Model independent explorations of the dark matter production mechanisms

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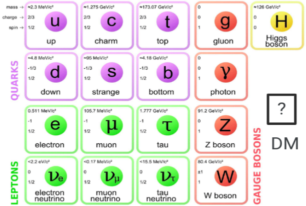
November 6, 2023

Dark matter as an hypothesis of missing mass

- The experimental observations at all scales can be explained if we hypothesize the missing mass as the new matter.



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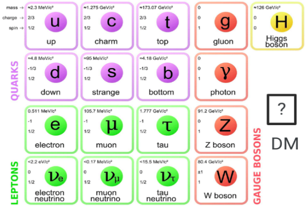

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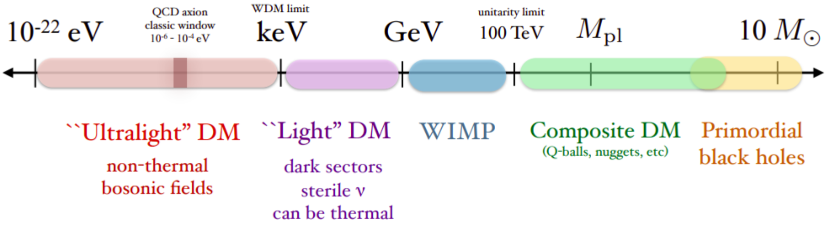
More on DM



(from T. Li, Tasi, 2019)

Natural question: how such wide mass range of DM got produced in early universe, and can we test it beyond gravitational interactions?

Dark matter observed density

- The most useful information about dark matter is it's present day energy density i.e.

$$\Omega_{\text{DM}} = \sum_i \frac{\rho_{\chi_i}}{\rho_{\text{crit}}} = \sum_i \frac{m_{\chi_i} n_{\chi_i}(\text{today})}{\rho_{\text{crit}}} = \sum_i \frac{m_{\chi_i} Y_{\chi_i}(\text{today})\, s(\text{today})}{\rho_{\text{crit}}}$$

- Assumption: One component of dark matter satisfying the full relic gives us a conservative range of the masses and couplings which can be probed at experiments.

- Assuming standard cosmological evolution of the early universe, the initial comoving DM density is

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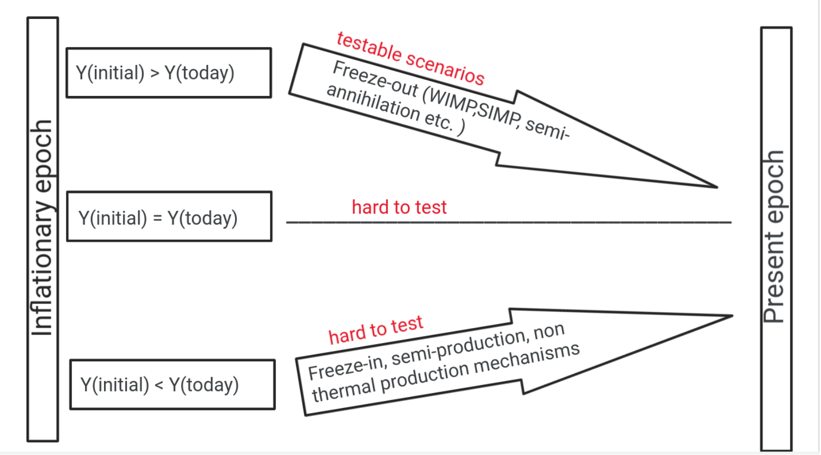
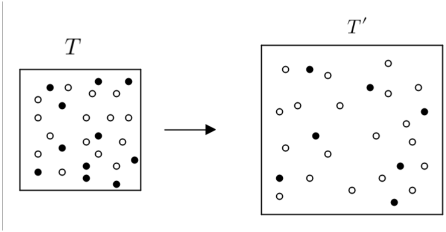


Thermal production of matter and dark matter



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- Since rate $\propto \sigma$, the cross-section of these interactions critical in determining DM densities.

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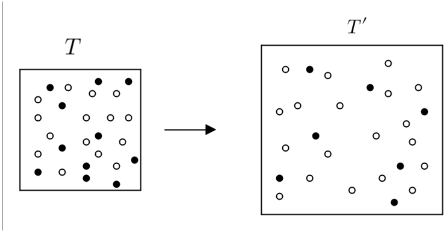

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Dark matter particle detection

- Mass range of $\mathcal{O}(10)(\text{GeV})$ — $\mathcal{O}(10\ \text{TeV})$ falls under the regime of WIMP.
- Lot of experimental and theoretical probes in this region (Null results).
- Derivation of generalised properties important.
- With $2 \to 2$ kind of interactions, a generalized upper bound on thermal DM ($\mathcal{O}(100)$ TeV) obtained using S-matrix unitarity. (Griest and Kammionkowsky, 1989)

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Few questions to ask:

- How holy is the above bound?
  (answering this requires the reconsidring the assumptions used in evaluating DM abundances.)

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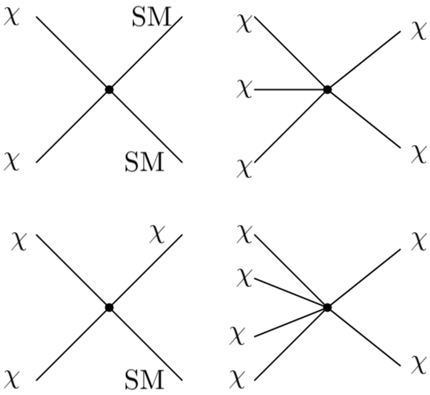
A. Determination of upper mass of dark matter for general $n \to 2$ annihilations

D. Bhatia and S. Mukhopadhyay, JHEP **03**, 133 (2021)



Why generalized $n \to 2$ annihilations are important?

- Non-observations of dark matter at experiments has led beleive that perhaps the couplings of DM with SM are even weaker than assumed.
- Different scenarios can set DM abundances instead of $\chi\chi \to$ SM SM, we can have

$$\chi\chi \to \text{HS HS} \quad or \quad \underbrace{\chi\chi\ldots\chi}_{\text{n}} \Leftrightarrow \chi\chi$$

- Self interacting scalars can easily give rise to above model $\Rightarrow$ $3 \to 2$ model in particular has gained lot of importance in literature $\to$ Cannibal models.
- Presence of tiny coupling within DM-SM sector to establish kinetic equilibrium but small enough to not have any significant contribution in the annihilation/creation of DM.
- Goal is to use S-matrix unitarity to determine the upper bound on the mass of the DM for generic $n \to 2$ annihilations.

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Assumptions (keep/lift)

- One stable massive particle which contributes maximally to the observed relic density.
- DM is atleast kinetically coupled with the SM bath.
- Dominant annihilations are through $2 \rightarrow 2$ reactions.
  (may or may not be to SM states).
- There is no asymmetry between DM and $\overline{\text{DM}}$ states.
- Universe is radiation dominated during freeze-out.
- The total entropy remains conserved as the universe expands adiabatically.

Determination of relic densities

- To determine DM abundance, one has to formally solve the Boltzmann equation i.e.

$$E\left(\partial_t - H\vec{p}.\bigtriangledown_p\right) f_\chi = C[f_\chi]$$

Since DM is in kinetic equilibrium with SM, solving zeroth order BE is sufficient.

$$\begin{aligned}\frac{1}{a^3}\frac{d(n_\chi a^3)}{dt} &= \langle\sigma v\rangle_f n_\chi^2 - \langle\sigma v\rangle_b n_{\rm SM}^2 \qquad \text{for } 2\to 2 \\ &= \langle\sigma v^{n-1}\rangle_f n_\chi^n - \langle\sigma v\rangle_b n_\chi^2 \quad \text{for } n\to 2\end{aligned}$$

S-matrix unitarity for $n \to 2$ annihilations

- The partial wave decomposition complicated for n $>$ 2 as more and more angular variables are involved.
- One has to repeat the process for each n in order to evaluate generalized bounds on $n \to 2$ cross-section
- Simple trick: we estimate the maximum value of thermal averaged cross-section for $n \to 2$ in terms of $2 \to n$.
- We use the equality of rates in equilibrium of forward-backward processes:

$$\frac{1}{a^3}\frac{dn_\chi a^3}{dt} = \left[\langle \sigma v^{n-1}\rangle_f n_\chi^n - \langle \sigma v\rangle_b n_\chi^2\right] = 0 \quad \text{for n}\to 2$$

- We now solve for optical theorem for 2 particle state scattering i.e.

$$\begin{aligned} 2\text{Im}\mathcal{M}_{\text{el}}(\alpha_2 \to \alpha_2) &= \int d\Pi_n (2\pi)^4 \delta^4(p_{\alpha_2} - p_{\beta_2}) |\mathcal{M}_{\text{el}}(\alpha_2 \to \beta_2)|^2 \\ &+ \sum_{n'} \int d\Pi_2 (2\pi)^4 \delta^4(p_{\alpha_2} - p_{\beta(n')}) |\mathcal{M}_{\text{in}}(\alpha_2 \to \beta_{n'}|^2) \end{aligned}$$

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S-matrix unitarity continued ...

- For maximizing inelastic scattering $S^\dagger S \to 1 \Rightarrow S_{\rm in}^\dagger S_{\rm in} \to 1 \Rightarrow S_{\rm el}^\dagger S_{\rm el} \to 0$.

$$\sigma_{\text{in,total}} = \sum_\ell \frac{\pi}{|\vec{p_1}|^2} S_2(2\ell+1)\left(1 - \langle \ell, m| S_{\rm el}^\dagger S_{\rm el} |\ell, m\rangle\right)$$

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$$\sigma_{\text{in,total}} \approx \sigma_{\text{in},2\to n}$$

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$$\langle \sigma_{n\to 2} v^{n-1}\rangle_{\rm max} = \sum_\ell (2\ell+1)\, \frac{2^{\frac{3n-2}{2}} (\pi x)^{\frac{3n-5}{2}}}{g_\chi^{k-2} m_\chi^{3n-4}}.$$

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Summarising the technique:

- Using the equality of rates, we converted the $n \rightarrow 2$ problem to $2 \rightarrow n$.
- Using the conservative limit of $2 \rightarrow n$ dominating the total inelastic cross-section, we determined the upper bound on cross-section simple using the knowledge of $2 \rightarrow 2$ elastic scattering.

Summarising the technique:

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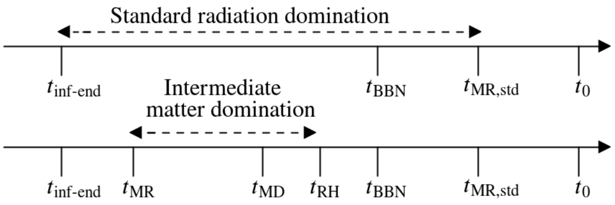
Results for radiation domination

Symmetry	Annihilation channels	$\ell = 0$	$\ell = 1$	$\ell = 0 + 1$
Z_2	$\chi + \chi^* \to \mathrm{SM} + \mathrm{SM}$	127.7 TeV	220 TeV	253.5 TeV
Z_3	$3\chi^{(*)} \to 2\chi^{(*)}$	1.15 GeV	1.72 GeV	1.91 GeV
Z_2	$4\chi \to 2\chi$	6.9 MeV	9.4 MeV	10.1 MeV
Z_5	$5\chi^{(^*)} \to 2\chi^{(*)}$	112.5 keV	138 keV	145.5 keV

Table: Unitarity upper limits on thermal DM mass in a radiation dominated Universe

The mass bounds decrease with increase in n to accomodate for flux factor suppressions.

Intermediate matter domination



t_{MR}: Epoch of matter-radiation equality
t_{MD}: Epoch where matter decays starts to become important
t_{RH}: Epoch where radiation domination is restored.

- BBN requires Universe to be RD at temperatures $\mathcal{O}$(MeV).
- No experimental information about the early universe for temperatures greater than roughly a MeV.
- We may have some period of MD, between inflation and BBN perhaps due to the presence of long lived massive particles which are decoupled from the thermal plasma.

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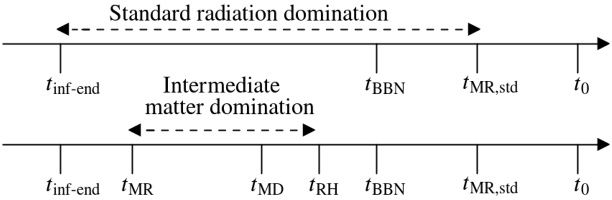

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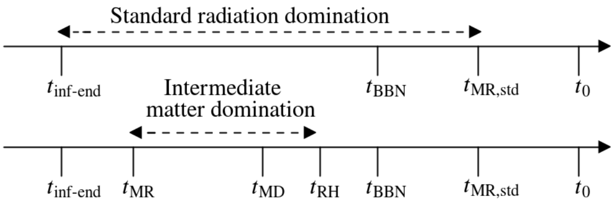

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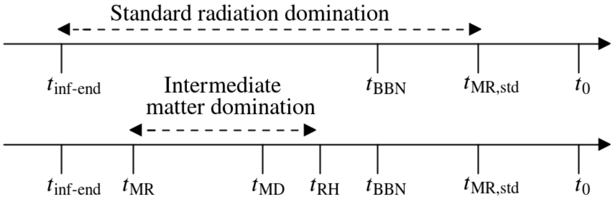

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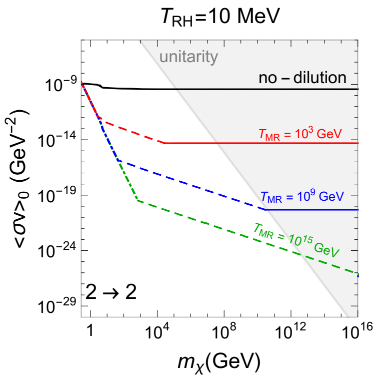
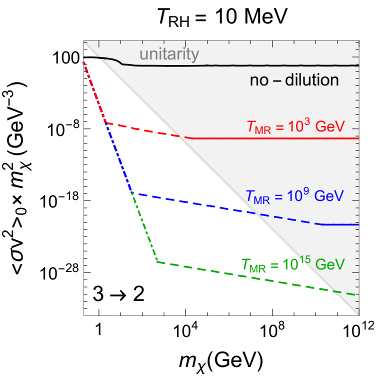
Unitarity limits with intermediate matter domination

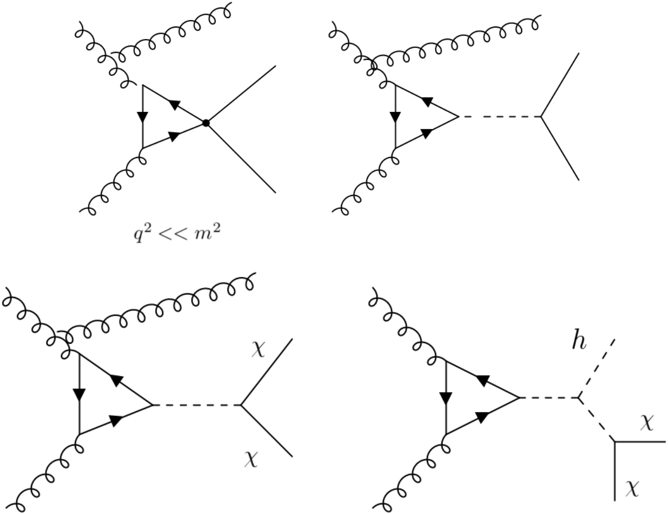




The consequence of entropy dilution is that we can overproduce DM in early universe which results in the larger masses.

B. Phenomenological analysis of multi-pseudoscalar mediated dark matter models

S. Banerjee, G. Bélanger, D. Bhatia, B. Fuks, S. Raychaudhuri



Introduction

- We return to WIMP DM candidates i.e. with mass ranges $\mathcal{O}$(10 GeV) - few TeVs.
- Experimentally null results so far.
- Signals hidden in un-conventional channels?
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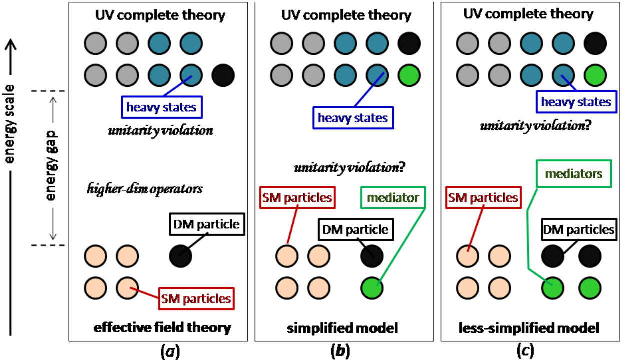
Three theoretical approaches of DM searches at the LHC



Disadvantages of the three frameworks

- EFT: fails to capture the correct momentum dependence, since the assumption $q^2 << m^2$ breaks.
- Simplified model: Although captures broad features of several models, however in doing so left with fewer channels to probe (mono-jet).
  - may be new physics lying in some other channels.
  - Simps like EFT's do not respect full gauge symmetry, construction based on gauge invariance $\Rightarrow$ more particles hence more phenomenological channels)
- Less simplified models: They are closer to UV complete models, hence more cumbersome. Not all particles lead to significant DM phenomenology. Several assumptions required.
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Revisiting the reasons for going to less-simplified models from simplified models

1. Gauge invariance: The requirement of gauge invariance is going to introduce more states and would prevent violation of unitarity i.e. $S^\dagger S = I$ in some processes.
   - But the question really is does this lead to violation of unitarity in the processes relevant for our purposes?
   - The ans. is it happens at really large couplings and has very little to do with addition of new states for typical mono-X searches (Englert, McCullough, Spannowsky, 2016)
2. More phenomenologically relevant channels:
   - They can be described in a model independent manner if we classify the models on the basis of additional number of relevant mediators + DM particles (S. Banerjee, G. Bélanger, D. Bhatia, B. Fuks and S. Raychaudhuri, JHEP 07, 111 (2022)).

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- Just like Simplified models, we can examine the constraints at LHC based on the well-defined mediators.
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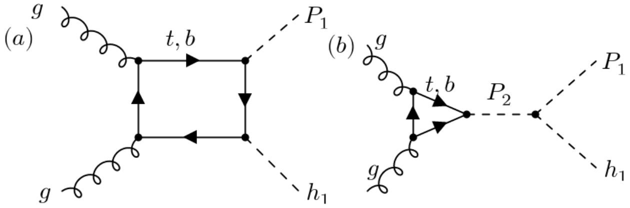
Example: Two mediated pseudoscalar models

- We extend our theoretical framework by considering two pseudoscalar mediators as apperance of the atleast a second pseudoscalar is inevitable in the UV completion.
- For example, with the interaction $P_2 P_1 h$, one can generate resonantly enhanced mono-higgs signatures.



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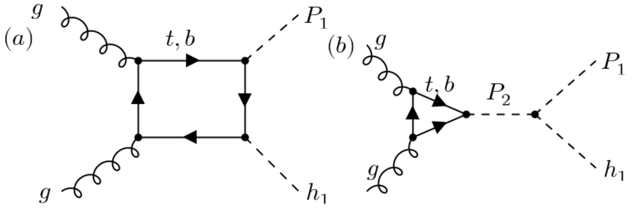

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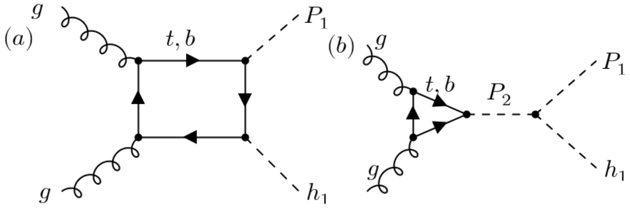

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Phenomenology of the 2-mediator pseudoscalar models

- The most immediate question which we may ask is when is the effect of second pseudoscalar mediator starts to important
- Alternatively what are the cases where we can still describe the analysis using single-mediator models.

Scenarios	Relic density	LHC phenomenology
$m_{P_2} \gg m_{P_1}$	single-mediator case	single-mediator case
$m_{P_2} > m_{P_1}$	single-mediator case	two-mediator case (enhanced mono-Higgs rates)
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Monohiggs

Approach:

- In order to derive constraints for the best possible scenario: assume BSM contributions to mono-jet production are dominated by the effect of the first mediator.
- Find the limit in which other mono-X signatures may become dominant.
- Criteria is set by:

$$\frac{g_q^2 y_\chi^2}{m_{P_2}^2} \leq 0.1 \ \frac{g_q^2 y_\chi^2}{m_{P_1}^2} \quad \text{or} \quad m_{P_2} \geq 3.16 \ m_{P_1} \ ,$$

  This demands the the cs contribution is less than equal to 10%, which easily lies in the theory error regime.
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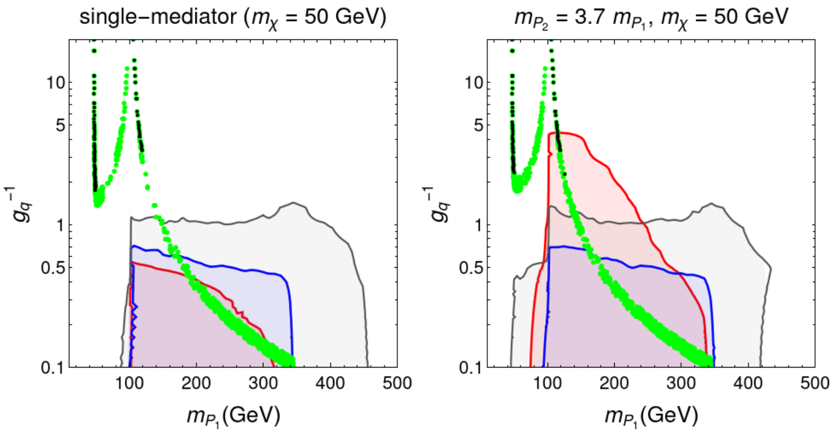

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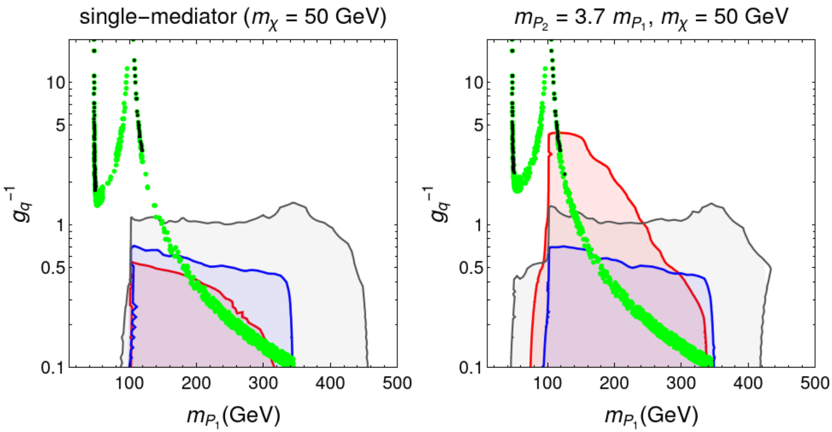

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Two-mediator dark matter models

To make results more accessible, we make following simplifying choices:

- The coupling constant modifiers g_q are assumed to be the same across all generations and for up-type and down-type quarks
- The mixing of the two pseudoscalars is taken maximal, $\theta = \pi/4$.
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