DM EFT with Vector Portal

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Work done in collaboration with Dr. José Wudka

Based on: Fortuna, Roig & Wudka *JHEP 02 (2021) 223*

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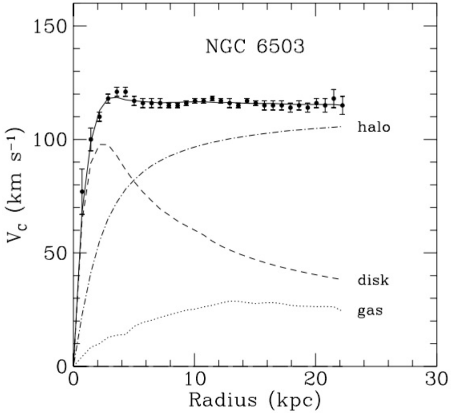
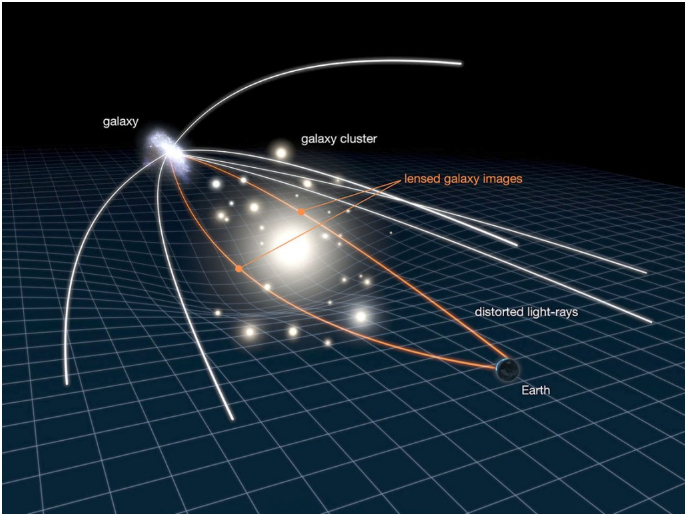
Outline

Rotation curves (NGC 6503)



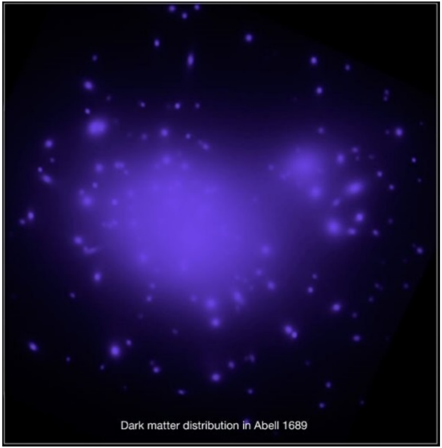
Gravitational lenses



Abell 1689

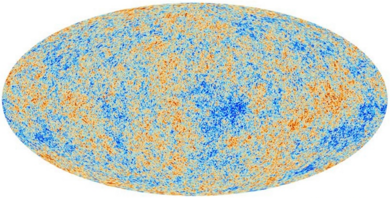
Abell 1689

Visible matter distribution in Abell 1689

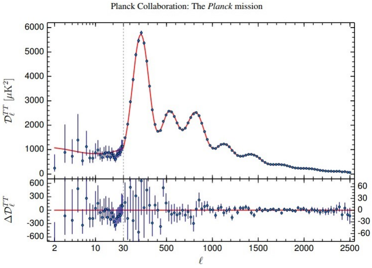


Dark matter distribution in Abell 1689

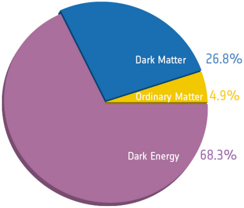
Cosmic Pie



(a) Cosmic Microwave Background



(b) Angular Power Spectrum



Effective Field Theory

- DM-SM interaction.[1]
- Heavy mediators that can be scalars, fermions or vectors.
- Dark sector:
  - Scalars Φ
  - Fermions Ψ
  - Vectors X
- The mediators are weakly coupled to both sectors, dark and standard.
- The dark fields transform non-trivially under $\mathcal{G}_{\text{DM}}$.
- All SM particles are singlets under $\mathcal{G}_{\text{DM}} \to$ stable DM particle.
- All dark fields are singlets under $\mathcal{G}_{\text{SM}} = SU(3) \otimes SU(2) \otimes U(1)$.
- The consequence of interactions generated by a mediator are:

$$\mathcal{O} = \mathcal{O}_{\text{SM}}\mathcal{O}_{\text{dark}} \tag{1}$$

- In the effective lagrangian, each term has a factor $1/\Lambda^n$, $n = \dim(\mathcal{O}) - 4$.
- As we assume that the dark fields transform non-trivially under $\mathcal{G}_{\text{DM}}$, we know that $\mathcal{O}_{\text{dark}}$ contains at least two fields.

[1] González-Macías & Wudka *JHEP 1507 (2015) 161.* Follow-up work: González-Macías et al. *JHEP 05 (2016) 171* and Lamprea et al. *Phys.Rev.D 103 (2021) 1, 015017.*

Lagrangian

- Terms with dark fermions (Ψ):

$$\mathcal{L}_{\text{eff}}^{\Psi} = \frac{\Upsilon_{\text{eff}}}{\Lambda} B_{\mu\nu} \bar{\Psi} \sigma^{\mu\nu} \Psi + \frac{A_{\text{eff}}^{L,R}}{\Lambda^2} \bar{\psi} \gamma_{\mu} \psi \bar{\Psi} \gamma^{\mu} P_{L,R} \Psi + \frac{\kappa_{\text{eff}}^{L,R}}{\Lambda^2} B_{\mu\nu} \bar{\Psi} (\gamma^{\mu} \overleftrightarrow{\mathcal{D}}^{\nu} - \gamma^{\nu} \overleftrightarrow{\mathcal{D}}^{\mu}) P_{L,R} \Psi. \quad (2)$$

- Terms with dark bosons (X, Φ):

$$\mathcal{L}_{\text{eff}}^{\Phi,X} = \frac{\zeta_{\text{eff}}}{\Lambda} B_{\mu\nu} X^{\mu\nu} \Phi + \frac{\epsilon_{\text{eff}}}{\Lambda^2} \bar{\psi} \gamma_{\mu} \psi \frac{1}{2i} \Phi^{\dagger} \overleftrightarrow{\mathcal{D}}^{\mu} \Phi. \quad (3)$$

Where

$$B = A \cos\theta - Z \sin\theta. \quad (4)$$

Z invisible decay width

The reported value of the invisible decay width of the Z boson is

$$\Gamma_Z^{\text{inv}} = (501.03 \pm 1.27)\ \text{MeV.}\ ^{2} \tag{5}$$

The theoretical value (SM) of the partial decay width to a neutrino antineutrino pair

$$\Gamma(Z \to \bar{\nu}\nu) \approx (167.15 \pm 0.01)\ \text{MeV.}\ ^{2} \tag{6}$$

Assuming the existence of 3 light neutrinos, we have

$$\Gamma_Z^{\text{inv}} - \Gamma_Z^{\bar{\nu}\nu} = (-0.42 \pm 1.30)\ \text{MeV.}$$

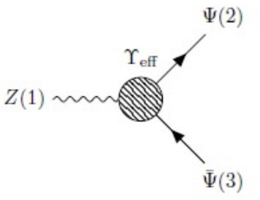
We use

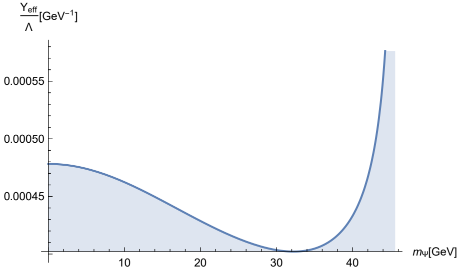
$$\Gamma_Z^{\text{inv}} - \Gamma_Z^{\bar{\nu}\nu} \leq 2.13\ \text{MeV}\ \ \text{at}\ \ 95\%\text{CL.} \tag{7}$$

$\rightarrow$ The invisible decay width of the Higgs boson does not restrict our EFT.

[2] M. Tanabashi et al. (Particle Data Group)(2018) *Phys. Rev. D 98.*

$Z \to \bar{\Psi}\Psi$





Operator: $B_{\mu\nu}\bar{\Psi}\sigma^{\mu\nu}\Psi$

Obtaining the effective coupling constant:

$$\frac{\Upsilon_{\rm eff}}{\Lambda} = \left\{ \frac{6\pi\Gamma_{Z\to\bar{\Psi}\Psi}}{\text{sen}^2\theta_W \sqrt{m_Z^2 - 4m_\Psi^2}(8m_\Psi^2 + m_Z^2)} \right\}^{\frac{1}{2}}. \quad (8)$$

Λ scale estimation

The relation between the EFT and the “fundamental” theory

$$\frac{\Upsilon_{\text{eff}}}{\Lambda} \leftrightarrow \frac{g_1 g_2}{\Lambda} \tag{9}$$

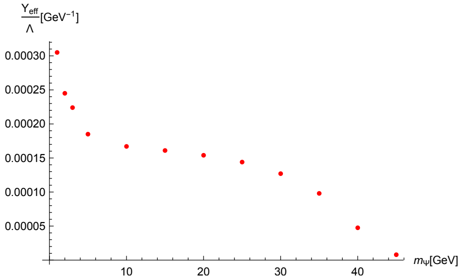
Taking g_1, g_2 as e or g, we obtain

$$230\text{GeV} \leq \Lambda \leq 1\text{TeV}. \tag{10}$$

Relic Density

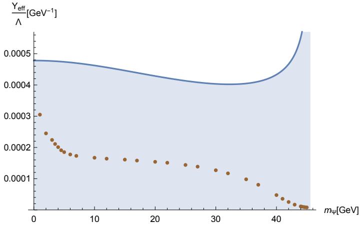
We use the micrOMEGAS [3] code to compute the relic abundance of dark matter in our effective theory.
We use the single operator hypothesis, and obtained the effective coefficient for each operator to reproduce the observed relic density [4]

$$\Omega_{\rm DM} h^2 = 0.1193 \pm 0.0009. \quad (11)$$

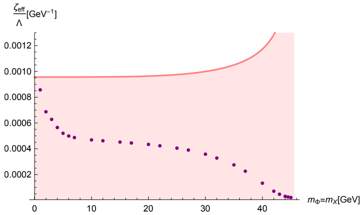


[3] G. Bélanger et al. (2015) *Comput. Phys. Commun. 192*
[4] M. Tanabashi et al. (Particle Data Group)(2018) *Phys. Rev. D 98.*

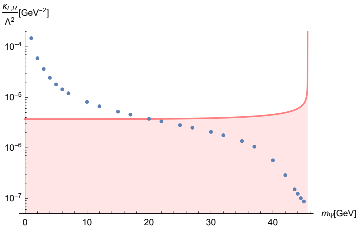
Z invisible decay width + Relic density



(a) $B_{\mu\nu}\bar{\Psi}\sigma^{\mu\nu}\Psi$



(b) $B_{\mu\nu}X^{\mu\nu}\Phi$



(c) $B_{\mu\nu}\bar{\Psi}(\gamma^\mu \overleftrightarrow{\mathcal{D}}^\nu - \gamma^\nu \overleftrightarrow{\mathcal{D}}^\mu)P_{L,R}\Psi$

Observational limits

We introduce the following notation that we will use below:

$$\begin{aligned} \text{OP1} &\equiv B_{\mu\nu}\bar{\Psi}\sigma^{\mu\nu}\Psi, \\ \text{OP2} &\equiv \bar{\psi}\gamma^{\mu}\psi\bar{\Psi}\gamma_{\mu}P_{L,R}\Psi, \\ \text{OP3} &\equiv B_{\mu\nu}\bar{\Psi}(\gamma^{\mu}\overleftrightarrow{\mathcal{D}}^{\nu} - \gamma^{\nu}\overleftrightarrow{\mathcal{D}}^{\mu})P_{L,R}\Psi, \\ \text{OP4} &\equiv B_{\mu\nu}X^{\mu\nu}\Phi, \\ \text{OP5} &\equiv \frac{1}{2i}\left(\bar{\psi}\gamma^{\mu}\psi\right)\left(\Phi^{\dagger}\overleftrightarrow{\partial}_{\mu}\Phi\right). \end{aligned} \tag{12}$$

Besides, we use the effective couplings that reproduce the correct relic abundance, eq. (11).

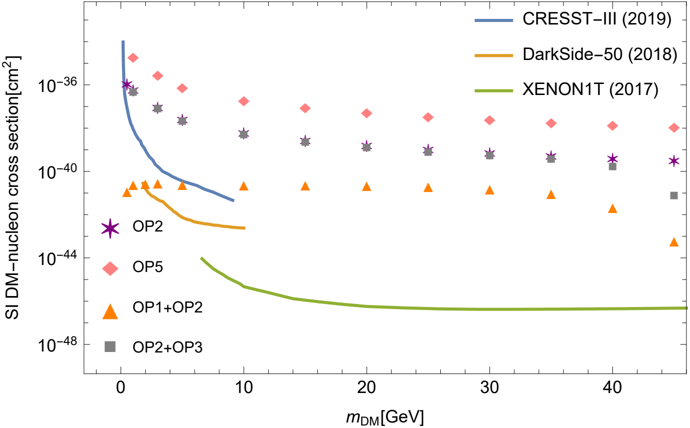
We also analyze the combined contributions with the same DM candidate, with the following relations between the Λ scales and the C coefficients of the operators:

$$\Lambda_{\text{dim }6} = \Lambda_{\text{dim }5}, \qquad C_{\text{dim }6} = \pm C_{\text{dim }5}. \tag{13}$$

The effects of the sign and the use of different values for Λ are negligible.

Direct Detection Experiments

Currently the most stringent limit on spin-independent scattering cross sections of DM-nucleon come from the XENON1T, CRESST-III and DarkSide-50. We study DM-nucleon cross sections in the limit where the relative velocity goes to zero, using micrOMEGAs.



Limits from dwarf spheroidal satellite galaxies (dSphs)

Recently, eight new dSph candidates were discovered using the first year of data from the Dark Energy Survey (DES). Drlica-Wagner et al. [5] searched for gamma-ray emission coincident with the positions of these new objects in six years of Fermi Large Area Telescope data. No significant excesses of gamma-ray emission were found. Individual and combined limits on the velocity-averaged DM annihilation cross section for these new targets were computed.

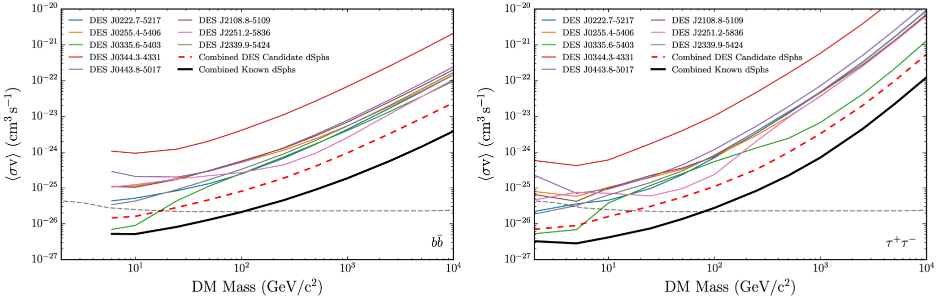
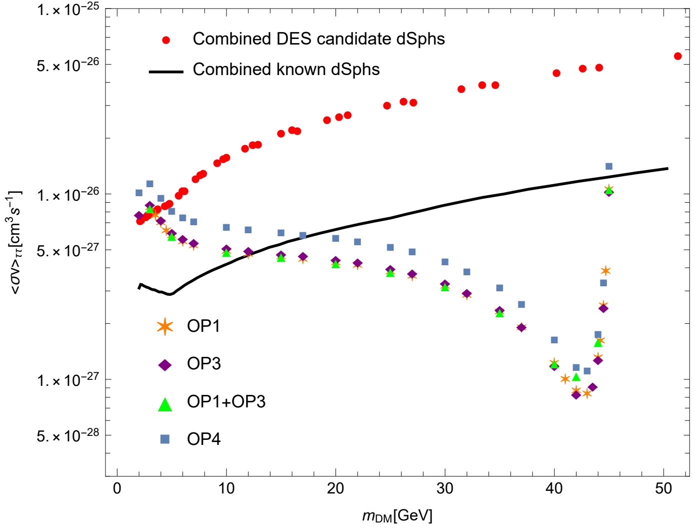


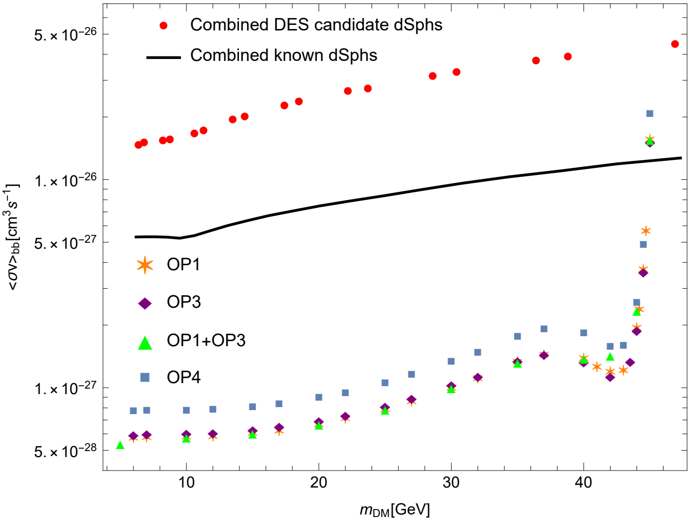
Figure: Left: annihilation to $\bar{b}b$, right: annihilation to $\tau^+\tau^-$.

[5] A. Drlica-Wagner et al. Search for Gamma-Ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data. *Astrophys. J., 809(1)*:L4, 2015.

Results for $\langle \sigma v \rangle_{\tau\tau}$

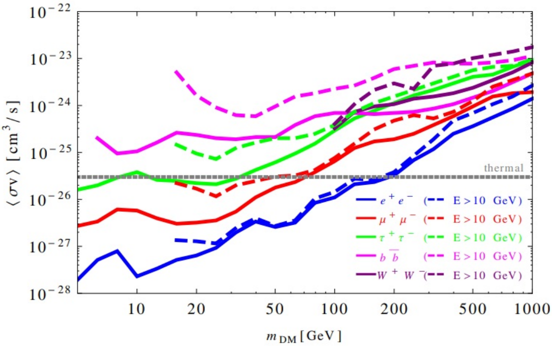


Results for $\langle \sigma v \rangle_{bb}$



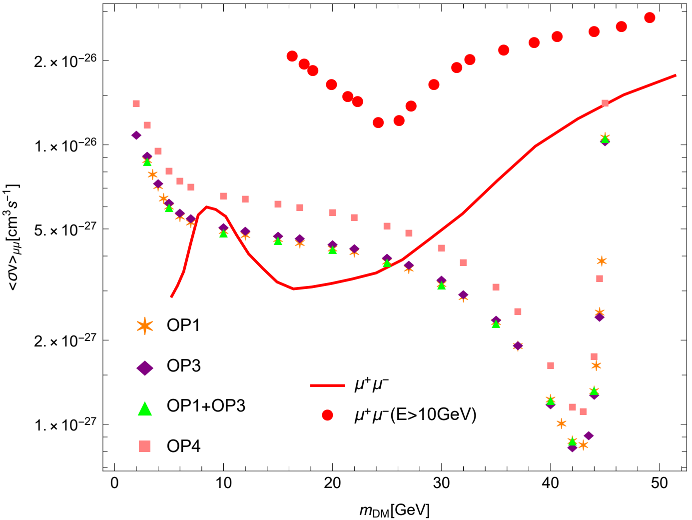
Limits from AMS-02 positron measurements

Ibarra, Lamperstorfer y Silk [6] used measurements of the positron flux to derive limits on the dark matter annihilation cross section and lifetime for various final states, and extracted strong limits on DM properties.

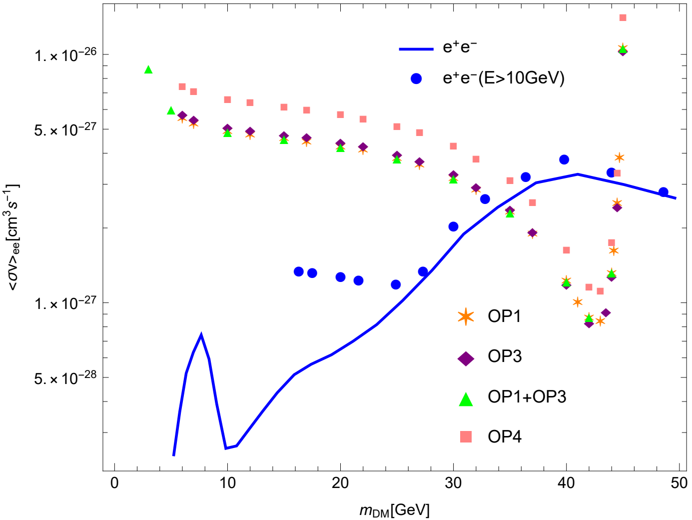


[6] Alejandro Ibarra, Anna S. Lamperstorfer, and Joseph Silk. Dark matter annihilations and decays after the AMS-02 positron measurements. *Phys. Rev.* D89(6):063539, 2014.

Results for $\langle \sigma v \rangle_{\mu\mu}$



Results for $\langle \sigma v \rangle_{ee}$



Summary of results

We recall that the effective coefficients are the ones that correctly reproduce the relic abundance.

Operator	Dim.	DM candidate	Allowed mass (GeV)
1.- $B_{\mu\nu}\bar{\Psi}\sigma^{\mu\nu}\Psi$	5	Ψ fermion	$\approx 0.0025-2, \approx 33-44.5$
2.- $\bar{\psi}\gamma_\mu\psi\bar{\Psi}\gamma^\mu P_{L,R}\Psi$	6	Ψ fermion	none
3.- $B_{\mu\nu}\bar{\Psi}(\gamma^\mu\overleftrightarrow{\mathcal{D}}^\nu - \gamma^\nu\overleftrightarrow{\mathcal{D}}^\mu)P_{L,R}\Psi$	6	Ψ fermion	$\approx 33-44.5$
4.- $B_{\mu\nu}X^{\mu\nu}\Phi$	5	vector X, scalar Φ	$\approx 0.11-2, \approx 36-44.5$
5.- $\bar{\psi}\gamma_\mu\psi\frac{1}{2i}\Phi^\dagger\overleftrightarrow{\mathcal{D}}^\mu\Phi$	6	scalar Φ	none
$1+2$	5+6	Ψ fermion	$\approx 0.0025-2$
$1+3$	5+6	Ψ fermion	$\approx 0.0025-2, \approx 33-44.5$
$2+3$	6	Ψ fermion	none

Thanks for your attention

dim.	category	
4	I	$\lvert\varphi\rvert^2(\Phi^\dagger\Phi)$
5	II	$\lvert\varphi\rvert^2\bar{\Psi}\Psi$ $\quad$ $\lvert\varphi\rvert^2\Phi^3$
	III	$(\bar{\Psi}\Phi)(\varphi^T\epsilon\ell)$
	IV	$B_{\mu\nu}X^{\mu\nu}\Phi$ $\quad$ $B_{\mu\nu}\bar{\Psi}\sigma^{\mu\nu}\Psi$
6	V	$\lvert\varphi\rvert^2\mathcal{O}^{(4)}_{\text{dark}}$ $\quad$ $\Phi^2\mathcal{O}^{(4)}_{\text{SM}}$
	VI	$(\bar{\Psi}\Phi^2)(\varphi^T\epsilon\ell)$ $\quad$ $(\bar{\Psi}\Phi)\not{\partial}(\varphi^T\epsilon\ell)$
	VII	$\mathcal{J}_{\text{SM}}\mathcal{J}_{\text{dark}}$
	VIII	$B_{\mu\nu}\mathcal{O}^{(4)\mu\nu}_{\text{dark}}$

Table: Effective operator list up to dimension ≤ 6 involving dark and SM fields; φ stands for the SM scalar isodoublet, B for the hypercharge gauge field, and ℓ is a left-handed lepton isodoublet.

Operators generated at tree level:

- Scalar mediators
  Categories II y V
- Fermionic mediators
  Categories III y VI
- Vector mediators
  Categories VII
- Antisymmetric tensor mediators
  Categories IV y VIII

¿Why must $m_X \simeq m_\Phi$?

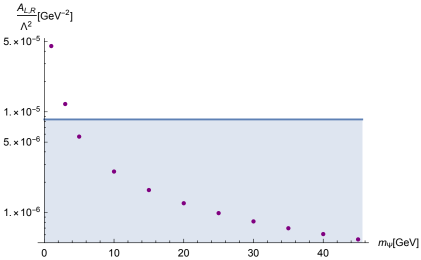
- $m_X \simeq m_\Phi$
  - Dominant process that regulates the relic abundance is $X\Phi \to \bar{f}f$, s channel.
  - Annihilation cross section and decay width $\propto 1/\Lambda^4$.
- $m_X > m_\Phi$ ($m_X < m_\Phi$)
  - Dominant process that regulates the relic abundance is $\Phi\Phi \to \gamma\gamma$ ($XX \to \gamma\gamma$), t channel.
  - Quadratic in the effective vertex.
  - Annihilation cross section $\propto 1/\Lambda^8$.
  - It is required a very small value of Λ to be consistent with the Z invisible decay width.

About the operators that do not contribute to the Z boson decay, we did a simple computation to analyze their effective couplings:
Using the scale estimates, previously obtained, we calculate reasonable values for the coefficients that we wanted to test.

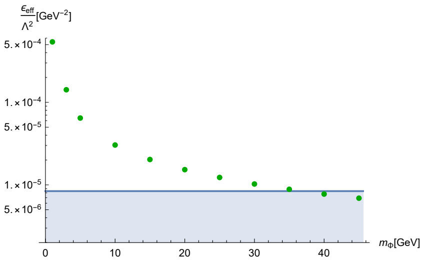
	$g_{1,2} \sim e$, $\Lambda \sim 1\text{TeV}$	$g_{1,2} \sim 0.66$, $\Lambda \sim 230\text{GeV}$
$g_1 g_2/\Lambda^2\,(\text{GeV}^{-2})$	$\sim 1.1 \times 10^{-7}$	8.4×10^{-6}

(14)

Relic Density + Estimates



(a) $\bar{\psi}\gamma^{\mu}\psi\bar{\Psi}\gamma_{\mu}P_{L,R}\Psi$



(b) $\bar{\psi}\gamma^{\mu}\psi\frac{1}{2i}\Phi^{\dagger}\overleftrightarrow{\mathcal{D}}_{\mu}\Phi$