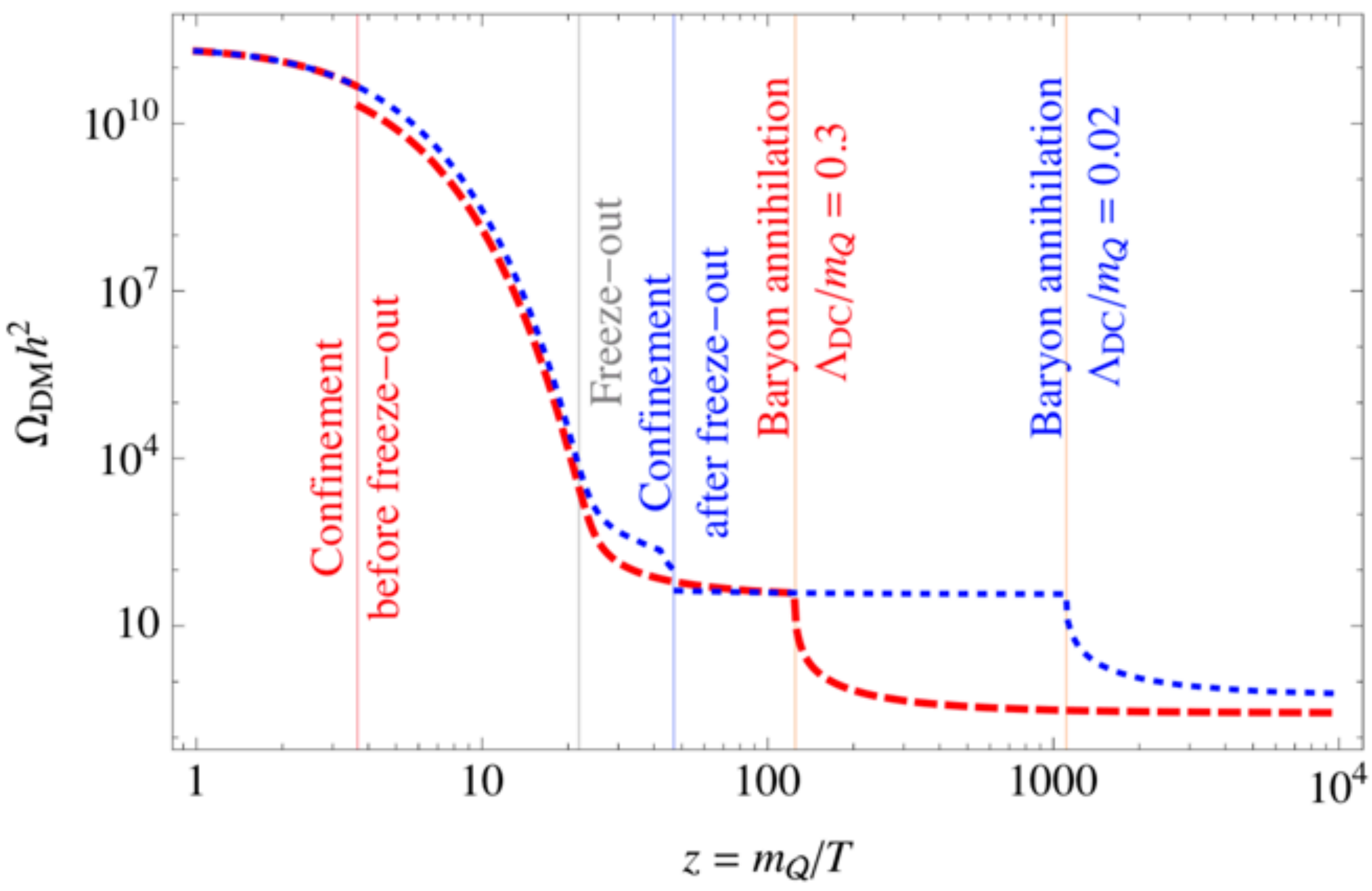
Freeze-out and Confinement



Geometrical Confinement

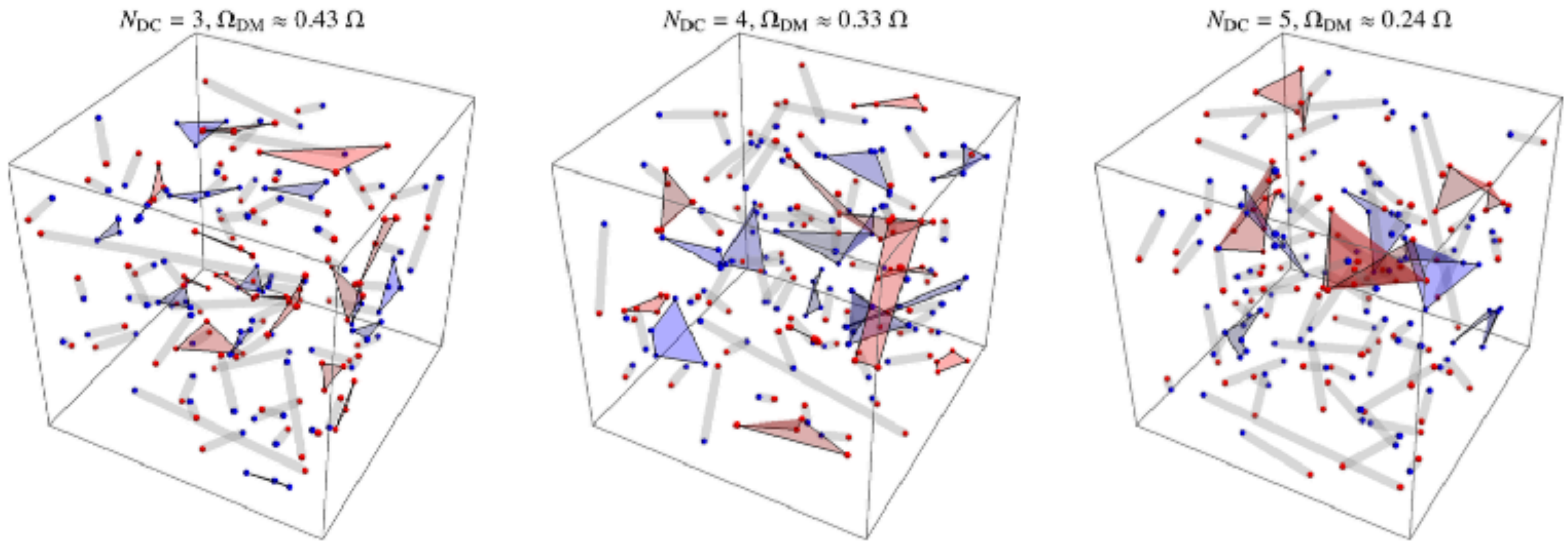
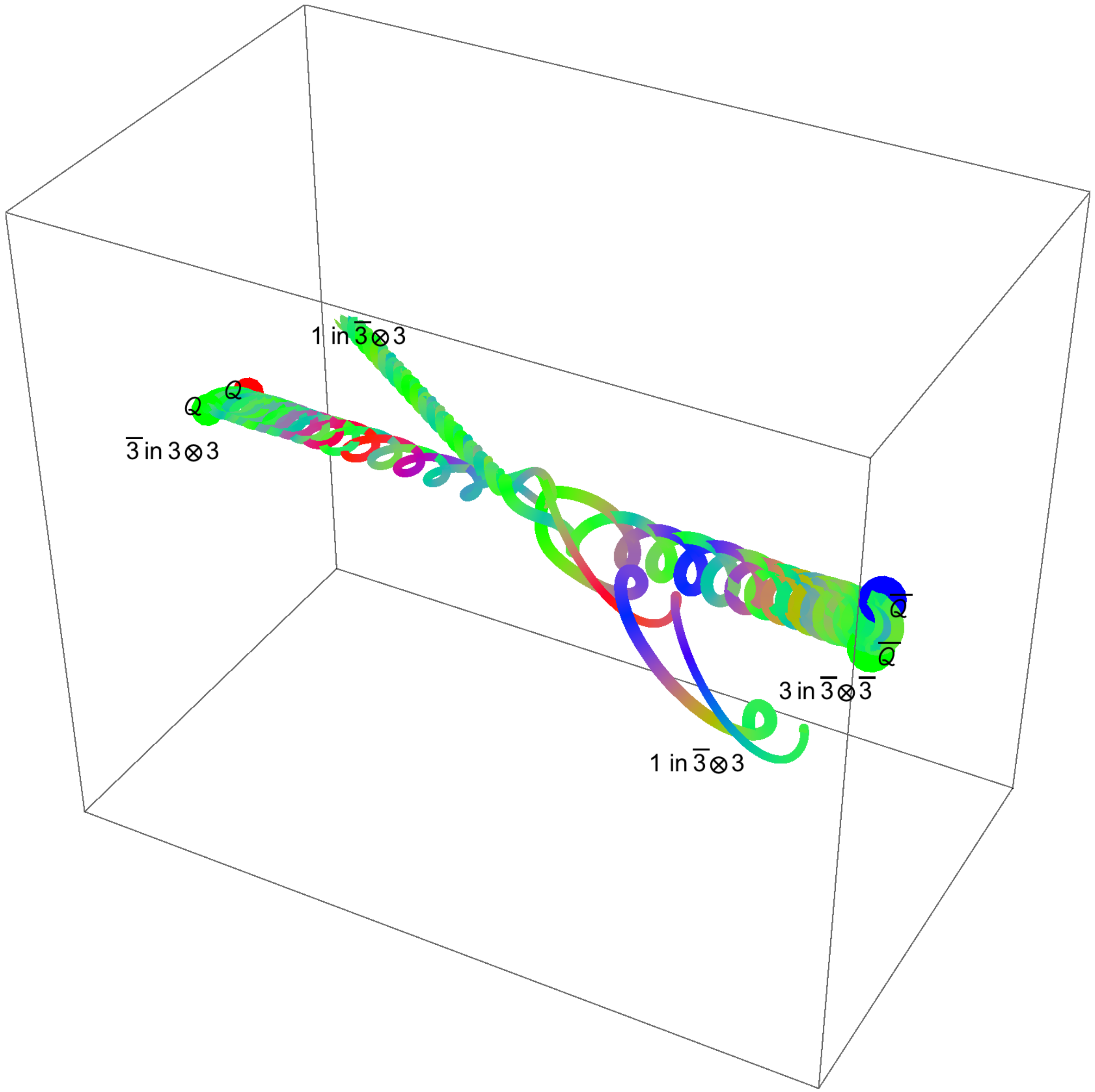


Figure 5: *Examples of dark condensation for* $N_{DC} = 3$ *(left),* 4 *(middle) and* 5 *(right). Dark quarks* $\mathcal{Q}$ *(anti-quarks* $\bar{\mathcal{Q}}$*) are denoted as red (blue) dots, placed at random positions. We assume that each DM particle combines with its dark nearest neighbour, forming either unstable* $\mathcal{Q}\bar{\mathcal{Q}}$ *dark mesons (gray lines) or stable* $\mathcal{Q}^{N_{DC}}$ *dark baryons (red regions) and* $\bar{\mathcal{Q}}^{N_{DC}}$ *dark anti-baryons (blue regions).*

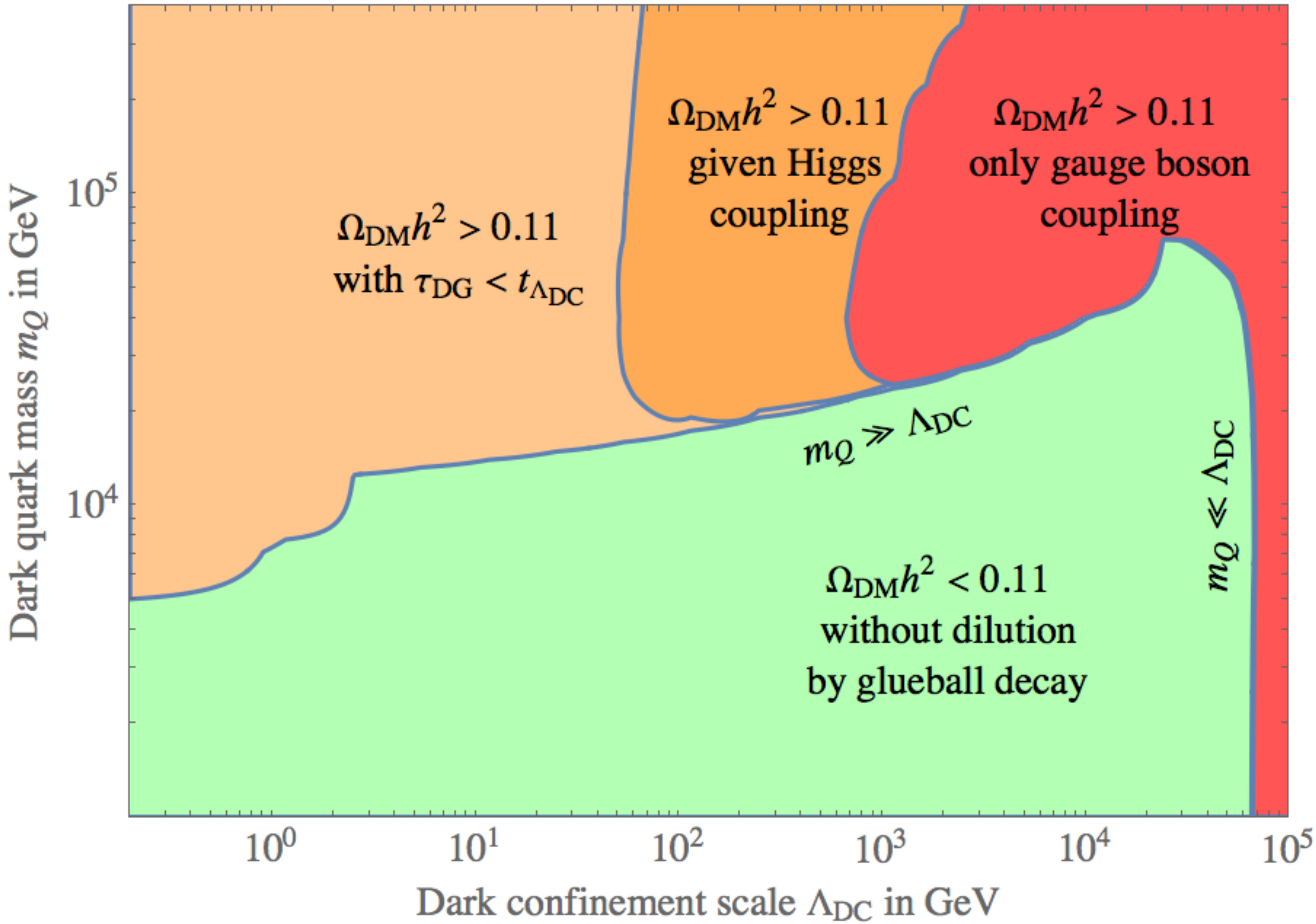
Rearrangement annihilation

Meson toy model



$$\sigma_{\rm ann} v_{\rm rel} \sim \frac{\pi a^2 v_{\rm rel}/2}{\sqrt{E_{\rm kin}/E_B}} = \frac{\sqrt{2}\pi}{3M_Q^2\alpha_3} = 1.5\ 10^{-24}\frac{\rm cm^3}{\rm sec} \times \left(\frac{20\,{\rm TeV}}{M_{\rm DM}}\right)^2 \left(\frac{0.1}{\alpha_3}\right).$$

The full thermal mass range



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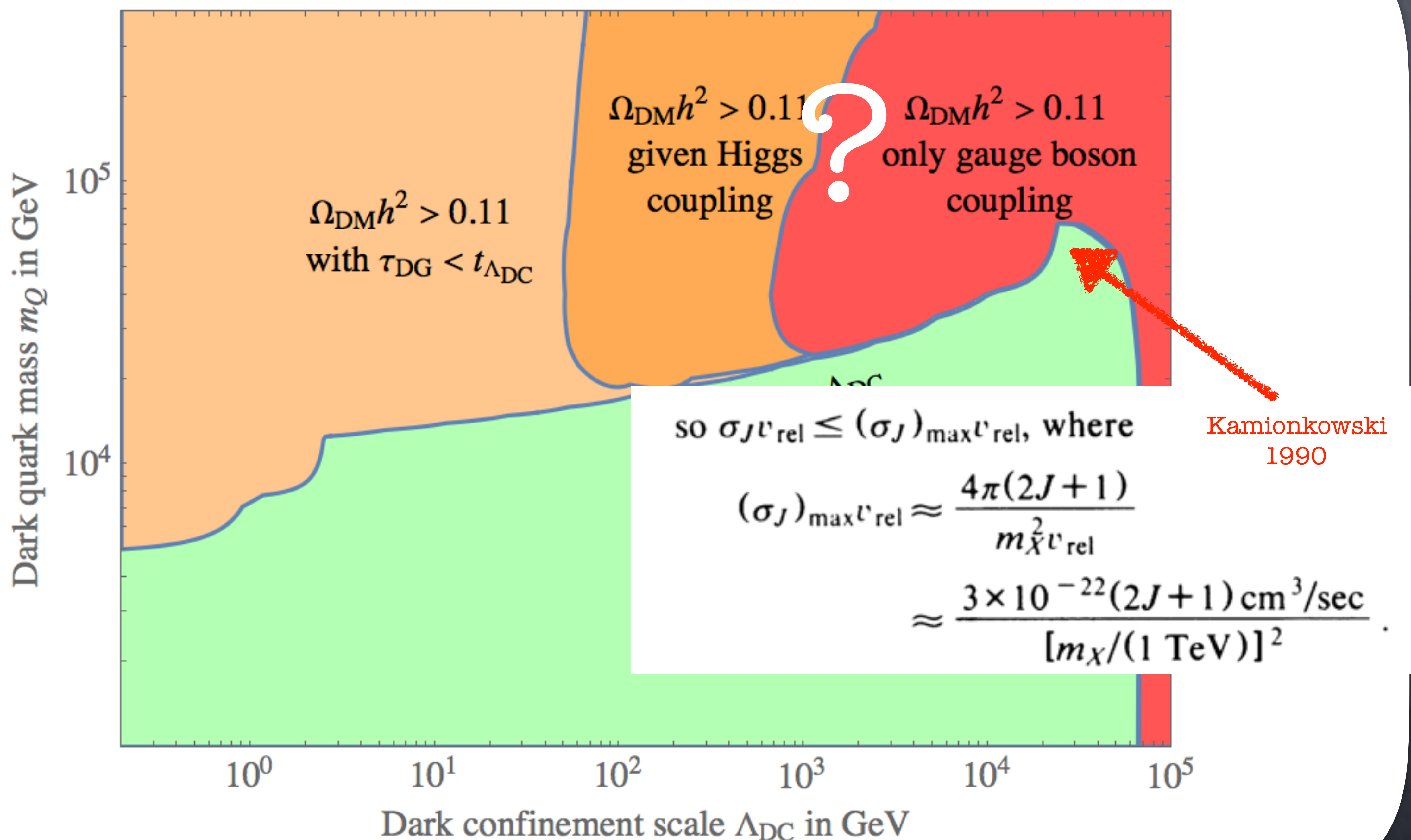
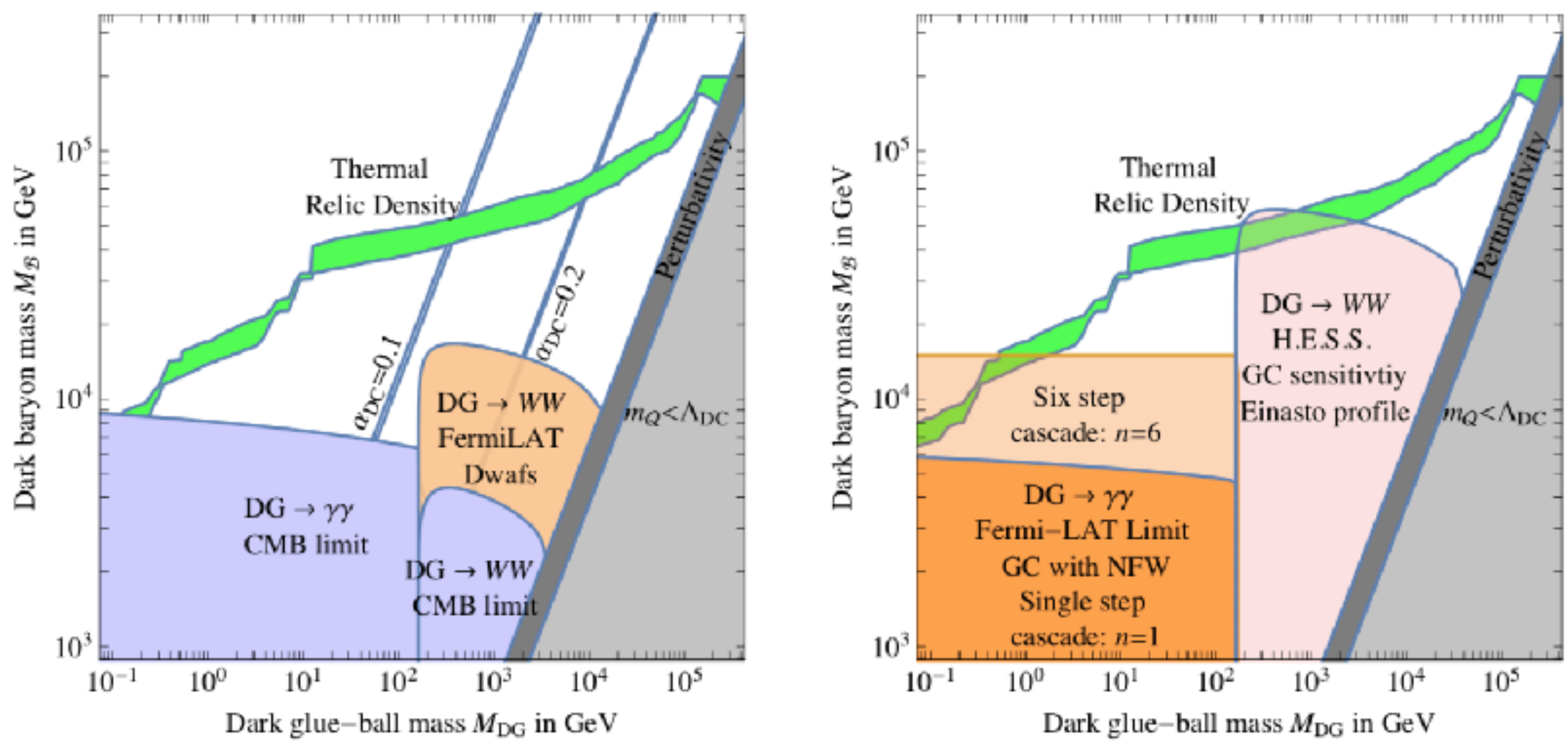


so $\sigma_J v_{\rm rel} \leq (\sigma_J)_{\max} v_{\rm rel}$, where

$$(\sigma_J)_{\max} v_{\rm rel} \approx \frac{4\pi(2J+1)}{m_X^2 v_{\rm rel}}$$

$$\approx \frac{3\times 10^{-22}(2J+1)\,{\rm cm}^3/{\rm sec}}{[m_X/(1\ {\rm TeV})]^2} .$$

Indirect Detection

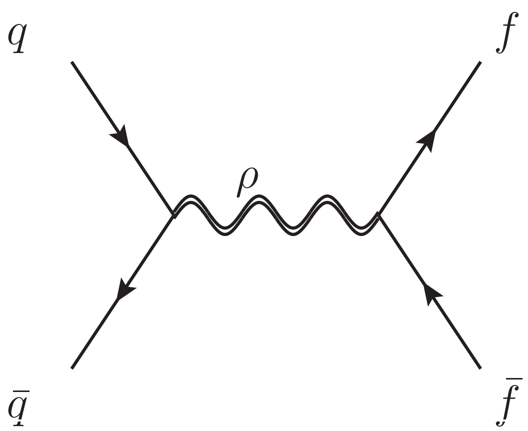


LHC signals

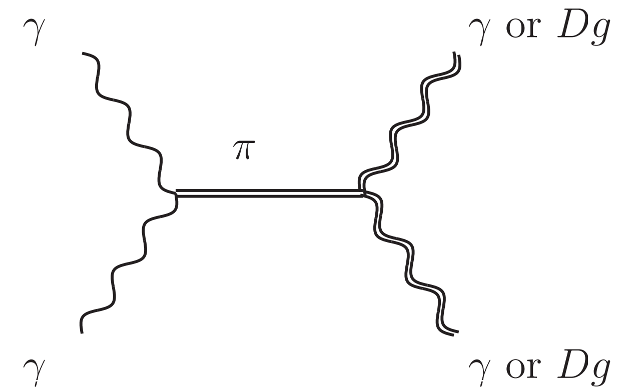
Direct production of a resonance

$$\Gamma(\rho \to f\bar{f}) = N_{DC} \frac{\alpha_{DC}^2}{12} \frac{|R_{n0}(0)|^2}{m_Q^2} T_2$$

$$\propto \alpha_{DC}^3$$



spin-1

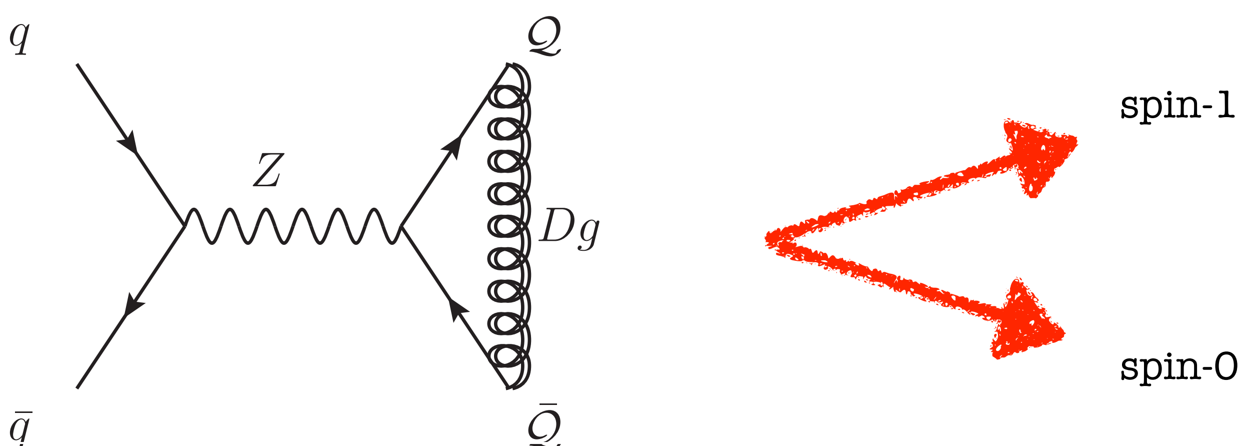


spin-0

Drell-Yan production

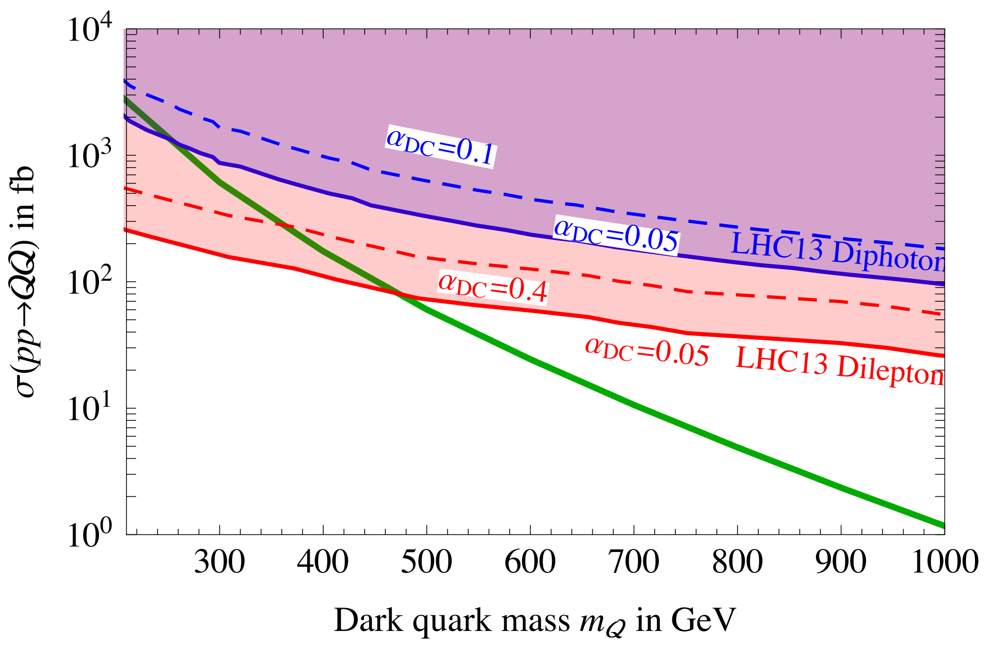
$$\Gamma(\rho \to \text{Inv.}) \propto \alpha_{DC}^6$$

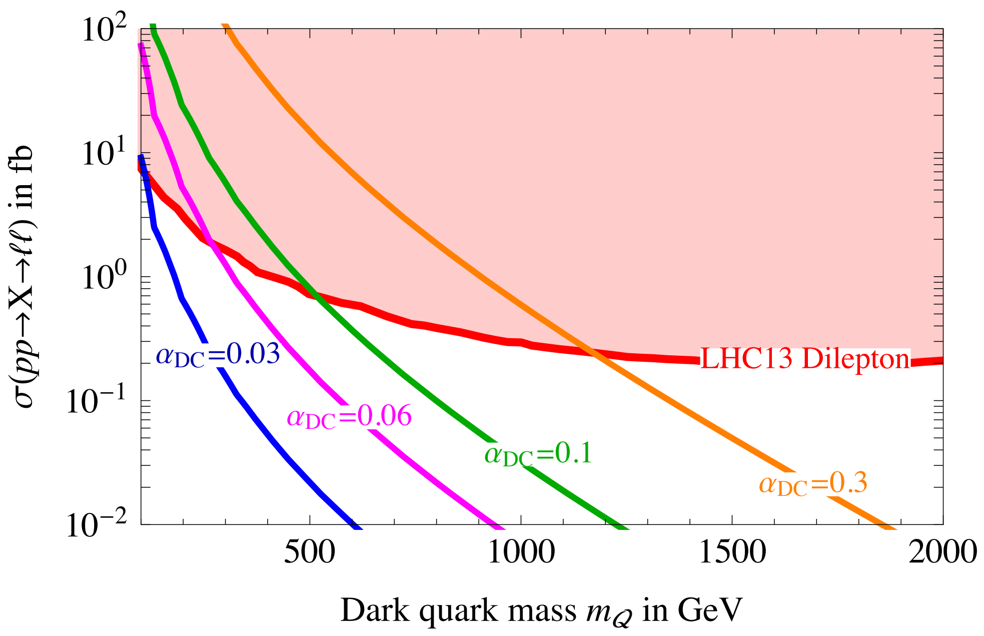
$$\Gamma(\pi \to \text{Inv.}) \propto \alpha_{DC}^5$$



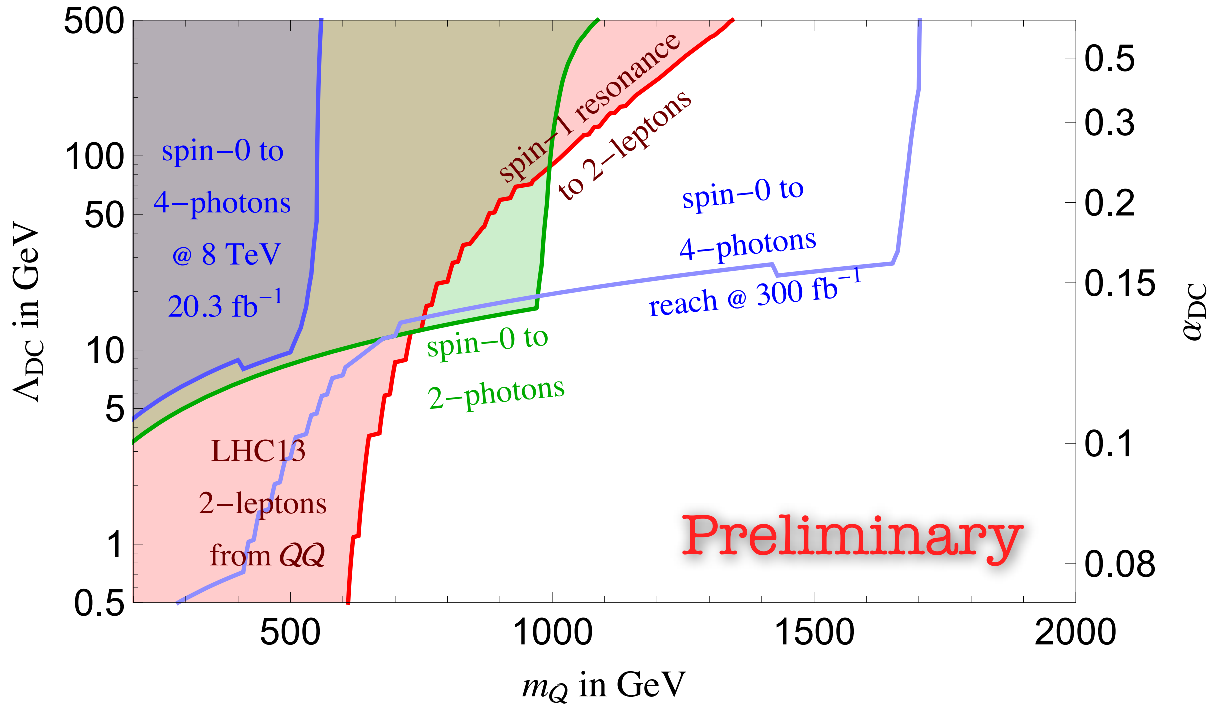
See also: 1707.05380 and 1801.07723

LHC limits



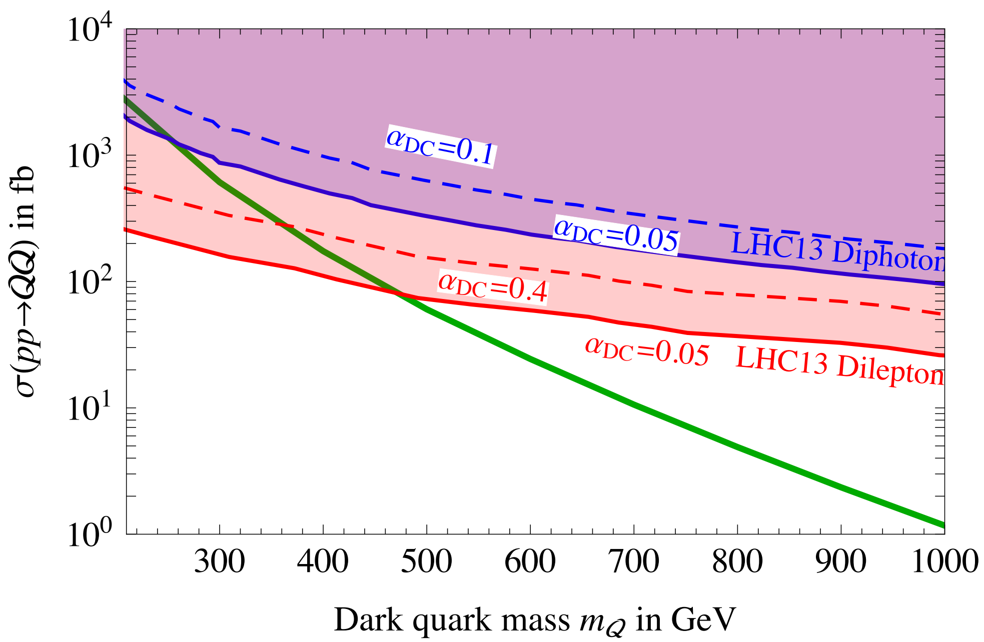


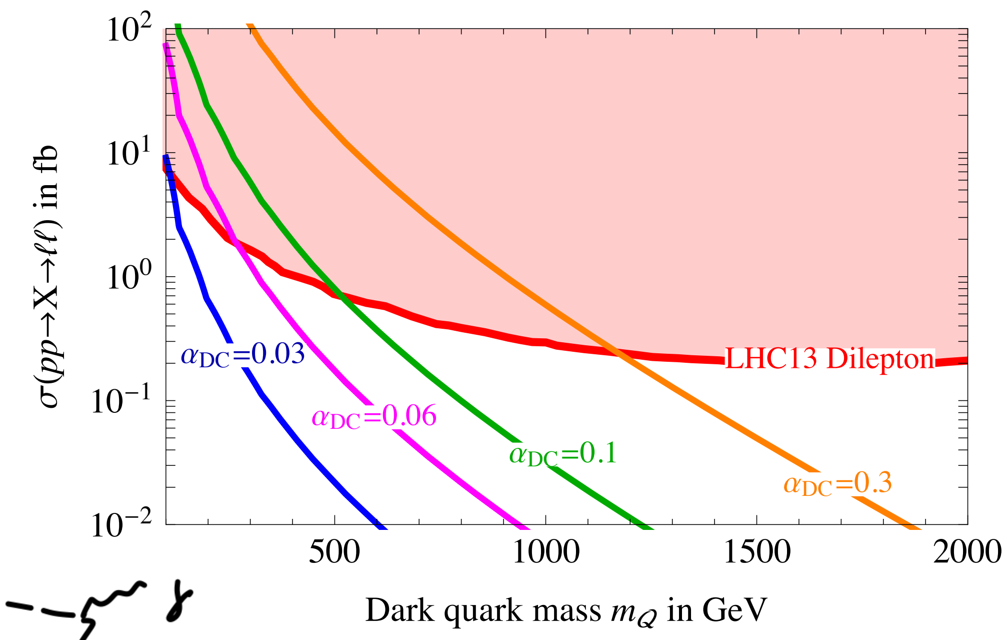
Compare to DD Limit on $M_B = 3\ m_Q = 780$ GeV thus: $m_Q > 260$ GeV

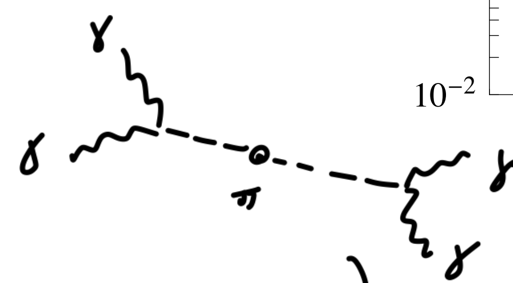


Thus $M_B > 3$ TeV

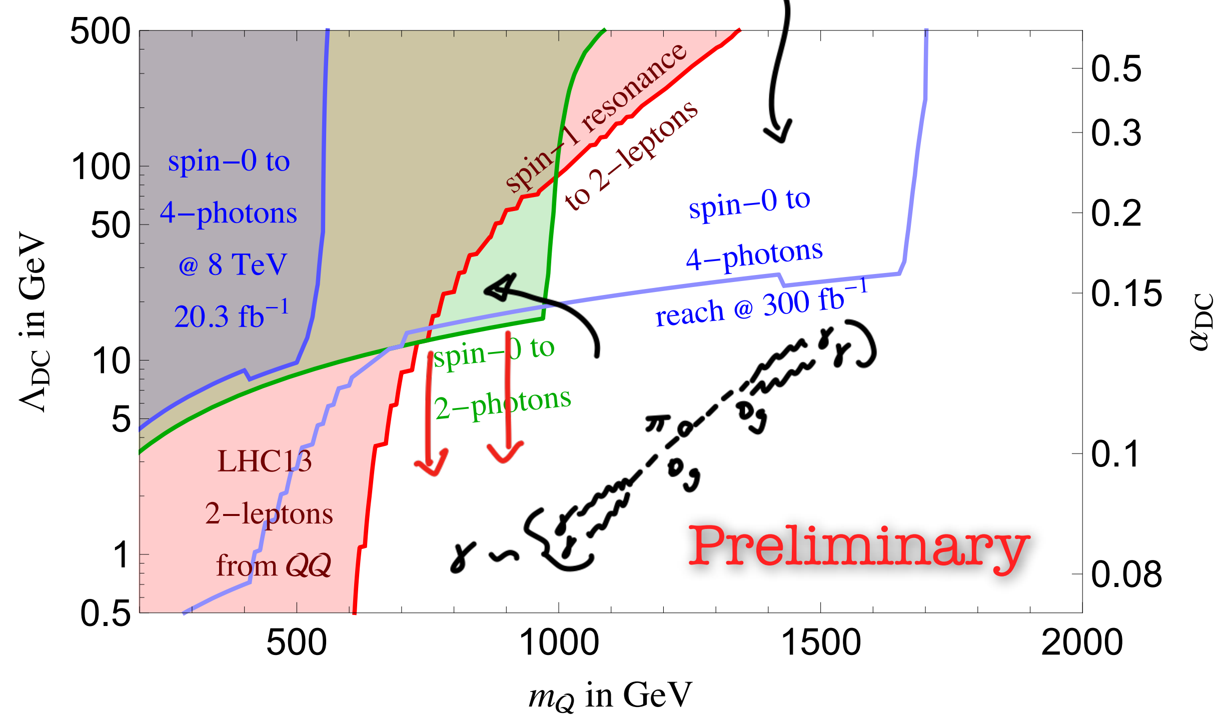
LHC limits





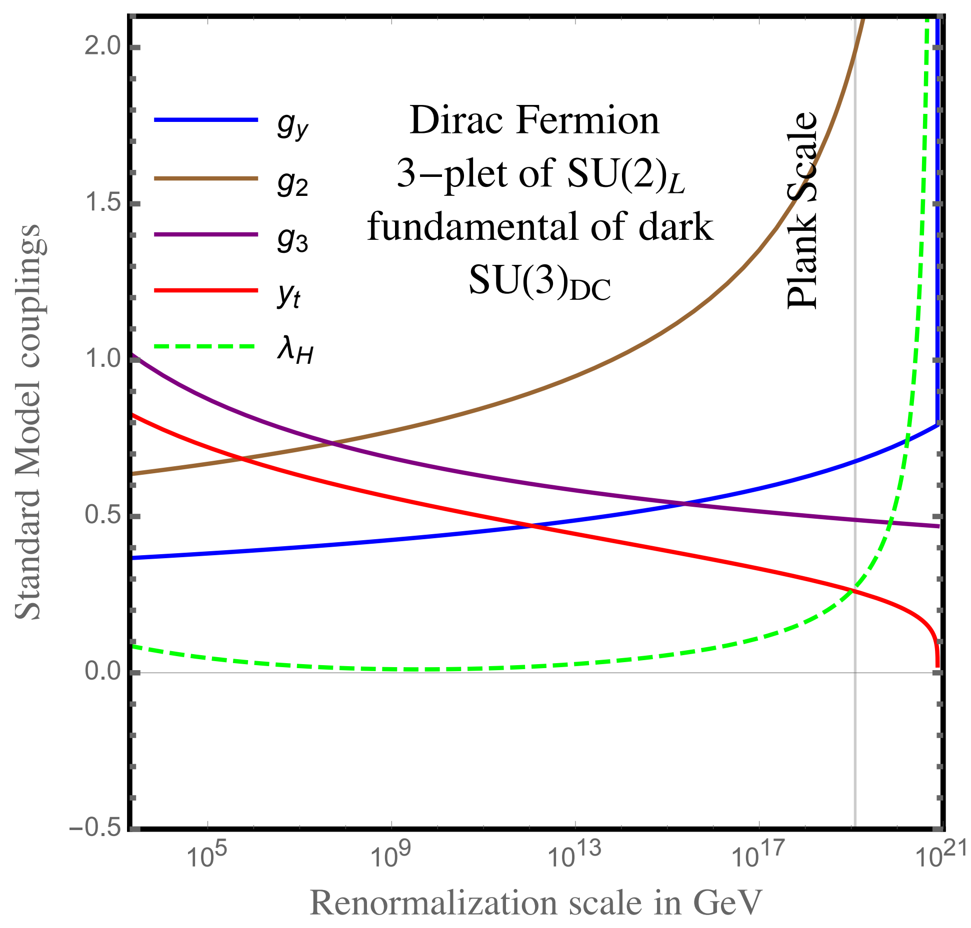


Compare to DD Limit
on $M_B = 3\ m_Q = 780$ GeV
thus: $m_Q > 260$ GeV

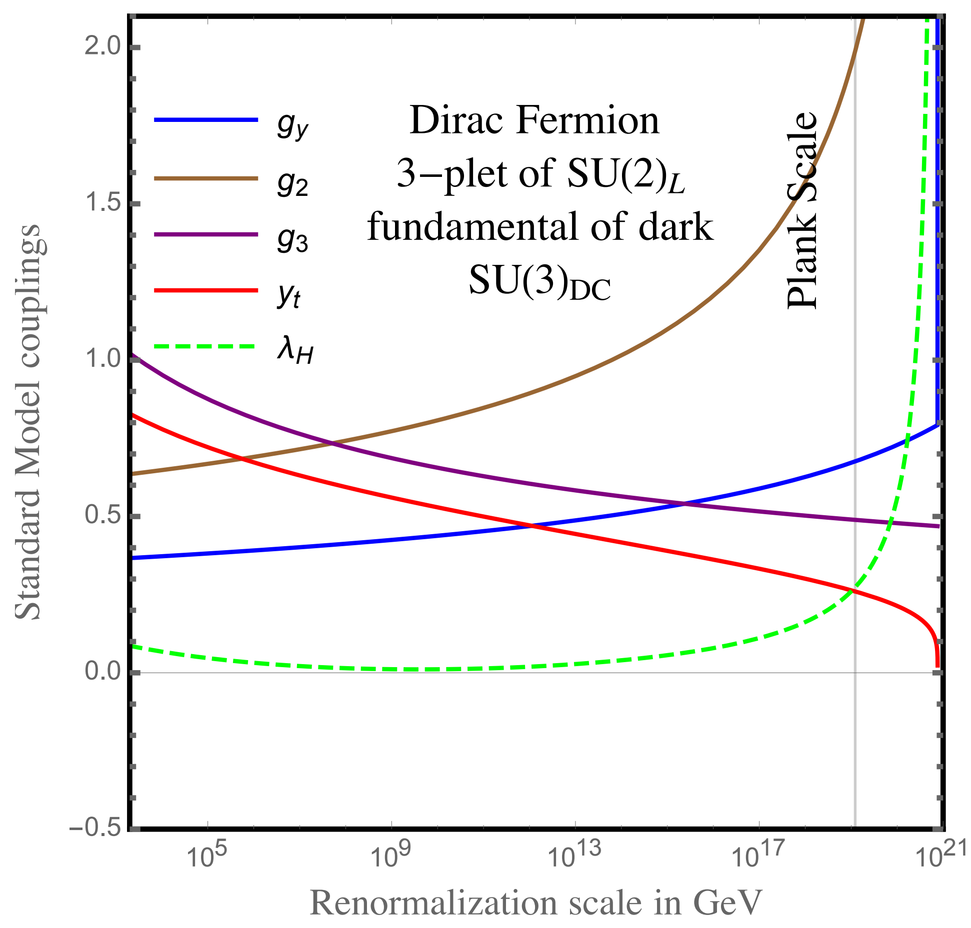


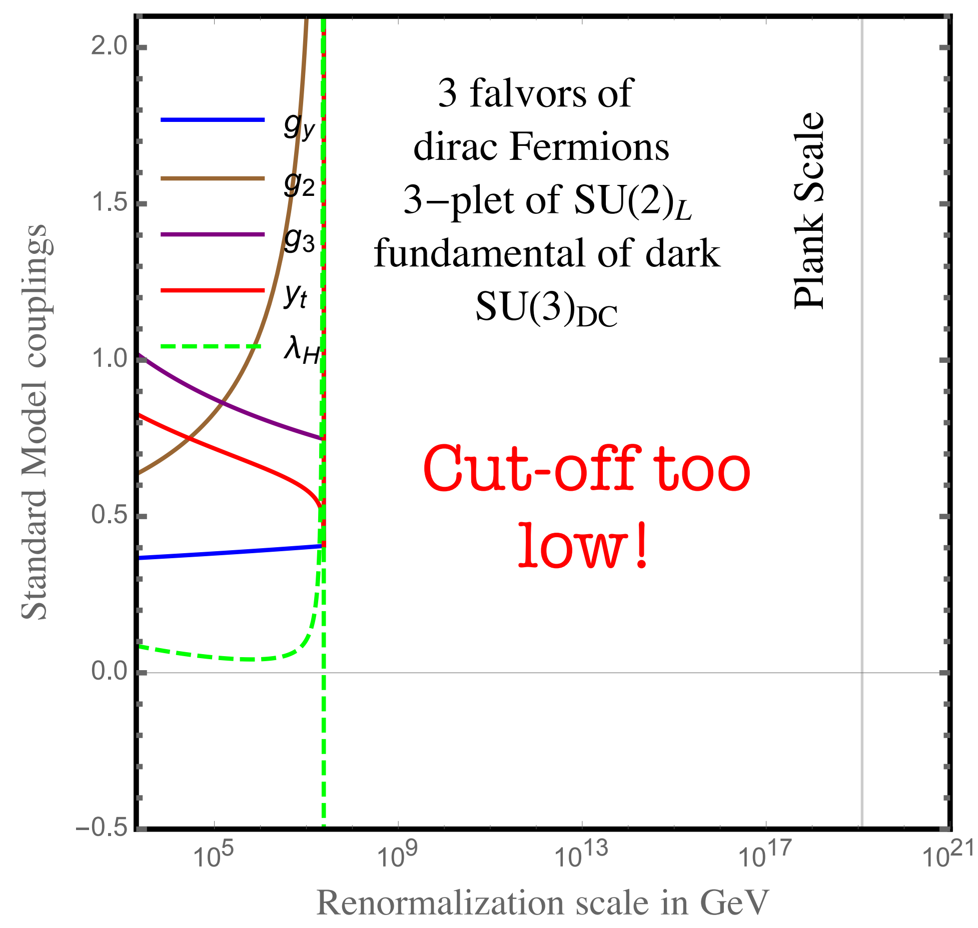
Thus
$M_B > 3$ TeV

RG (in-)stability



RG (in-)stability





Better safe than sorry

Leading diagrams in $1/N_f$

1708.00437
G.M. Pelaggi, A.D. Plascencia, A. Salvio, F. Sannino, J.S., A. Struma

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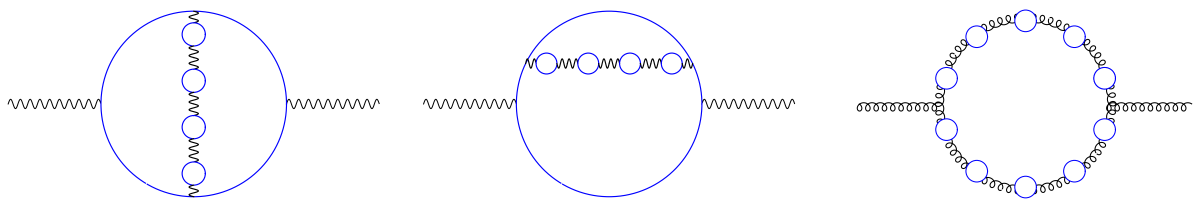
Leading diagrams in $1/N_f$



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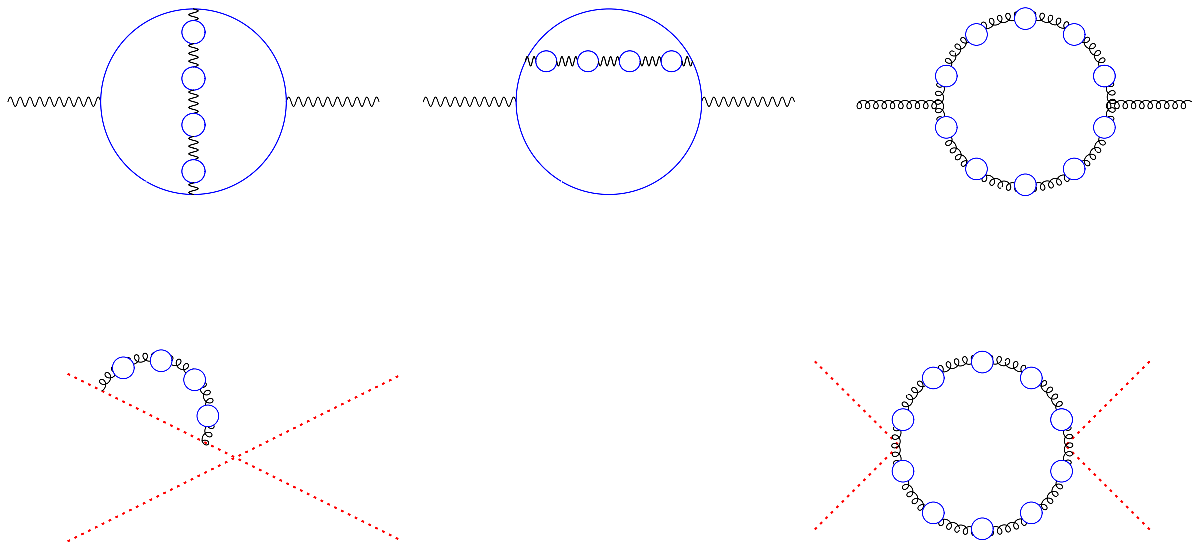

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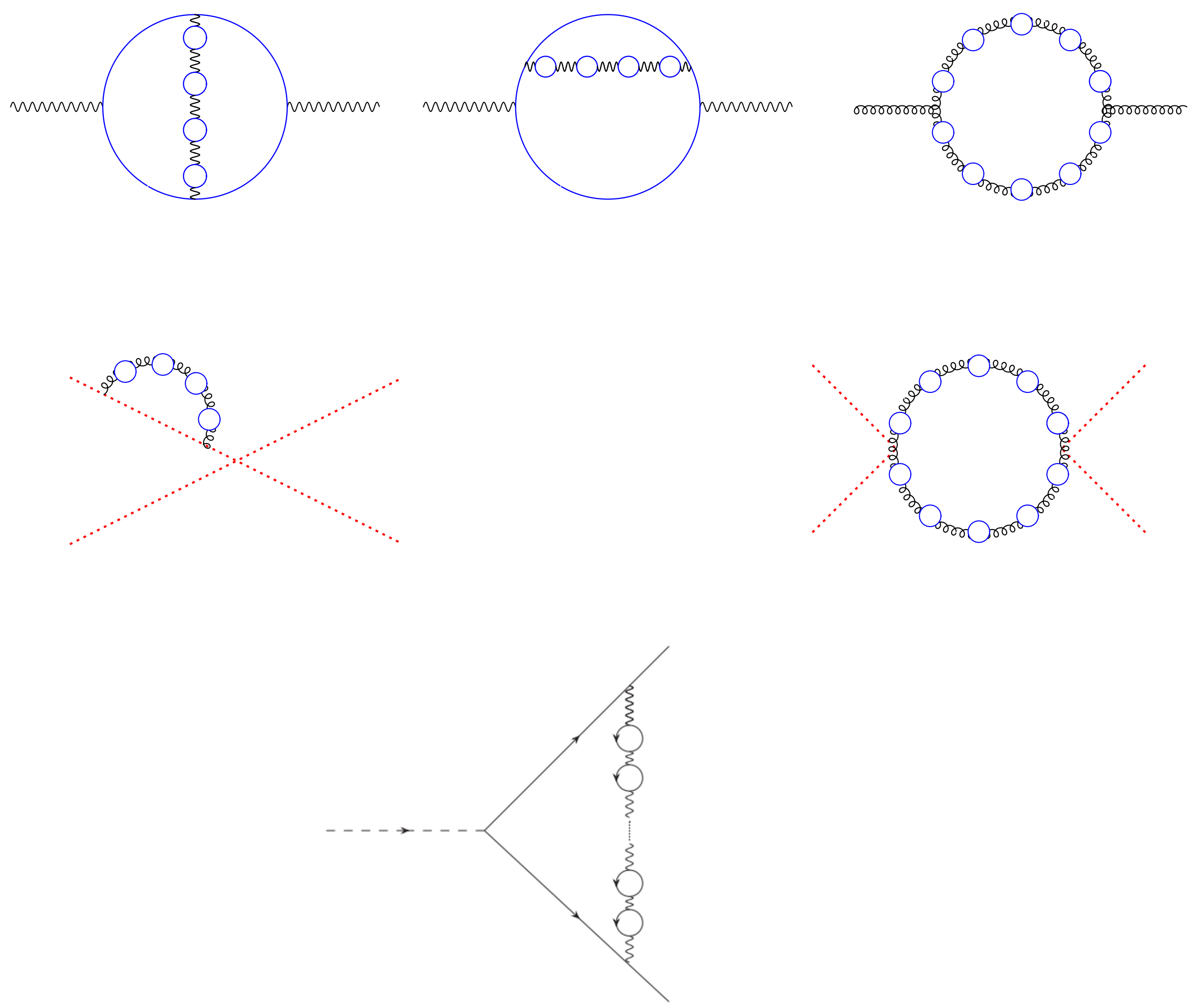
Leading diagrams in $1/N_f$



1708.00437

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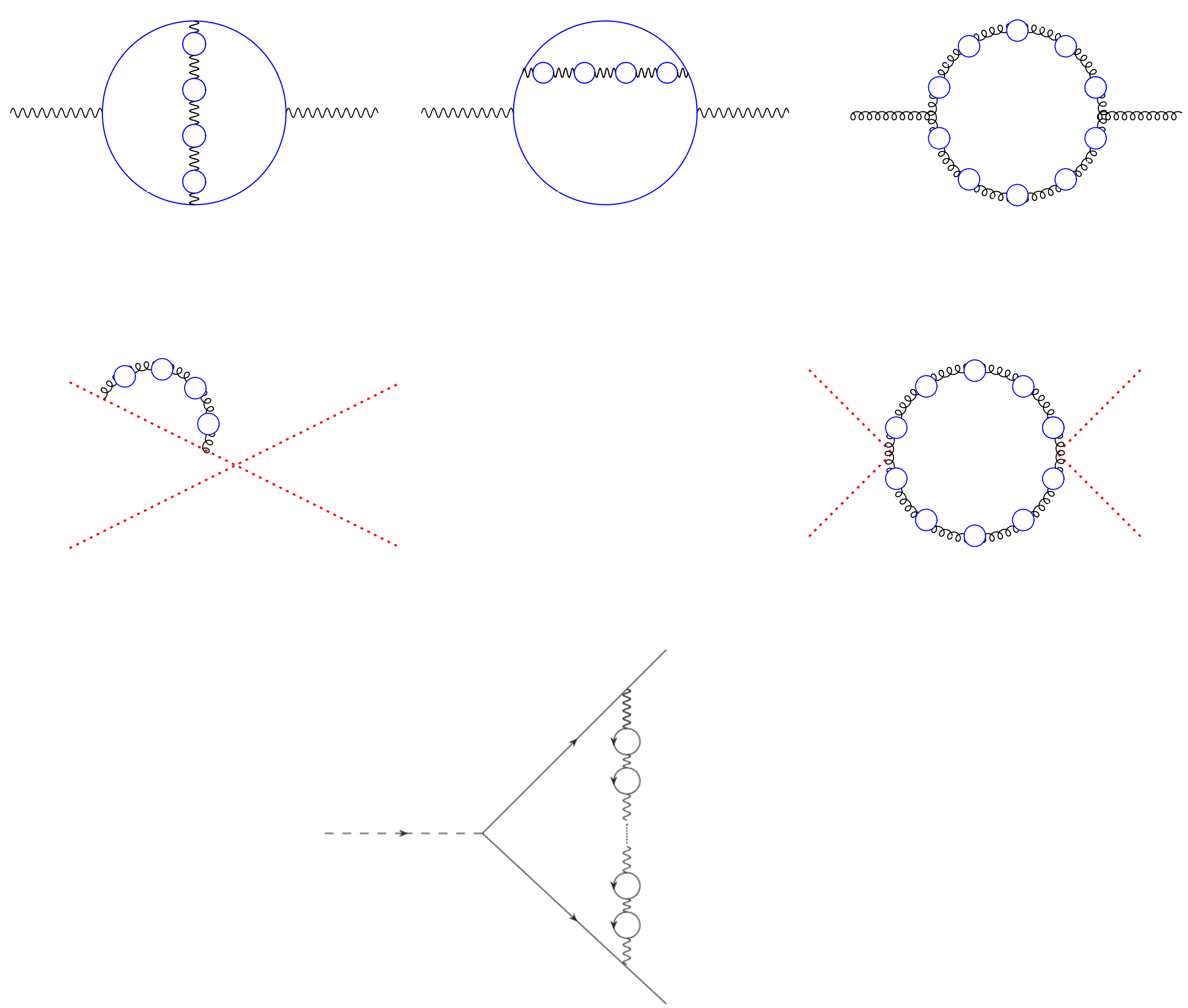
Leading diagrams in $1/N_f$



$$(4\pi)^2\frac{dy_t}{d\ln\mu} = \frac{9}{2}y_t^3 - y_t\left(8g_3^2 + \frac{9}{4}g_2^2 R_y(A_2) + \frac{17}{12}g_Y^2\right)$$

$$(4\pi)^2\frac{d\lambda_H}{d\ln\mu} = 24\lambda_H^2 + \lambda_H\left(12y_t^2 - 9g_2^2 R_\lambda(A_2) - 3g_Y^2\right) + $$

$$+\frac{9g_2^4}{8}R_g(A_2) + \frac{3g_Y^4}{8} + \frac{3g_2^2 g_Y^2}{4}R_g(A_2,0) - 6y_t^4.$$

$$R_g(A,A) = \frac{[(2A-3)A\,(H_A - 3H_{1-A} + 2H_{3-2A}) - 4A + 3]\,\Gamma(4-2A)}{18\Gamma(2-A)^3\Gamma(A+1)},$$

$$R_g(A,0) = \frac{(3-2A)\Gamma(4-2A)}{18\Gamma(2-A)^3\Gamma(A+1)},$$

$$R_\lambda(A) = \frac{2(3-2A)\Gamma(4-2A)}{9A(4-2A)\Gamma(2-A)^3\Gamma(A)},$$

$$R_y(A) = \frac{(3-2A)^2(2-A)\sin(\pi A)\Gamma(2-2A)}{9\pi A\Gamma(3-A)^2}\left(2 + A\frac{C_H}{C_{\psi_1} + C_{\psi_2}}\right)$$

1708.00437

G.M. Pelaggi, A.D. Plascencia, A. Salvio, F. Sannino, J.S., A. Struma

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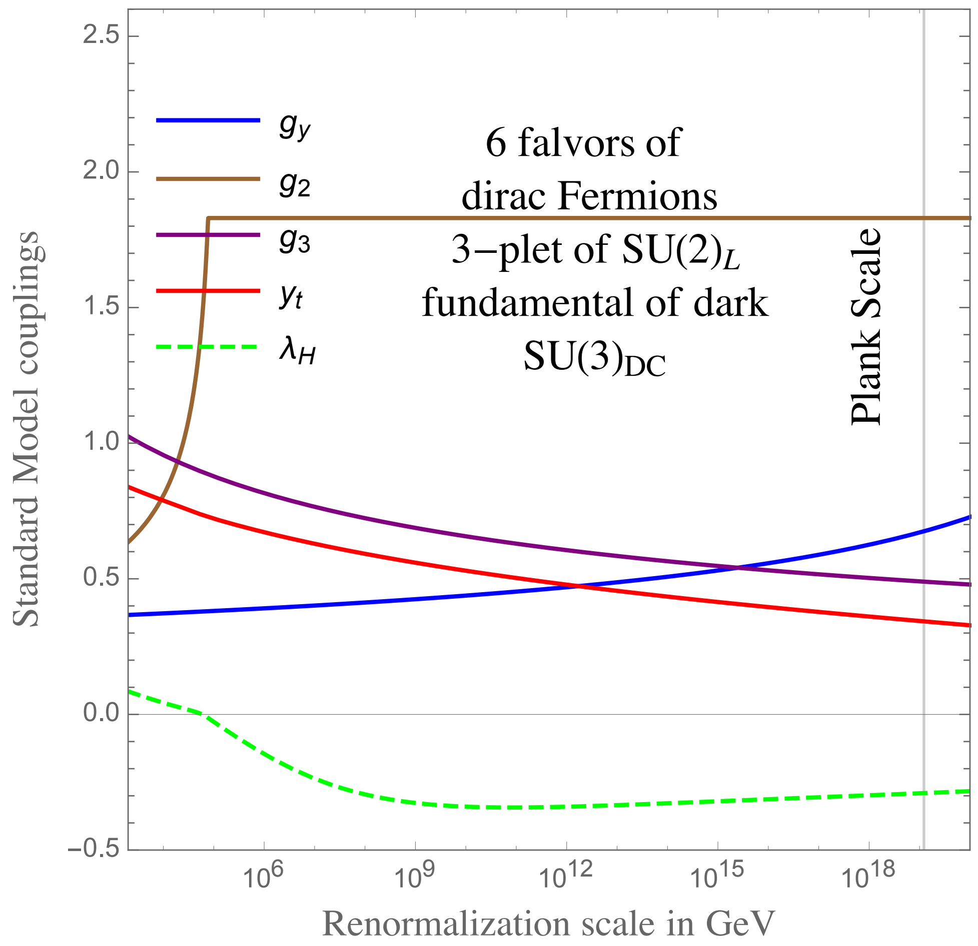


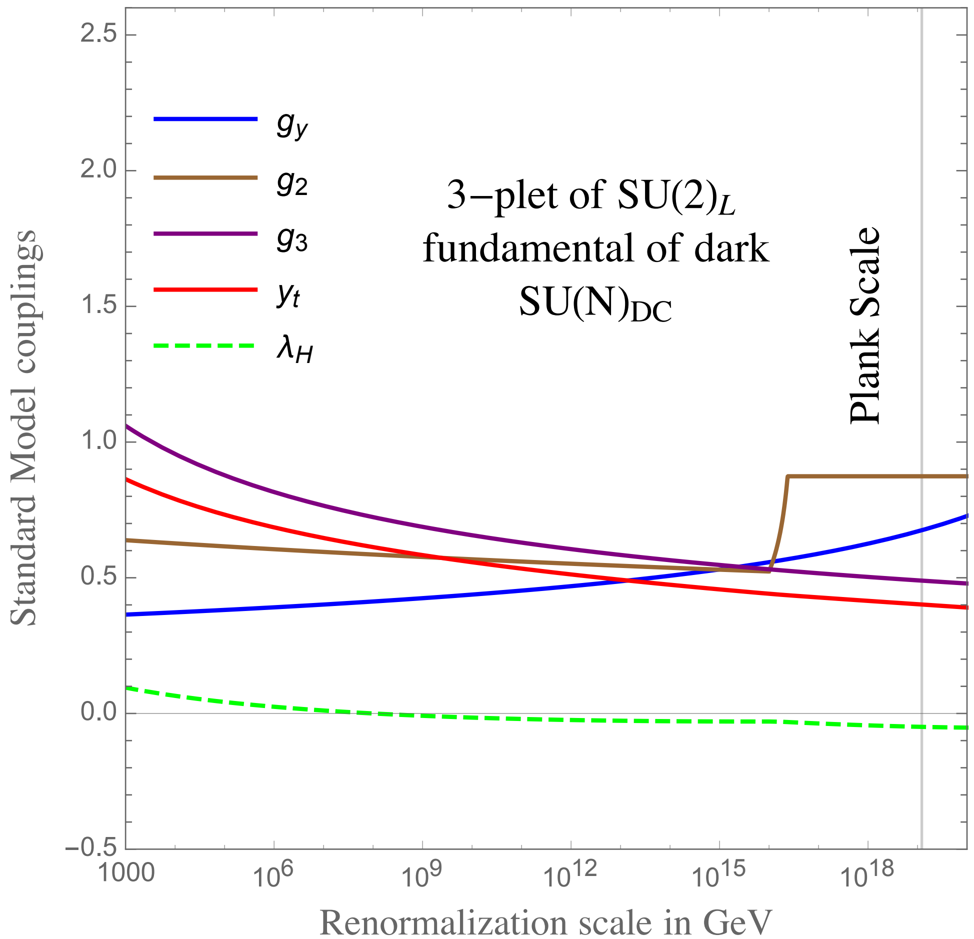
$$g_2^* \approx \frac{4\pi\sqrt{3}}{2\sqrt{I(R) N_f D_{R'}}}$$

$N_f \propto N_{DC}$

for $N_{DC} = 3$

$N_f < 60$

Un-natural Dark Matter



for N_{DC} = 80
and $M_{DM} = 10^{16}$ GeV

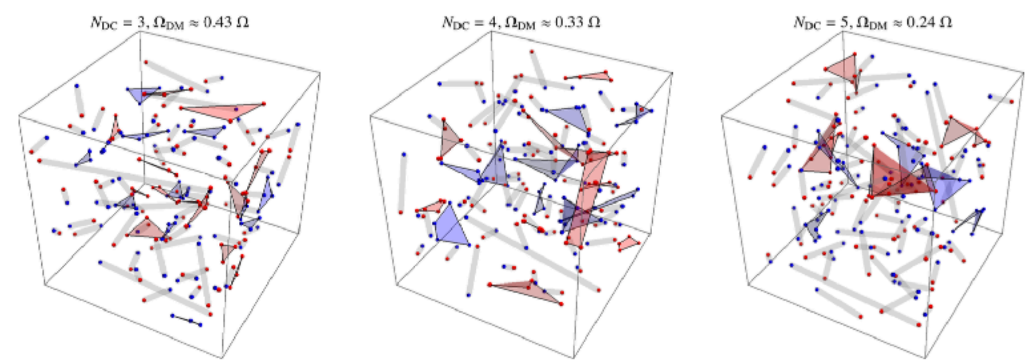


Figure 5: *Examples of dark condensation for $N_{DC} = 3$ (left), 4 (middle) and 5 (right). Dark quarks $\mathcal{Q}$ (anti-quarks $\bar{\mathcal{Q}}$) are denoted as red (blue) dots, placed at random positions. We assume that each DM particle combines with its dark nearest neighbour, forming either unstable $\mathcal{Q}\bar{\mathcal{Q}}$ dark mesons (gray lines) or stable $\mathcal{Q}^{N_{DC}}$ dark baryons (red regions) and $\bar{\mathcal{Q}}^{N_{DC}}$ dark anti-baryons (blue regions).*

$$\wp_{\mathcal{B}} \approx \frac{1}{1 + 2^{N_{DC}-1}/N_{DC}}.$$

Summary II

- Stable Dark Matter bound states may be related to new symmetries
- Opens up the parameter space for the WINO for example
- The full range possible, up to Unitarity bound
- Violation of unitarity bound?
- Beyond the minimal model, we need to be safe

Details in: JHEP 1710 (2017) 210
arXiv:1707.05380

Thank you!