Effective Theories for Spinning Dark Matter [1]

Dark Side of the Universe 2019

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[1] Based on i) PRD**88**, 096012 (2013), Selim Gomez-Avila, M.N. ; ii) PRD **93**, 076003 (2016), M.N.,Simon Rodriguez,Rodolfo Ferro-Hernandez, S.G.A.; iii) PRD **98**,015001 (2018), Haydee Hernandez-Arellano, M.N.,S.R, iv) Work in progress, H.H.A., M.N., S.R.

Outline

1. Motivations
2. Spin-one matter, $(1,0)\oplus(0,1)$ fields: Brief review
3. Spin-one matter dark fields (SOMDF): effective theory.
4. Light SOMDF: constraints from Z^0, H invisible widths.
5. SOMDF and DM relic density.
6. SOMDF and FermiLAT-DES upper bounds on DM annihilation into $\tau^+\tau^-$ and $\bar{b}b$
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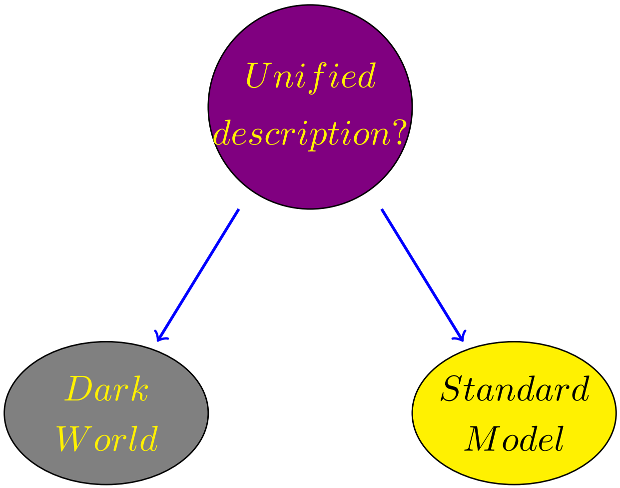
WIMP paradigm



- A $\langle\sigma v_r\rangle(T_f)\approx G_F^2T_f^2=10^{-9}GeV^{-2}$ with $T_f/M_D\approx 25$ yields dark matter freeze out and reproduces the observed DM relic density. Relic DM is non-relativistic and a mass of the order of the electroweak scale is required.
- Appealing scheme pointing to weak interactions of dark matter at the electroweak scale (unification route).
- We propose here an alternative idea:dark matter with an unconventional space-time structure.

Theory of Quantum Fields (Weinberg)

1. Quantum mechanics $\leftrightarrow$ Poincaré group $\leftrightarrow$ $|\Gamma\rangle = a^{\dagger}(\Gamma)|0\rangle$
   - $\Gamma \equiv \{m^2, j, p^{\mu}, \sigma\}$ = good quantum numbers of the Poincaré group.
   - σ the quantum number of the little group (i.e., spin projection for massive fields or helicity for massless fields).
2. Causality + Locality + Poincaré invariance of the S-matrix $\Leftrightarrow$ Fields transforms in a HLG irrep

$$\psi_{ab}(x) = \int d\Gamma(\kappa e^{ip\cdot x} u_{ab}(\Gamma) a(\Gamma) + \lambda e^{-ip\cdot x} u^{c}_{ab}(\Gamma) b^{\dagger}(\Gamma)),$$

where

- κ, λ are constants fixed by discrete symmetries.
- u_{ab} and u^{c}_{ab} transform in some representation of the HLG.

HLG irreps and SM fields

$HLG \simeq SU(2)_A \otimes SU(2)_B \Rightarrow$ irreps classified according to two $SU(2)$ quantum numbers:

$$
\begin{array}{ccccccccc}
 & & & & (0,0) & & & & \\
 & & & (\frac{1}{2},0) & & (0,\frac{1}{2}) & & & \\
 & & (1,0) & & (\frac{1}{2},\frac{1}{2}) & & (0,1) & & \\
 & (\frac{3}{2},0) & & (1,\frac{1}{2}) & & (\frac{1}{2},1) & & (0,\frac{3}{2}) & \\
(2,0) & & (\frac{3}{2},\frac{1}{2}) & & (1,1) & & (\frac{1}{2},\frac{3}{2}) & & (0,2)
\end{array}
$$

HLG irreps and SM fields

$HLG \simeq SU(2)_A \otimes SU(2)_B \Rightarrow$ irreps classified according to two $SU(2)$ quantum numbers:

Higgs					$(0,0)$				
Quarks & Leptons				$(\frac{1}{2},0)$		$(0,\frac{1}{2})$			
Gauge bosons			$(1,0)$		$(\frac{1}{2},\frac{1}{2})$		$(0,1)$		
Gravitino		$(\frac{3}{2},0)$		$(1,\frac{1}{2})$		$(\frac{1}{2},1)$		$(0,\frac{3}{2})$	
Graviton	$(2,0)$		$(\frac{3}{2},\frac{1}{2})$		$(1,1)$		$(\frac{1}{2},\frac{3}{2})$		$(0,2)$

HLG irreps and SM fields

$HLG \simeq SU(2)_A \otimes SU(2)_B \Rightarrow$ irreps classified according to two $SU(2)$ quantum numbers:

$$(0,0)$$

$$(\tfrac{1}{2},0) \qquad (0,\tfrac{1}{2})$$

Dark Matter ? $\qquad \boxed{(1,0)} \qquad (\tfrac{1}{2},\tfrac{1}{2}) \qquad \boxed{(0,1)}$

$$(\tfrac{3}{2},0) \qquad (1,\tfrac{1}{2}) \qquad (\tfrac{1}{2},1) \qquad (0,\tfrac{3}{2})$$

$$(2,0) \qquad (\tfrac{3}{2},\tfrac{1}{2}) \qquad (1,1) \qquad (\tfrac{1}{2},\tfrac{3}{2}) \qquad (0,2)$$

Contents

Spin-one matter, $(1,0)\oplus(0,1)$ fields: Brief review.

- First principles (irreps of the HLG): Dirac equations is just the covariant projection on subspaces of well defined parity in the $(\frac{1}{2},0)\oplus(0,\frac{1}{2})$ representation space.
- For $(j,0)\oplus(0,j)$ parity transforms as the time-component $(S^{00\ldots0})$ of a symmetric traceless tensor $S^{\mu_1\mu_2\cdots\mu_{2j}}$.
- A basis for $(j,0)\oplus(0,j)$ induced by parity can be constructed.
- For $(1,0)\oplus(0,1)$ it is given by the 6×6 covariant matrices:
  1. $\mathbb{I}$, identity matrix (1).
  2. χ, chirality operator (1).
  3. $S^{\mu\nu}$, $\chi S^{\mu\nu}$ symmetric traceless tensors (9+9).
  4. $M^{\mu\nu}$, HLG generators (6).
  5. $C^{\mu\nu\alpha\beta}$, antisymmetric under $\alpha\leftrightarrow\beta$ or $\mu\leftrightarrow\nu$; symmetric under $(\alpha,\beta)\leftrightarrow(\mu,\nu)$. Satisfies Bianchi identity (10).
- Covariant parity projection and well defined P^2 yields the following equation

$$\boxed{\left[\frac{1}{2}(g^{\mu\nu}+S^{\mu\nu})\partial_\mu\partial_\nu+m^2\right]\Psi(x)=0}$$

- The free Lagrangian for spin-one matter fields is given by,

$$\mathcal{L} = \partial_\mu \overline{\Psi} \Sigma^{\mu\nu} \partial_\nu \Psi - m^2 \overline{\Psi} \Psi \tag{1}$$

where $\Sigma^{\mu\nu} = \frac{1}{2}(g^{\mu\nu} + S^{\mu\nu})$ and the field Ψ is a six component "spinor": $\Psi(x) = U(p,\lambda)e^{-ip\cdot x}$.

- Constrained dynamics, second class constraints, can be solved following the Dirac algorithm.
- Algebra satisfied by S crucial in obtaining a sensible QFT.

$$\{S^{\mu\nu}, S^{\alpha\beta}\} = \frac{4}{3}(g^{\mu\alpha}g^{\nu\beta} + g^{\nu\alpha}g^{\mu\beta} - \frac{1}{2}g^{\mu\nu}g^{\alpha\beta}) - \frac{1}{6}(C^{\mu\alpha\nu\beta} + C^{\mu\beta\nu\alpha})$$

- The solutions $U(p,\lambda)$ satisfy

$$\sum_\lambda U(p,\lambda)\bar{U}(p,\lambda) = \frac{S^{\mu\nu}p_\mu p_\nu + M^2}{2M^2} \equiv \frac{S(p) + M^2}{2M^2} \tag{2}$$

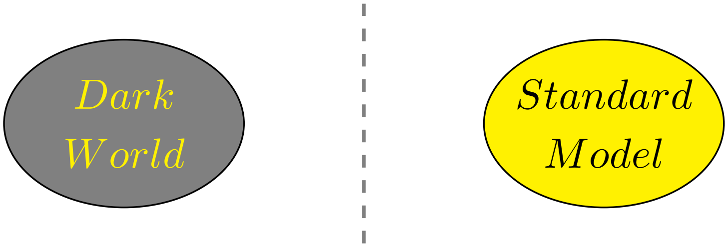
- Propagator

$$\Delta(p) = \frac{S(p) - p^2 + 2M^2}{2M^2(p^2 - M^2 + i\varepsilon)}$$

Contents

Effective theory

- We consider spin-one matter dark fields (SOMDF) as SM singlets (no SM charges) with their own (dark) gauge group (DG).
- SM fields assumed as singlets of the Dark Group (no DG charges).



- General form of the DM-SM interaction

$$\mathcal{L}_{int} = \sum_{i,n} \frac{g_n^i}{\Lambda^{n-4}} \mathcal{O}^i_{SM}(k)\mathcal{O}^i_{DM}(q) \qquad k+q=n.$$

- For the sake of simplicity we consider $DG = U(1)_D$.

- The lowest dimension standard model singlet operators are:

$$\mathcal{O}^1_{SM}(2) = B^{\mu\nu}, \qquad \mathcal{O}^2_{SM}(2) = \widetilde{H}H.$$

with $B^{\mu\nu}$ the $U(1)_Y$ stress tensor.

- The lowest dimension SOMDF operators are:

$$\mathcal{O}^i_{DM}(2) = \bar{\Psi}\Gamma^i\Psi$$

with Γ^i an element of the basis $\{\mathbb{I}, \chi, S^{\mu\nu}, \chi S^{\mu\nu}, M^{\mu\nu}, C^{\mu\nu\alpha\beta}\}$.

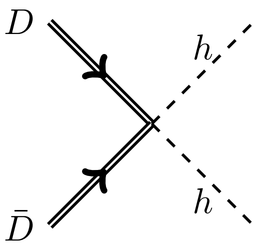
- The leading terms in the effective theory are

$$\boxed{\mathcal{L}_{int} = \bar{\Psi}(g_s\mathbb{I} + ig_p\chi)\Psi\widetilde{H}H + g_t\bar{\Psi}M_{\mu\nu}\Psi B^{\mu\nu} + \mathcal{L}_{selfint}(\Psi).}$$

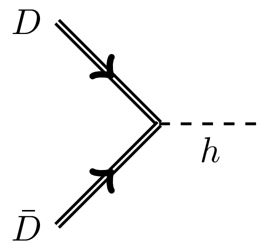
- We obtain a **spin portal** and a Higgs portal to SODM. Neutral gauge fields of the SM couple to higher multipoles of SODM.
- In the unitary SM gauge, after SSB we get

$$\mathcal{L}_{int} = \frac{1}{2}\overline{\Psi}(g_s\mathbb{I} + ig_p\chi)\Psi(v+h)^2 + g_t cos\theta_W\overline{\Psi}M_{\mu\nu}\Psi F^{\mu\nu}$$
$$-g_t sin\theta_W\overline{\Psi}M_{\mu\nu}\Psi Z^{\mu\nu}$$

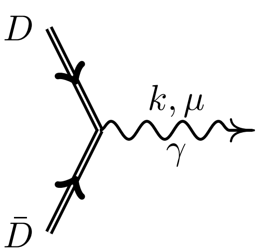
Feynman rules.



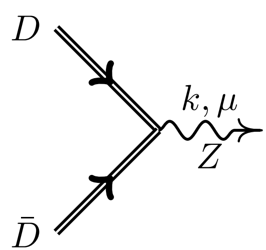
$$= i(g_s \mathbb{I} + i g_p \chi)$$



$$= i(g_s \mathbb{I} + i g_p \chi) v$$



$$= 2 g_t \cos\theta_W M^{\mu\nu} k_\nu$$



$$= -2 g_t \sin\theta_W M^{\mu\nu} k_\nu$$

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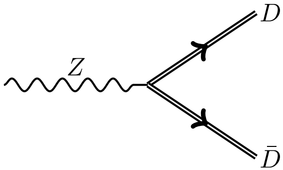
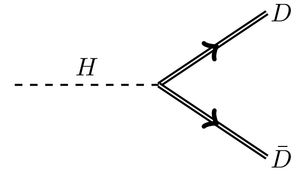
$Z^0 \to \bar{D}D$ and $H \to \bar{D}D$decays.





- For low dark matter mass the transitions $Z^0 \to \bar{D}D$ and $H \to \bar{D}D$ are kinematically allowed and contribute to the invisible Z and H widths.

$$\Gamma_{Z\to D\bar{D}} = \frac{g_t^2 sin^2\theta_W (M_Z^2 - 4M^2)^{3/2}}{24\pi M^4}(M_Z^2 + 2M^2)$$

$$\Gamma_{H\to D\bar{D}} = \frac{v^2\sqrt{M_H^2 - 4M^2}}{32\pi M^4 M_H^2}\,[g_s^2(M_H^4 - 4M_H^2M^2 + 6M^4) + g_p^2 M_H^2(M_H^2 - 4M^2)]$$

- The measured invisible width $\Gamma_{exp}^{inv}(Z) = 499.0 \pm 1.5\ MeV$ (PDG), includes the decay to $\nu\bar{\nu}$. A calculation considering massive neutrinos yields $\Gamma(Z^0 \to \bar{\nu}\nu) = 497.64 \pm 0.03\ MeV$.
- Subtracting this quantity from the PDG reported value for the invisible width we get the constraint

$$\Gamma(Z \to \bar{D}D) < 1.4 \pm 1.5\ MeV.$$

- The invisible Higgs decay width has been recently measured as [2]

$$\Gamma_H^{inv} = 1.14 \pm 0.04 \; MeV.$$

Upper limits for g_t, g_s, g_p

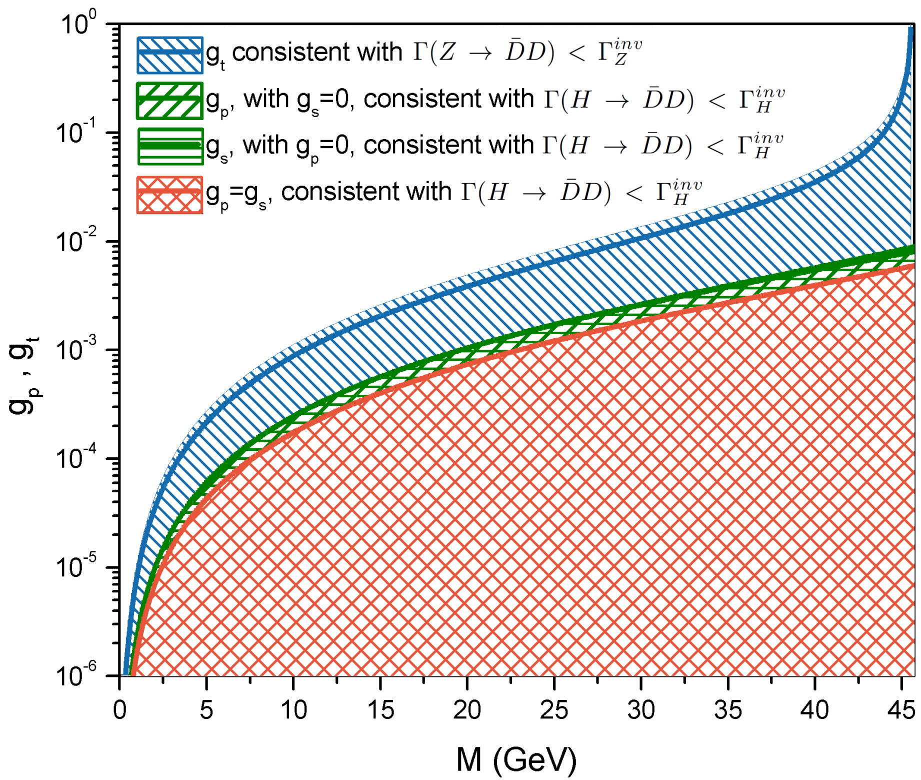
$$g_t \leq \sqrt{\frac{(1.4)24\pi M^4}{sin^2\theta_W(M_Z^2 - 4M^2)^{3/2}(M_Z^2 + 2M^2)}}$$

$$g_s \leq \sqrt{\frac{(1.14)32\pi M^4 M_H^2}{v^2\sqrt{M_H^2 - 4M^2}[M_H^2(M_H^2 - 4M^2) + 6M^4]}}$$

$$g_p \leq \sqrt{\frac{(1.14)32\pi M^4}{v^2(M_H^2 - 4M^2)^{3/2}}}$$

[2] V. Khachatryan et al., CMS Coll.; J. High Energy Phys. 02 (2017) 135..

Invisible width constraints on the values of g_t, g_s and g_p.



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Dark matter relic density.

- The measured dark matter relic density is

$$\Omega_D^{exp} h^2 = 0.1186 \pm 0.0020^3$$

- This is the remnant after the decoupling of dark mater from the primordial soup.
- The evolution of the dark matter comoving number density $n_D(T)$ is given by the Boltzmann equation

$$\frac{dY(x)}{dx} = -\frac{M^3\langle\sigma v_r\rangle(x)}{H(M)}[Y^2(x) - Y_{eq}^2(x)]$$

where M stands for the dark matter mass and

$$x \equiv \frac{M}{T}, \qquad Y \equiv \frac{n_D}{T^3}, \qquad H(M) = \frac{M^2\sqrt{8\pi G_N g^*(M)}}{90}.$$

- Dark matter relic density is related to $Y(x_0)$ by

$$\Omega_D = \frac{\rho_D(x_0)}{\rho_c} = \frac{M n_D(x_0)}{\rho_c} = \frac{MY(x_0)T_0^3}{\rho_c}.$$

[3] PDG

The thermal average $\langle \sigma v_r \rangle$ is given by

$$\langle \sigma v_r \rangle = \frac{1}{n_D^{eq} n_{\bar{D}}^{eq}} \int \frac{g_D d^3 p_1}{(2\pi)^2} e^{-E_1/T} \int \frac{g_{\bar{D}} d^3 p_2}{(2\pi)^2} e^{-E_2/T} \sigma v_r, \tag{3}$$

where g_D ($g_{\bar{D}}$)denotes the number of internal d.o.f of the dark matter particle (antiparticle) and σ is the conventional cross section for the annihilation of dark matter into SM particles.
For non-relativistic dark matter ($v_r << 1$)

$$Flux = 4\sqrt{(p_1 \cdot p_2)^2 - M^4} = 2(s - M^2) v_r \tag{4}$$

where v_r is related to s as

$$s = 2M^2 \left(1 + \frac{1}{\sqrt{1 - v_r^2}}\right) = 4M^2 + M^2 v_r^2 + ... \tag{5}$$

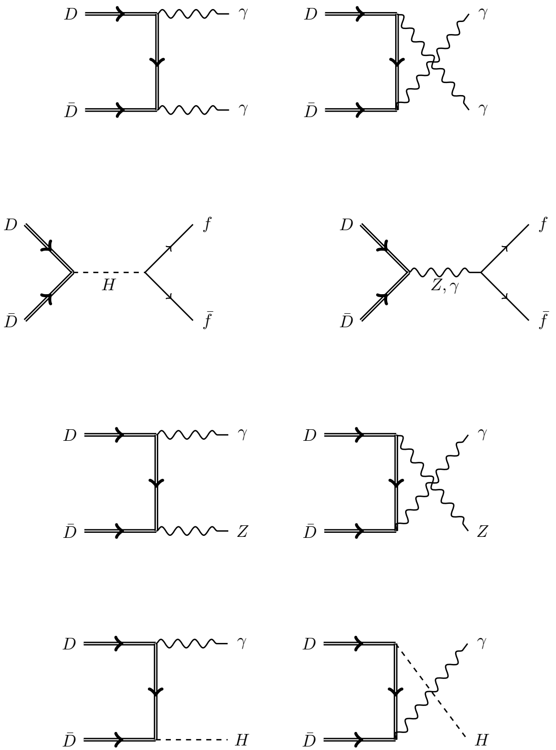
The cross section σ can be expanded as

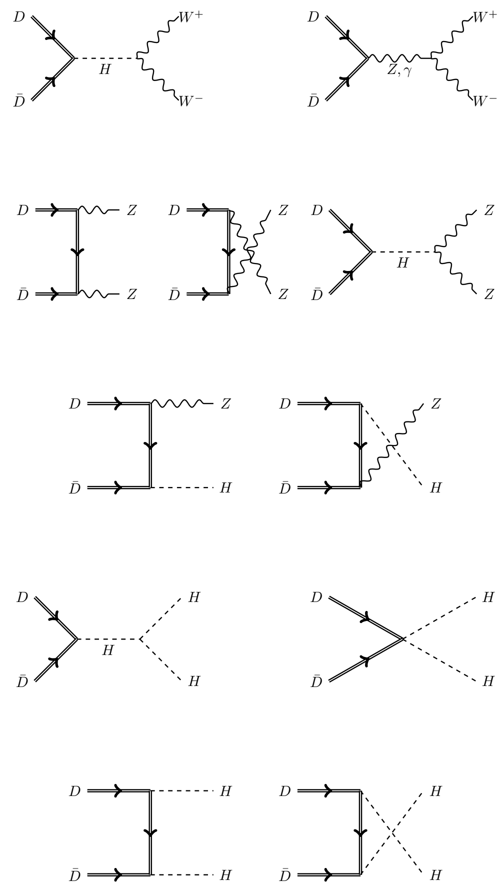
$$\sigma v_r = a + b v_r^2, \tag{6}$$

and performing the thermal average we obtain

$$\langle \sigma v_r \rangle = a + \frac{6b}{x}, \qquad x = M/T. \tag{7}$$

Annihilation of SODM into SM particles.





Relic density.

The relic dark matter density is given by
$\Omega_{DM} = M(2 * Y(T_0))T_0^3/\rho_c$.

$$\Omega_{DM} \simeq \Big(\sqrt{\frac{16\pi^3 G}{90}}\frac{T_0^3}{\rho_c}\Big)\Big[\int_{T_0}^{T_f} g_*^{-1/2}\langle\sigma v\rangle\frac{dT}{M}\Big]^{-1} \tag{8}$$

The freezing value x_f can be found from the condition that the annihilation rate equals the expansion rate of the universe

$$n_{eq}(x_f)\langle\sigma v_r\rangle(x_f) = H(x_f), \tag{9}$$

which using the non-relativistic form for $n_{eq}(x)$ and Eq. (7) leads to

$$\left(a + \frac{6b}{x_f}\right)\sqrt{x_f}e^{-x_f} = \frac{(2\pi)^3}{3M}\sqrt{\frac{G_N g^*(x_f)}{90}}. \tag{10}$$

SODM relic density for $M < M_H/2$

- $D\bar{D} \to \gamma\gamma$.
- $D\bar{D} \to f\bar{f}$, for $m_f < M < M_H/2$.

$$\langle \sigma v_r \rangle = \langle \sigma v_r \rangle_{\gamma\gamma} + \sum_f \langle \sigma v_r \rangle_{f\bar{f}} = a + b/x$$

with

$$a = \frac{29 C_W^4 g_t^4}{18\pi M^2} + \sum_f \frac{N_f g_s^2 m_f^2 (M^2 - m_f^2)^{3/2}}{12\pi M^3 (M_H^2 - 4M^2)^2}$$

$$b = \frac{365 C_W^4 g_t^4}{216\pi M^2} + \sum_f \frac{N_f \sqrt{M^2 - m_f^2}}{864\pi M^5} \Big[\frac{96 M^4 g_t^2 M_Z^2 S_W^2 ((A_f^2 - 2B_f^2) m_f^2 + 2M^2 (A_f^2 + B_f^2))}{v^2 (M_Z^2 - 4M^2)^2}$$
$$+ \frac{192 A_f M^2 C_W Q_f g_t^2 M_W M_Z S_W^2 (m_f^2 + 2M^2)}{v^2 (M_Z^2 - 4M^2)} + \frac{96 C_W^2 Q_f^2 g_t^2 M_W^2 S_W^2 (m_f^2 + 2M^2)}{v^2}$$
$$- \frac{6 M^2 m_f^2 (8 g_p^2 (4M^2 - M_H^2)(M^2 - m_f^2) + g_s^2 (-8 m_f^2 (M^2 - M_H^2) - 11 M^2 M_H^2 + 20 M^4))}{(M_H^2 - 4M^2)^3}$$
$$- \frac{9 M^2 m_f^2 g_s^2 (4M^2 - 5m_f^2)}{(M_H^2 - 4M^2)^2} \Big]$$

$$A_f = 2T_f^{(3)} - 4Q_f S_W^2, \qquad B_f = -2T_f^{(3)}, \qquad C_W = \cos\theta_W, \qquad S_W = \sin\theta_W.$$

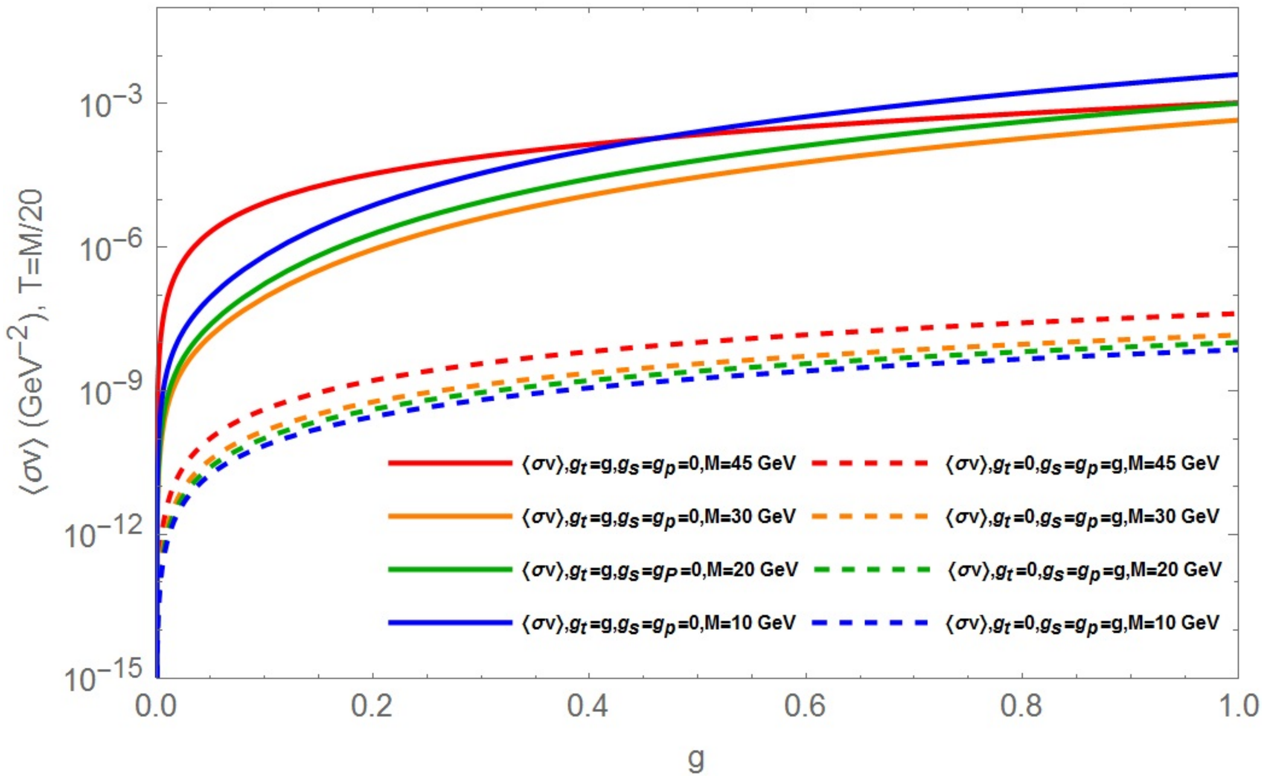


Figura 1: Individual contributions of the spin portal $(g_t = g,\ g_s = g_p = 0)$ and the Higgs portal $(g_t = 0,\ g_s = g_p = g)$ to $\langle \sigma v_r \rangle$. Similar results are obtained in the second case when varying independently g_s or g_p. We plot the results for $M = 45, 30, 20$ and 10 GeV, with $T = M/20$.

Solution to the Boltzmann equation.

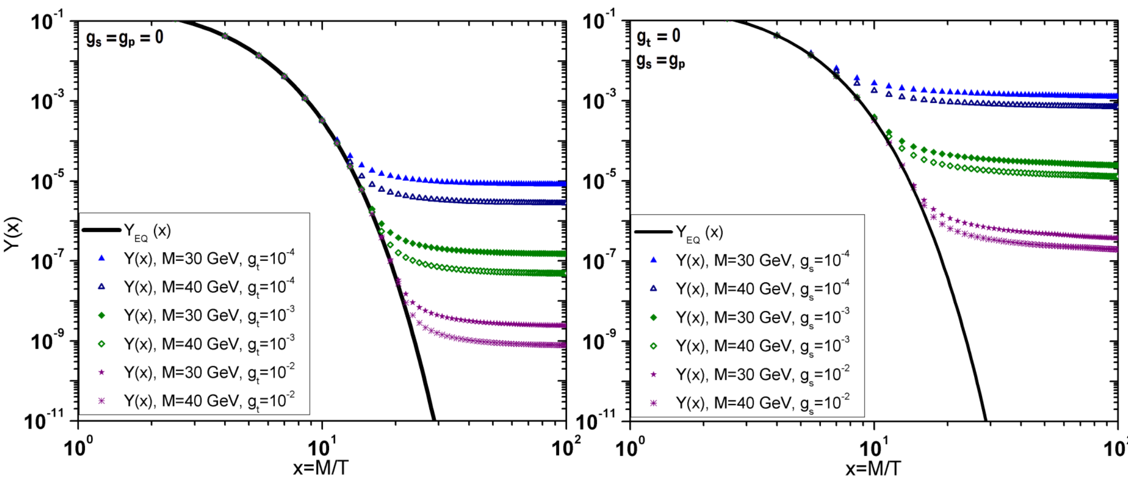
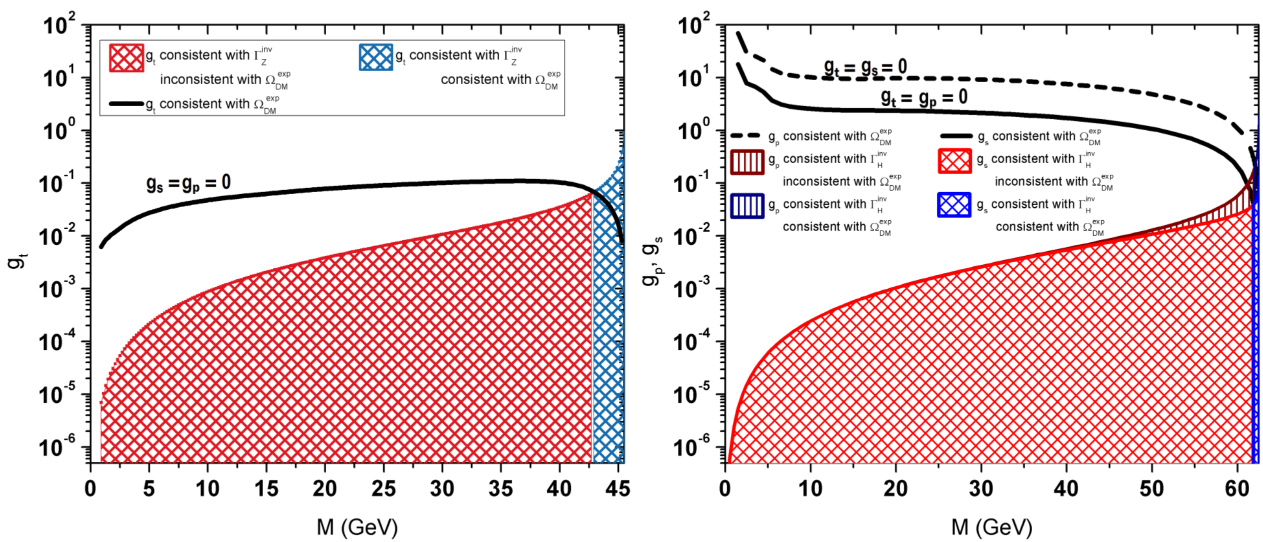


Figura 2: Solution of the Boltzman equation for the spin portal (left) and Higgs portal (right). Similar results are obtained in the later case when varying independently g_s and g_p. The solid line corresponds to $Y_{eq}(x)$.

Constraint on the values of g_t, g_s y g_p for $M < M_H/2$.

Values of the couplings consistent with the measured dark matter relic density, $\Omega_{DM}^{exp}h^2 = 0.1186 \pm 0.0020$ (solid line), as a function of M. These constraints exclude masses below 43 GeV for the spin portal, and 62 GeV for the Higgs portal.



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Dwarf Spheroidal Satellite Galaxies (dSphs)

- Milky Way dSphs: large DM content, low diffuse Galactic γ-ray foregrounds, lack of γ-ray production mechanisms.

The γ-ray flux integrated over a certain region on the sky, in a specific energy range is given by

$$\phi_S = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2M^2}\int_{E_{min}}^{E_{max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma \times \int_{\delta\Omega}\int_{\mathrm{l.o.s}}\rho^2_{DM}(\boldsymbol{r})ds d\Omega \tag{11}$$

.

The last term is known as *J factor*, and can be inferred by fitting the spatial and color-magnitude distributions of the stars.

Velocity-averaged cross section for the annihilation of dark matter into $\tau^+\tau^-$ and $\bar{b}b$

$$
\begin{aligned}
\langle \sigma v_r \rangle_{\tau^+\tau^-} &= \frac{g_s^2 m_\tau^2 \left(M^2 - m_\tau^2\right)^{\frac{3}{2}}}{12\pi M^3 \left(M_H^2 - 4M^2\right)^2} + \mathcal{O}(\langle v_r^2 \rangle), \\
\langle \sigma v_r \rangle_{\bar{b}b} &= \frac{3 g_s^2 m_b^2 \left(M^2 - m_b^2\right)^{\frac{3}{2}}}{12\pi M^3 \left(M_H^2 - 4M^2\right)^2} + \mathcal{O}(\langle v_r^2 \rangle). \qquad (12)
\end{aligned}
$$

Annihilation into fermions and FERMILAT-DES upper bounds

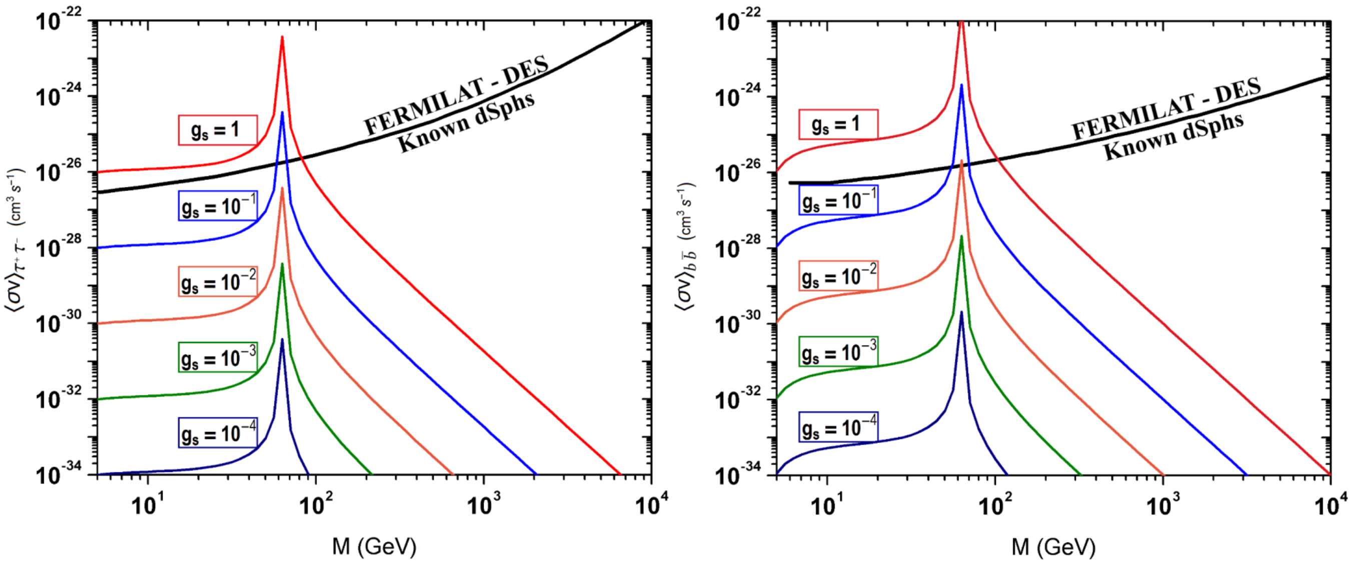


Figura 3: Velocity averaged cross section for dark matter annihilation into $\tau^+\tau^-$ (left) and $\bar{b}b$ (right) and comparison with Fermilat-DES upper bounds, for different values of g_s (Higgs portal). The spin portal yields contributions even smaller and are consistent with these upper bounds.

Contents

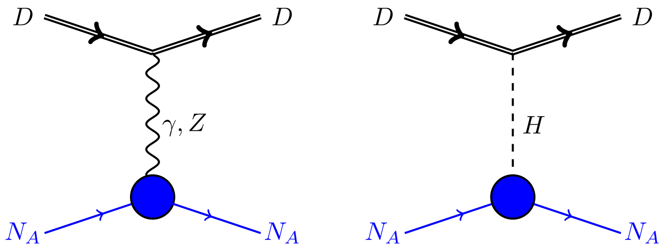
Direct detection of Dark Matter

The rate of interactions of a DM particle of mass M with a nucleus of mass M_A in the detector is given by

$$\frac{dR}{dT} = \frac{\rho}{M M_A} \int_{v_{min}}^{v_{esc}} |\mathbf{v}| f(\mathbf{v}) \frac{d\sigma}{dT}(T, \mathbf{v}) d^3\mathbf{v},$$

where $v_{min}(T)$ is the minimal velocity of the incoming DM particle to produce a nuclear recoil energy T, and $v_{esc} = 557\ km/s$ is the escape velocity in our galaxy.

DM-Nucleus scattering: $D(p_1)N_A(p_2) \to D(p_3)N_A(p_4)$



- In the LAB system where $p_1 = (E_1, \mathbf{p}_1)$, $p_2 = (M_A, \mathbf{0})$, $p_3 = (E_3, \mathbf{p}_3)$, $p_4 = (M_A + T, \mathbf{p}_A)$

$$\frac{d\sigma}{dT}(T, \mathbf{v}) = \frac{|\bar{\mathcal{M}}|^2(s,t,u)}{32\pi M_A \mathbf{p}_1^2}.$$

- The Mandelstam variables in the LAB frame are

$$\begin{aligned}
s &= (E_1 + M_A)^2 - \mathbf{p}_1^2 = (M + M_A)^2 + M M_A \mathbf{v}^2 + \mathcal{O}(\mathbf{v}^4), \\
t &= T^2 - |\mathbf{p}_A|^2 = -2M_A T, \\
u &= (M - M_A)^2 + 2M_A T - M M_A \mathbf{v}^2 + \mathcal{O}(\mathbf{v}^4) \\
|\bar{\mathcal{M}}|^2(s,t,u) &= |\bar{\mathcal{M}}|^2(T, \mathbf{v}^2)
\end{aligned}$$

- For a given incoming momentum p_1, the nuclear recoil energy is given by

$$T = \frac{2M_A M^2 \mathbf{v}^2 \cos^2\theta}{(E_1 + M_A)^2 - M^2 \mathbf{v}^2 \cos^2\theta} = \frac{2M_A M^2 \mathbf{v}^2 \cos^2\theta}{(M + M_A)^2} + \mathcal{O}(\mathbf{v}^4),$$

- The minimal velocity to produce a recoil energy T, $v_{min}(T)$ is obtained when $\theta = 0$.

$$v^2_{min}(T) = \frac{(M + M_A)^2}{2M_A M^2} T = \frac{M_A}{2\mu_A^2} T,$$

- For a given velocity the maximal T produced is

$$T_{max} = \frac{2\mu_A^2}{M_A} \mathbf{v}^2.$$

Nucleus-DM interactions: three layers of effective theory

1. Calculate the interactions of nucleons in terms of the interactions of the constituent quarks.
2. Calculate the interactions of a point-like nucleus in terms of interactions the constituent nucleons.
3. Consider the finite size of the nucleus

$$\mathcal{M}=\mathcal{M}_0 F_{SI}(q^2),$$

where $\mathcal{M}_0$ is the amplitude for point-like nucleus.

- Differential cross section conventionally written in terms of σ_{SI}

$$\frac{d\sigma}{dT}(T,\mathbf{v})=\frac{M_A}{2\mu_A^2 v^2}\sigma_{SI}F_{SI}^2(T),$$

with σ_{SI} = total cross section at $q^2=0$

$$\sigma_{SI}=\frac{\mu_A^2}{16\pi M_A^2 M^2}|\bar{\mathcal{M}}|^2(T=0,\mathbf{v}^2).$$

- Problem: photon pole at $q^2=-2M_A T=0$.

- Experiments start detecting nuclear recoil at a given $T = T_{min}$. Expand around this point to get

$$\frac{d\sigma}{dT}(T,\mathbf{v}) = \frac{M_A}{2\mu_A^2 v^2}\sigma_{SI} F_{SI}^2(T),$$

but now

$$\sigma_{SI} = \frac{\mu_A^2}{16\pi M_A^2 M^2}|\bar{\mathcal{M}}|^2(T_{min},\mathbf{v}^2).$$

- Careful with the v expansion, v^2/T terms.
- XENON1T, measures the dark matter-nucleus σ_{SI}. Then, assuming isospin conserving interactions, report results in terms of the following observable

$$\sigma_p = \frac{\mu_p^2}{A^2\mu_A^2}\sigma_{SI}.$$

- It corresponds to the dark matter-nucleon cross section only in the case of isospin conserving interactions.
- It is not our case. We calculate σ_{SI} and normalize with the same factors to calculate XENON1T observable.

From quarks to nucleons

At the nucleon level, the effective Lagrangian is given by [4]

$$\mathcal{L}^N_{eff} = \sum_{N=p,n}\left(g_{HNN}H\bar{N}N - e\bar{N}Q_N\gamma^\mu N A_\mu - \frac{M_Z}{2v}\bar{N}\gamma^\mu(A_N + B_N\gamma^5)NZ_\mu\right)$$

$$\begin{aligned}
g_{HNN} &= -\left(7\sum_{u,d,s} f^{(N)}_{Tq} + 2\right)\frac{m_N}{9v}, \\
A_p &= 2A_u + A_d = 1 - 4\sin^2\theta_W, \\
A_n &= A_u + 2A_d = -1, \\
B_N &= -\Delta^{(N)}_u + \Delta^{(N)}_d + \Delta^{(N)}_s, \\
B_p &= -\Delta^{(p)}_u + \Delta^{(p)}_d + \Delta^{(p)}_s, \\
B_n &= -\Delta^{(p)}_d + \Delta^{(p)}_u + \Delta^{(p)}_s,
\end{aligned}$$

where

	$f^{(p)}_{Tq}$	$f^{(n)}_{Tq}$	$\Delta^{(p)}_q$
u	0.023	0.019	0.77
d	0.034	0.041	−0.40
s	0.14	0.14	−0.12

.

[4] M. Cirelli, E. Del Nobile, P. Panci, JCAP Phys. 10 (2013) 019; P. Gondolo, J Edsjo, P Ullio, L Bergstrom, M Schelke, E. A Baltz, JCAP 07 (2004) 008.

From nucleons to nucleus

At the nuclear level, the effective Lagrangian is

$$\mathcal{L}^A_{eff} = g_{HN_AN_A} H\bar{N}_A N_A - Ze\bar{N}_A\gamma^\mu N_A A_\mu - \frac{M_Z}{2v}\bar{N}_A\gamma^\mu(A_A + B_A\gamma^5)N_A Z_\mu,$$

with

$$\begin{aligned} g_{HN_AN_A} &= Zg_{Hpp} + (A-Z)g_{Hnn}, \\ A_A &= ZA_p + (A-Z)A_n, \\ B_A &= ZB_p + (A-Z)B_n. \end{aligned}$$

$$|\bar{\mathcal{M}}|^2(T,\mathbf{v}^2) = a_0 + \left(\frac{b_0}{T} + c_0\right)\mathbf{v}^2 + \mathcal{O}(T,\mathbf{v}^4).$$

$$a_0 = \frac{4g_s^2 g_{DN_AH}^2 M_A^2}{m_H^4} + \frac{2g_{DN_A\gamma}^2}{3M^2}\left(M^2 - 2MM_A + 3M_A^2\right) + \frac{16 g_s g_{DN_A\gamma} g_{DN_AH} M_A^2}{3Mm_H^2},$$

$$b_0 = \frac{4g_{DN_A\gamma}^2 M_A}{3},$$

$$c_0 = -\frac{16 A_A g_{DN_A\gamma} g_{DN_AZ} M_A^2}{3M_Z^2} + \frac{8 g_s g_{DN_A\gamma} g_{DN_AH} M_A^2}{3Mm_H^2} - \frac{2g_{DN_A\gamma}^2 M_A}{3M^2}\left(M - 4M_A\right).$$

where

$$\begin{aligned} g_{DN_AH} &= -v g_{HN_AN_A}, \\ g_{DN_A\gamma} &= 2Zeg_t\cos\theta_W, \\ g_{DN_AZ} &= \frac{M_Z g_t \sin\theta_W}{v}. \end{aligned}$$

- The observable σ_p reported by XENON is given by

$$\sigma_p = \frac{1}{16\pi A^4 (M+M_p)^2}\left[a_0 + \frac{b_0}{T_{min}}\mathbf{v}^2 + \mathcal{O}(T_{min},\mathbf{v}^4)\right].$$

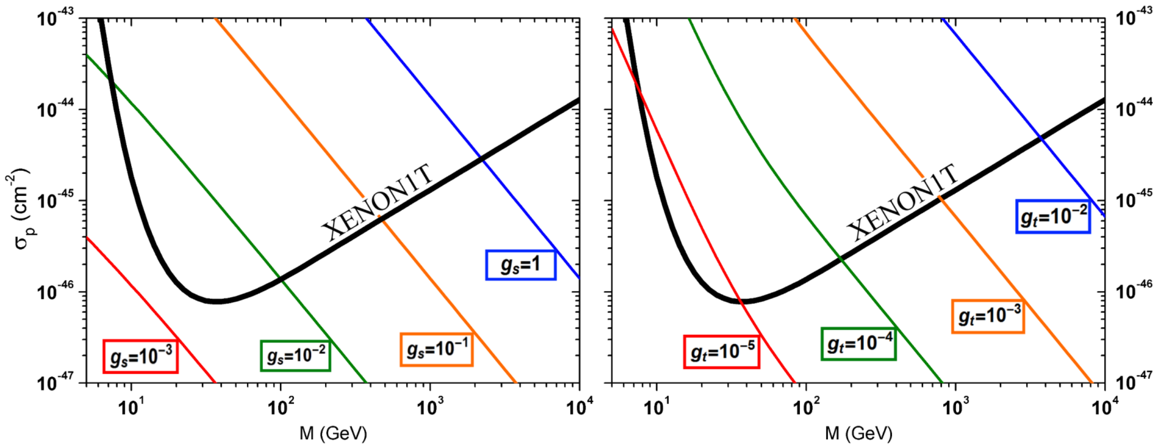


Figura 4: Observable σ_p as a function of the dark matter mass for the Higgs ($g_t = 0$, left panel) and spin ($g_s = 0$, right panel) portals, compared with the XENON1T upper bounds. We consider $A = 129$, $Z = 54$ and $T_{min} = 3\ KeV$ as appropriate for XENON experiment and compare with the recently published XENON1T results.

Contents

Gamma-ray Emission Excess in the Galactic Center

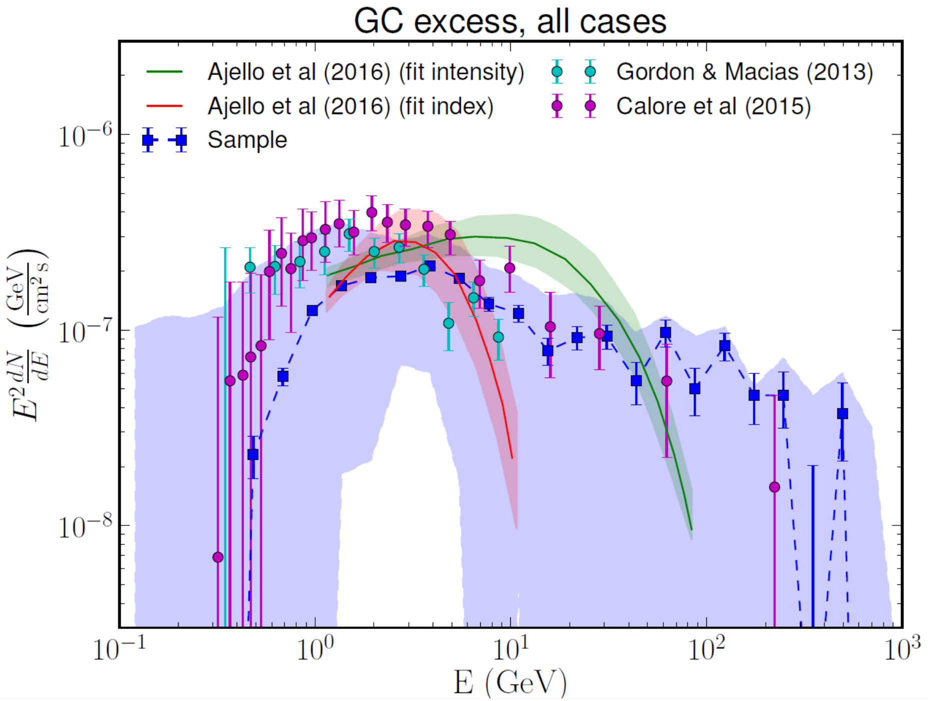


Figura 5: Spectrum of the Galactic center excess for different analysis configurations (M. Ackermann *et al.* [Fermi-LAT Collaboration] Astrophys. J. **840**, no. 1, 43 (2017) doi:10.3847/1538-4357/aa6cab [arXiv:1704.03910 [astro-ph.HE]].).

The gamma-ray differential intensity from the annihilation of dark matter is

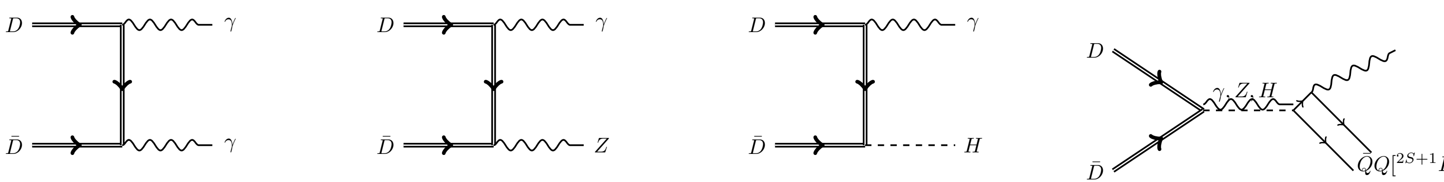
$$\frac{dN}{d\omega} = \Big(\sum_i \frac{B_i}{4\pi M^2}\frac{d\langle\sigma v\rangle_i}{d\omega}\Big)\Big(\int_{\Delta\Omega}\int_{l.o.s}\rho^2(\vec{l})dld\Omega\Big)$$

- The sum runs over all annihilation channels containing at least one photon in the final state.
- $\langle\sigma v\rangle_i$ is the thermally averaged cross section corresponding to the i process, B_i is the number of photons produced in the process.
- The term in the first set of parentheses contains the information from the model.
- The second set of parentheses depends only on the distribution of DM, and it's called the *J-factor*.
- We use the same DM profile ($gNFW$), local DM density ($0.4\mathrm{GeV}/\mathrm{cm}^3$) and J factor ($1.53\times10^{22}\mathrm{GeV}^2\mathrm{cm}^{-5}$) as Fermi-LAT [6].

[6] M. Ackermann *et al.* [Fermi-LAT Collaboration], Astrophys. J. **840**, no. 1, 43 (2017) doi:10.3847/1538-4357/aa6cab [arXiv:1704.03910 [astro-ph.HE]].

Photons from SODM annihilation

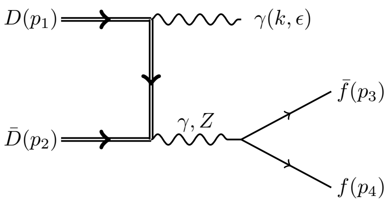
Two body final state

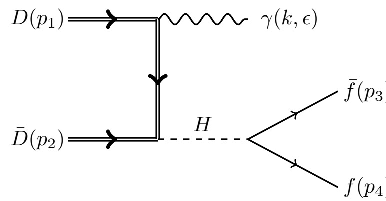


- $\gamma\gamma$: Sharply peaked spectrum at $\omega = M$.
- γR: Peaks expected at $\omega = M(1 - \frac{M_R^2}{4M^2})$. We need to study the corresponding processes with three body in the final state.
- Interferences can change the shape of the photon spectrum.
- Depending on the DM mass we can be in the resonance region or not.

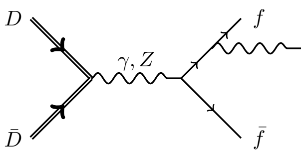
Three body final state

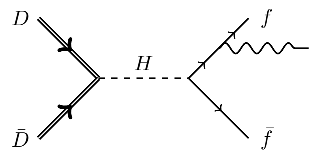
- Initial state radiation.





- Final state radiation.





- Initial state radiation is promising: peak around 3 GeV requires $M = 63\ GeV$ from the Higgs resonance or $M = 46\ GeV$ for the Z^0 resonance.

Initial state radiation: results

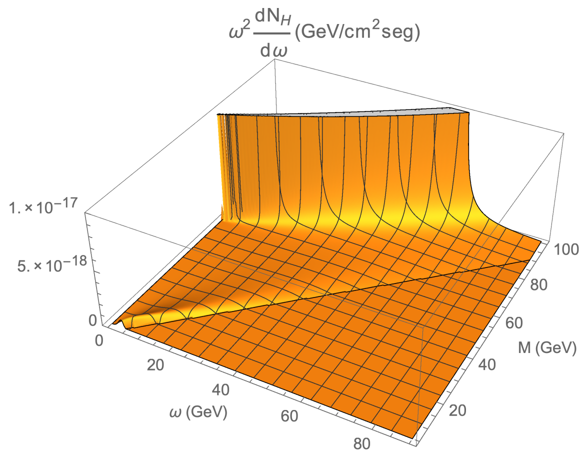


Figura 6: $\omega^2 \frac{dN}{d\omega}$ as a function of ω, M for $g_t = 10^{-3}$, $g_p = g_s = 10^{-2}$.

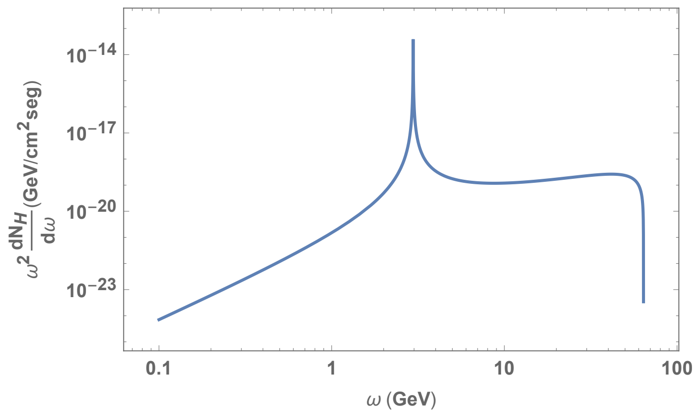


Figura 7: $\omega^2 \frac{dN}{d\omega}$ as a function of ω for $M = 64\ GeV, g_t = 10^{-3}, g_p = g_s = 10^{-2}$.

- Leading contributions from the Higgs exchange $(\mathcal{O}(v_r^0))$.
- Resonant contributions yield the appropriate shape in the spectrum for $M \approx 64\ GeV$.
- But the flux is very small compared to the FermiLAT excess.

Final state radiation: Preliminary results.

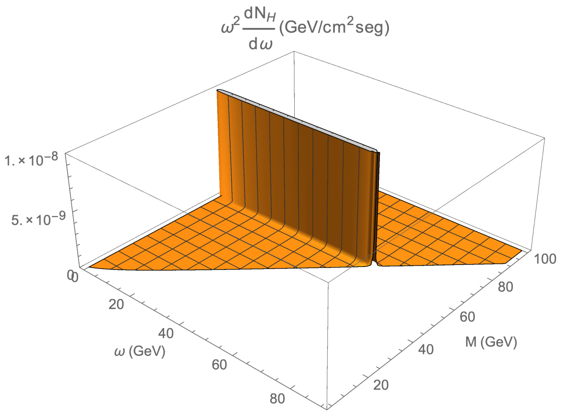


Figura 8: $\omega^2 \frac{dN}{d\omega}$ as a function of ω, M for $g_p = g_s = 10^{-2}$.

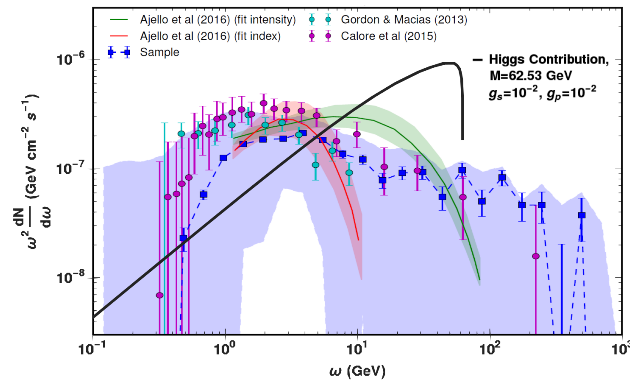


Figura 9: $\omega^2 \frac{dN}{d\omega}$ as a function of ω for $M = 64.53\ GeV, g_p = g_s = 10^{-2}$ compared to FermiLAT results.

- Flux of the order of the FermiLAT excess is obtained only for $M \approx M_H/2$, i.e. at the Higgs resonance.
- The shape of the spectrum is different at high energies.
- Definitive results requires to calculate all the contributions, specially those diagrams with hadronic resonances.

Contents

Conclusions

- We propose an unconventional $(1,0)\oplus(0,1)$ space-time structure for dark matter: spin-one matter dark fields.
- The singlet-singlet principle for the effective field theory of SM fields interacting with SOMDF at leading order yields:
  1. A spin portal : coupling of γ, Z^0 to higher multipoles of DM.
  2. A Higgs portal with two couplings g_s (scalar interactions) and g_p (pseudoscalar interaction).
- Consistency of Invisible widths of Z^0, H^0 and DM relic density constrain $M > 43GeV$ and $g_i \leq 10^{-2}$.
- XENON1T yield stronger constraints on the spin portal coupling (depending on M) $g_T \leq 10^{-3}$, similar constraints for g_s and no constraints for g_p or M.
- FERMILAT-DES upper bounds on $\bar{D}D \rightarrow \tau^+\tau^-, \bar{b}b$ from gamma rays produced in dwarf spheroidal satellite galaxies (dSphs) are satisfied.
- If GRE from the galactic center is produced by DM annihilation, SODM can account for it only if $M = M_H/2$. Preliminary.