

# Dark matter annihilation through nonminimal coupling to gravity as an explanation of the cosmic electron/positron excess

---

Sun Xu-Dong and Dai Ben-Zhong<sup>1</sup>

*School of Physics and Astronomy, Yunnan University, Kunming, 650091, China*

*Key Laboratory of Astroparticle Physics, Yunnan Province, Kunming 650091, China*

*E-mail:* [bestsunxudong@126.com](mailto:bestsunxudong@126.com), [bzhdai@ynu.edu.cn](mailto:bzhdai@ynu.edu.cn)

**ABSTRACT:** The possibility remains that the excess of electrons/positrons in cosmic rays originate from dark matter (DM). This work assumes that a leptonphilic SU(2) scalar doublet exists in nature as one of the mediators connecting DM with the visible sector. Since general relativity is not renormalizable at the quantum level, it is conjectured that there are nonminimal couplings between the Ricci scalar and other scalars such as the scalar DM, the leptonphilic SU(2) scalar doublet, the Higgs doublet. It was found that these couplings can cause efficient scalar DM annihilation after electroweak symmetry breaking. As an application of the proposed model, the cosmic electron/positron excess observed by the Dark Matter Particle Explorer has been successfully explained. It was also shown that the number of photons annihilated by scalar DM could meet the constraints from the isotropic diffuse  $\gamma$ -ray background observed by the Fermi Large Area Telescope.

**KEYWORDS:** Cosmology of Theories beyond the SM, Beyond Standard Model

---

<sup>1</sup>Corresponding author.

---

## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Dark matter annihilation through nonminimal coupling to gravity</b>	<b>2</b>
2.1	The effective field theory treatment of quantum gravity	2
2.2	Gravity-induced DM annihilation	3
2.3	The properties of the scalar mediator $\eta$ determines the annihilation channels	4
2.4	Breit–Wigner resonance	5
<b>3</b>	<b>Application</b>	<b>7</b>
3.1	Interpretation of the cosmic electron/positron excess	7
3.2	Constraints from the isotropic diffuse $\gamma$ -ray background	9
<b>4</b>	<b>Conclusions</b>	<b>11</b>
<b>A</b>	<b>Vertex rules in the Einstein Frame</b>	<b>12</b>

---

## 1 Introduction

Many satellites and Earth-based instruments are being used to search for signals from dark matter (DM) particles. In the process of detecting cosmic rays, electron and positron excesses have been detected below 2 TeV (between 100 GeV and several TeV) by HEAT [1], ATIC [2], PAMELZ [3], Fermi [4] [5], and AMS-02 [6]. The latest exploration of the cosmic electron energy spectrum was performed by the DArk Matter Particle Explorer (DAMPE) [7], whose data show a broad excess up to TeV energy and a possible line structure at about 1.4 TeV. This excess of electrons/positrons in cosmic rays could be a signal from DM [8].

Meanwhile, all evidence for the existence of DM comes from gravitational interaction, including observations of the rotation curves of galaxies, the Bullet Cluster, gravitationally lensed galaxy clusters, type Ia supernovae, baryonic acoustic oscillations, and anisotropies in the cosmic microwave background [9]. This inspires us to study DM from the perspective of gravity.

Since general relativity is not renormalizable at the quantum level, it is conjectured that the Ricci scalar and curvature tensor could exist in various operators. Nonminimal coupling between the Ricci scalar and other scalar fields could be one type of them [10] [11] [12]. It is found that nonminimal coupling between the Ricci scalar and the scalar DM could be a connection between the DM and the visible sector. However, in many scenarios [13] [14] [15], the decay or annihilation products of DM are not dominated by leptons. Given this, we assume that leptonphilic SU(2) scalar doublets exist in nature as possible mediators connecting DM with the visible sector. Consequently, these leptonphilic SU(2) scalar doublets

could also couple to the Ricci scalar. This work investigates the behaviour of scalar DM under the influence of these nonminimal coupling operators.

This paper is organized as follows. Section 2.1 points out possible nonminimal coupling operators. Section 2.2 describes the discovery that two nonminimal coupling operators acting together can induce DM annihilation through the  $s$ -channel in the Einstein Frame and that the final states of all these channels depend on the properties of a scalar mediator,  $\eta$ . Section 2.3 states assumptions about the properties of  $\eta$  and gives Feynman diagrams of all  $s$ -channels determined by  $\eta$ . Section 2.4 shows that the Breit–Wigner resonance is responsible for the abundance of correct DM relics. Section 3.1 describes the successful fitting of the predicted cosmic electron/positron energy spectrum with DAMPE data. Section 3.2 shows that the number of photons annihilated by DM could satisfy the constraints imposed by the isotropic diffuse  $\gamma$ -ray background (IGRB) observed by Fermi-LAT.

## 2 Dark matter annihilation through nonminimal coupling to gravity

### 2.1 The effective field theory treatment of quantum gravity

Despite the great success of DM research in the framework of general relativity, general relativity is not the correct theory at the quantum level because it is not renormalizable. Hence, general relativity should be regarded as the leading-order term in an effective field theory that describes a more fundamental high-energy theory [10]. Any diffeomorphism-invariant quantum theory of gravity can be described at energies below the reduced Planck scale  $\kappa^{-1} = 2.435 \times 10^{18}$  GeV by an effective theory, whose leading-order terms are:  $-R/2\kappa^2 - c_1 R^2 - c_2 R_{\mu\nu} R^{\mu\nu}$  [10] [11] [12], where  $R$  is the Ricci scalar,  $R_{\mu\nu}$  is the Ricci tensor, and  $c_1$  and  $c_2$  are coupling constants. Because the Higgs boson was found on the Large Hadron Collider, an additional dimension-four operator,  $\mathcal{L} \supset -\xi_h (H^\dagger H) R$ , should be present as the next to leading-order term in the effective theory, where  $H$  represents the Higgs doublet, and  $\xi_h$  is the coupling constant [10]. Similarly, the existence of other scalar fields could also lead to additional dimension-four operators in the effective theory.

Based on the excess of electrons in cosmic rays, this work assumes a leptonphilic SU(2) scalar doublet  $\Phi$  that exists in nature, and that has the same gauge quantum numbers as the Standard Model Higgs doublet. This leptonphilic SU(2) scalar doublet could couple to leptons directly or couple to leptons indirectly through coupling to another leptonphilic field. Consequently, the dimension-four operator  $\mathcal{L} \supset -\xi_\eta (H^\dagger \Phi + \Phi^\dagger H) R$  could be present in the effective theory, where  $\xi_\eta$  is a coupling constant. The scalar DM could also lead to a possible dimension-four operator,  $\mathcal{L} \supset -\xi_\phi \phi^2 R$ , where  $\phi$  represents the scalar singlet DM and  $\xi_\phi$  is a coupling constant [15] [16] [17] [18]. Although some other dimension-four operators could also exist, they are not related to the present work. Higher-dimensional operators are suppressed by  $\kappa$  and can be neglected at low energies.

It has been found that after electroweak symmetry breaking, two dimension-four operators,  $\mathcal{L} \supset -\xi_\eta (H^\dagger \Phi + \Phi^\dagger H) R$  and  $\mathcal{L} \supset -\xi_\phi \phi^2 R$ , act together, which can lead to efficient DM annihilation.

## 2.2 Gravity-induced DM annihilation

The action written in the Jordan Frame is:

$$\mathcal{S}^{(\text{JF})} \supset \int d^4x \sqrt{-g} \left[ -\frac{R}{2\kappa^2} - \xi_\eta (H^\dagger \Phi + h.c.) R - \xi_\phi \phi^2 R + \mathcal{L}_\Phi \right] \quad (2.1)$$

where  $g$  is the determinant of the metric tensor  $g_{\mu\nu}$ ,  $\kappa = \sqrt{8\pi G}$  is the inverse (reduced) Planck mass,  $h.c.$  is the abbreviation of the Hermitian conjugation,  $\mathcal{L}_\Phi = \mathcal{T}_\Phi - m_\Phi^2 \Phi^\dagger \Phi$ , and  $\mathcal{T}_\Phi$  is the kinetic term of the SU(2) doublet  $\Phi$ .

By performing the Weyl transformation of Eq. 2.2 on the metric tensor,  $\Phi$ ,  $H$ , and  $\phi$  can be decoupled from the Ricci scalar in the Einstein Frame [13] [19]:

$$\tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \quad (2.2)$$

where  $\Omega^2 = 1 + 2\kappa^2 \xi_\eta (H^\dagger \Phi + h.c.) + 2\kappa^2 \xi_\phi \phi^2$ . The decoupled action in the Einstein Frame is:

$$\mathcal{S}^{(\text{EF})} \supset \int d^4x \sqrt{-\tilde{g}} \left[ -\frac{\tilde{R}}{2\kappa^2} + \frac{3}{\kappa^2} \frac{\Omega_{,\rho} \tilde{\Omega}^{\rho}}{\Omega^2} + \tilde{\mathcal{L}}_\Phi \right] \quad (2.3)$$

where  $\tilde{\mathcal{L}}_\Phi = \Omega^{-2} \tilde{\mathcal{T}}_\Phi - \Omega^{-4} m_\Phi^2 \Phi^\dagger \Phi$ . In these expressions, all quantities with a tilde are formed from  $\tilde{g}^{\mu\nu}$ . The second term in Eq. 2.3 indicates that gravity could induce DM annihilation.

Working in the unitary gauge, after electroweak symmetry breaking, the scalar fields can be expressed as:

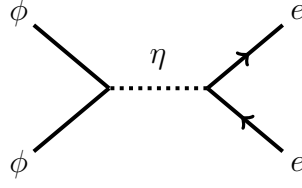
$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \quad \Phi = \begin{pmatrix} \omega^+ \\ \frac{1}{\sqrt{2}}(\eta + iA) \end{pmatrix}, \quad (2.4)$$

where  $v = 246$  GeV is the vacuum expectation value of the Higgs field and  $h$  is the Standard Model Higgs boson. The SU(2) scalar doublet  $\Phi$  contains two charged scalar fields ( $\omega^\pm$ ) and two neutral fields: the CP even scalar  $\eta$  and the CP odd scalar  $A$ . In the unitary gauge, the term  $H^\dagger \Phi + \Phi^\dagger H$  reduces to  $\eta(v + h)$ , so that although  $\Phi$  has four degrees of freedom, only the scalar field  $\eta$  couples to the Ricci scalar.

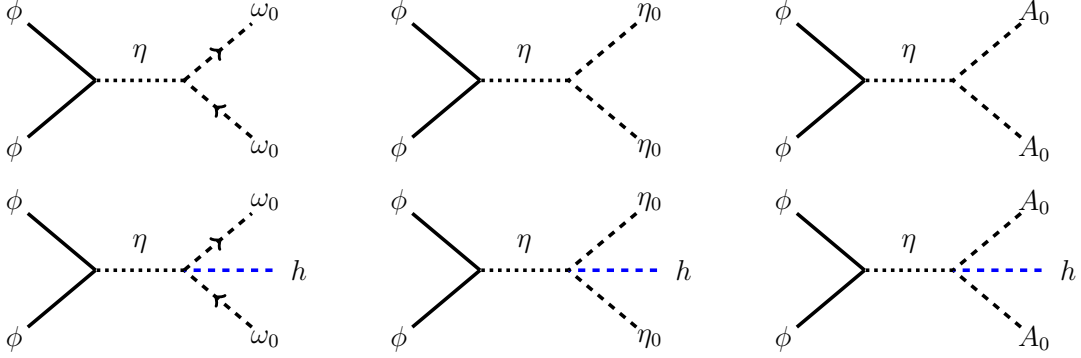
In the Lagrangian in Eq. 2.3, the first focus should be  $3\Omega_{,\rho} \tilde{\Omega}^{\rho}/(\kappa^2 \Omega^2)$ , because it is greatly enhanced by the Planck mass. After electroweak symmetry breaking, it could be expressed as:

$$\begin{aligned} \frac{3}{\kappa^2} \frac{\Omega_{,\rho} \tilde{\Omega}^{\rho}}{\Omega^2} = & \frac{12\kappa^2 \xi_\eta \xi_\phi v}{\Omega^4} \tilde{g}^{\mu\nu} \phi_{\eta,\mu} \phi_{,\nu} + \frac{3\kappa^2 \xi_\eta^2 v^2}{\Omega^4} \tilde{g}^{\mu\nu} \eta_{,\mu} \eta_{,\nu} + \frac{6\kappa^2 \xi_\eta^2 v}{\Omega^4} \tilde{g}^{\mu\nu} (h \eta_{,\mu} + \eta h_{,\mu}) \eta_{,\nu} \\ & + \frac{3\kappa^2}{\Omega^4} \tilde{g}^{\mu\nu} (\xi_\eta h \eta_{,\mu} + \xi_\eta \eta h_{,\mu} + 2\xi_\phi \phi \phi_{,\mu}) \times (\xi_\eta h \eta_{,\nu} + \xi_\eta \eta h_{,\nu} + 2\xi_\phi \phi \phi_{,\nu}). \end{aligned} \quad (2.5)$$

The first term on the right-hand side of Eq. 2.5 shows that the scalar DM can annihilate through the  $s$ -channel,  $\phi\phi \rightarrow \eta \rightarrow \text{final-state particles}$ . The final-state particles of all these channels depend on the properties of the scalar mediator,  $\eta$ . The reason for this exclusive focus on  $s$ -channels will be given in Section 2.4. The second term on the right-hand side of Eq. 2.5 indicates that the scalar field  $\eta$  should be renormalized via  $\eta \rightarrow \zeta \eta$ , with  $\zeta \equiv (1 + 6\xi_\eta^2 v^2 \kappa^2)^{-1/2}$ . In consequence, the mass of  $\eta$  is given by  $m_\eta = \zeta m_\Phi$ , and all the  $\eta$  couplings should be rescaled accordingly [20].



**Figure 1:** Scalar singlet DM annihilates into leptons directly. When  $m_\phi \approx m_\eta/2$ , the channel benefits from Breit–Wigner enhancement. Consequently, DM could leave considerable annihilation products in the cosmic ray.



**Figure 2:** Scalar singlet DM annihilates into leptons indirectly (through  $\omega_0^\pm$ ,  $\eta_0$ ,  $A_0$  and  $h$ ). When  $m_\phi \approx m_\eta/2$ , all channels benefit from Breit–Wigner enhancement. Consequently, DM could leave considerable annihilation products in the cosmic ray.

### 2.3 The properties of the scalar mediator $\eta$ determines the annihilation channels

As mentioned previously, there is an excess of electrons in the cosmic ray, and the annihilation properties of DM depend on the properties of  $\eta$ . Hence, it can be assumed that  $\eta$  couples to leptons directly and indirectly (couples to another leptonphilic field), and the Lagrangian can be split by involving properties of  $\eta$  into direct and indirect parts:

$$\mathcal{L}_{\text{direct}} = \xi_e (\bar{L}_e \Phi e_R + h.c.) \quad (2.6)$$

$$\mathcal{L}_{\text{indirect}} = (\xi_\mu \bar{L}_\mu \Psi \mu_R + \xi_\tau \bar{L}_\tau \Psi \tau_R + \xi_0 H^\dagger \Phi \Psi^\dagger \Psi + h.c.) \quad (2.7)$$

where  $L_e$ ,  $L_\mu$ , and  $L_\tau$  are three generations of SU(2) doublet pairs of leptons,  $e_R$ ,  $\mu_R$ , and  $\tau_R$  are three generations of right-handed leptons,  $\xi_e$ ,  $\xi_\mu$ ,  $\xi_\tau$ , and  $\xi_0$  are coupling constants,  $\Psi$  is a newly introduced leptonphilic SU(2) scalar doublet that also has the same gauge quantum numbers as the Standard Model Higgs doublet,  $\mathcal{L}_\Psi = \mathcal{T}_\Psi - m_0^2 \Psi^\dagger \Psi$ , and  $\mathcal{T}_\Psi$  is the kinetic term of  $\Psi$ . Coupling constants  $\xi_e$ ,  $\xi_\mu$  and  $\xi_\tau$  should be large enough so that lifetime of  $\Phi$  and  $\Psi$  is short enough and does not affect the evolution of the early universe. In the unitary gauge,  $\Psi$  can be expressed as:

$$\Psi = \begin{pmatrix} \omega_0^+ \\ \frac{1}{\sqrt{2}}(\eta_0 + iA_0) \end{pmatrix}. \quad (2.8)$$

Similarly to  $\Phi$ , the SU(2) scalar doublet  $\Psi$  also contains two charged scalar fields ( $\omega_0^\pm$ ) and two neutral fields: the CP even scalar  $\eta_0$  and the CP odd scalar  $A_0$ .

In the Einstein Frame, an action involving properties of  $\eta$  becomes:

$$\mathcal{S}^{(\text{EF})} \supset \int d^4x \sqrt{-\tilde{g}} [(\mathcal{L}_{\text{direct}} + \mathcal{L}_{\text{indirect}}) \frac{1}{\Omega^4} + \tilde{\mathcal{L}}_\Psi] \quad (2.9)$$

where  $\tilde{\mathcal{L}}_\Psi = \Omega^{-2} \tilde{\mathcal{T}}_\Psi - \Omega^{-4} m_0^2 \Psi^\dagger \Psi$ .

After electroweak symmetry breaking, the  $\eta$ -related part of the interaction term  $(\mathcal{L}_{\text{direct}} + \mathcal{L}_{\text{indirect}})/\Omega^4$  in eq. 2.9 simplifies to:

$$\frac{\xi_e \bar{e} \zeta \eta e}{\sqrt{2} \Omega^4} + \xi_0 \zeta \eta (v+h) (\omega_0^+ \omega_0^- + \frac{1}{2} \eta_0^2 + \frac{1}{2} A_0^2) \frac{1}{\Omega^4} = \frac{\xi_e \bar{e} \zeta \eta e}{\sqrt{2}} + \xi_0 \zeta \eta (v+h) (\omega_0^+ \omega_0^- + \frac{1}{2} \eta_0^2 + \frac{1}{2} A_0^2) + \mathcal{O}(\kappa^2) \quad (2.10)$$

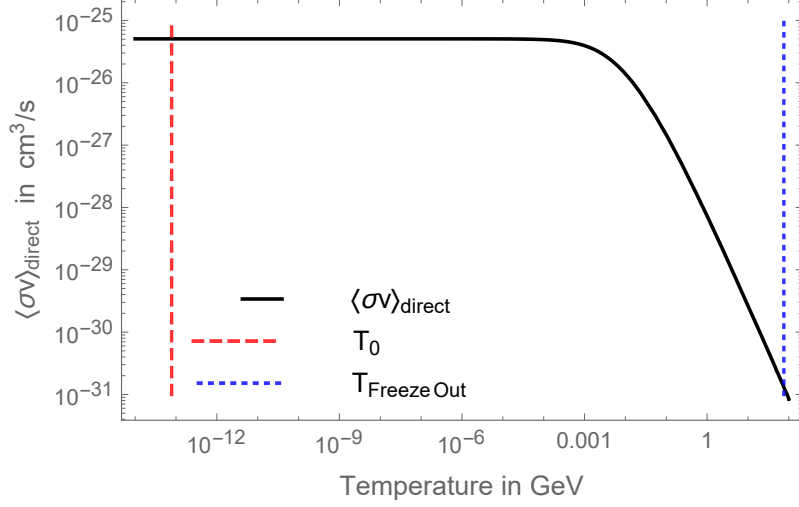
where  $e = e_R + e_L$ ,  $e_L$  is the left-handed lepton. By reading off from Eqs. 2.5 and 2.10, Feynman diagrams can be drawn of the direct and indirect annihilation channels and are shown in Figures 1 and 2 respectively. Note that only  $s$ -channels are included.

## 2.4 Breit–Wigner resonance

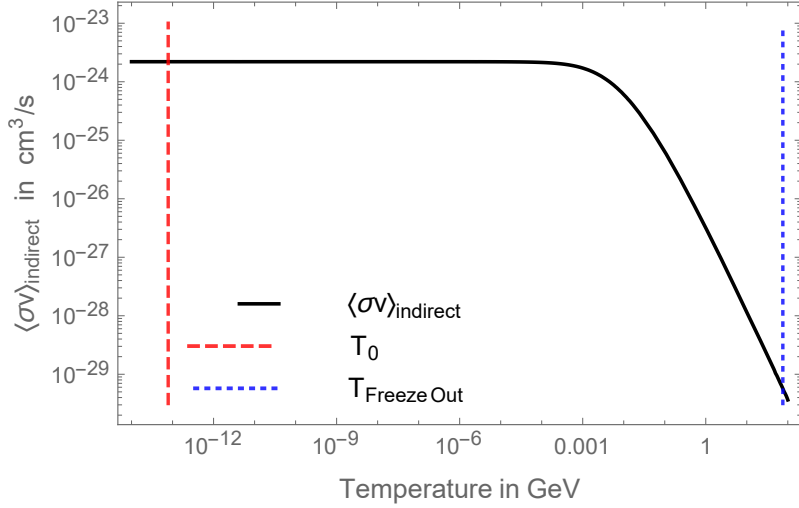
An important problem is that the thermal average annihilation cross-section needed to explain the excess of electrons/positrons in the cosmic ray is much larger than the canonical thermal DM annihilation cross section [8]. Fortunately, when the mass of the scalar DM is about half the mass of the mediator  $\eta$ , the annihilation cross-section of all  $s$ -channels is greatly improved due to Breit–Wigner resonance. Breit–Wigner resonance is the phenomenon that when two particles annihilate through the  $s$ -channel, if the total energy of the center-of-mass frame is close to the mass of the propagator, the annihilation cross-section will be greatly enhanced [21] [22].

Figures 3 and 4 show how the thermal average annihilation cross-section of the direct channels in Figure 1 (denoted by  $\langle \sigma v \rangle_{\text{direct}}$ ) and that of the indirect channels in Figure 2 (denoted by  $\langle \sigma v \rangle_{\text{indirect}}$ ) change with DM temperature when the mass of the propagator  $\eta$  is  $m_\eta = 3027.19$  GeV and the mass of DM is  $m_\phi = 1513.6$  GeV. Compared with the freeze-out epoch, the current thermal average annihilation cross-section of DM has been greatly improved. This is why the focus on Feynman diagrams of  $s$ -channels in Section 2.2 was maintained. In this case, the annihilation of DM particles is quite efficient, and the DM annihilation products can be observed in cosmic rays.

It is worth explaining the rationale for the large coupling constants  $\xi_\eta$  and  $\xi_\phi$ . Because non-zero  $\xi_\eta$  and  $\xi_\phi$  do not destroy any symmetries of the Standard Model, the dimensionless coupling constants  $\xi_\eta$  and  $\xi_\phi$  have no preferred natural values [10] [19] [20]. In the Feynman vertices,  $\xi_\eta$  and  $\xi_\phi$  are always suppressed by the inverse Planck mass. Hence, a large  $\xi_\eta$  and  $\xi_\phi$  are acceptable as long as they satisfy the perturbation expansion.



**Figure 3:** Dependence of DM thermal average annihilation cross section  $\langle\sigma v\rangle_{\text{direct}}$  on DM temperature when  $\xi_\eta\xi_\phi\xi_e\zeta^2 = 4.38 \times 10^{24}$  (e.g.,  $\xi_e = 4.38 \times 10^{-4}$ ,  $\xi_\phi = 10^{14}$ ,  $\xi_\eta = 10^{14}$ ),  $m_\phi = 1513.6$  GeV,  $m_\eta = 3027.19$  GeV. The temperature of the freeze-out epoch has been marked as  $T_{\text{Freeze Out}}$  and the current DM temperature as  $T_0$ .



**Figure 4:** Dependence of the DM thermal average annihilation cross section  $\langle\sigma v\rangle_{\text{indirect}}$  on DM temperature when  $\xi_\eta\xi_\phi\xi_0\zeta^2 = 2.34 \times 10^{26}$  (e.g.,  $\xi_0 = 2.34 \times 10^{-2}$ ,  $\xi_\phi = 10^{14}$ ,  $\xi_\eta = 10^{14}$ ),  $m_\phi = 1513.6$  GeV,  $m_\eta = 3027.19$  GeV,  $m_0 = 600$  GeV. The temperature of the freeze-out epoch has also been marked as  $T_{\text{Freeze Out}}$  and the current DM temperature as  $T_0$ .

### 3 Application

#### 3.1 Interpretation of the cosmic electron/positron excess

The analysis in Section 2 shows that DM could annihilate through a gravity portal and could leave signals in electron/positron cosmic rays. The latest exploration of the cosmic electron/positron energy spectrum was performed by DAMPE [7]; their data show a broad excess in the energy spectrum up to TeV energy and a possible line structure at about 1.4 TeV. Because DAMPE does not discriminate positrons from electrons, "electron" is used hereafter to denote electron/positron. Assuming that there exists a DM sub-halo near the solar system, many groups use specific DM models to explain cosmic electron and positron excess [21] [23] [24] [25] [26] [27]. In the same way, the model proposed here can also explain the broad excess and resonance at around 1.4 TeV on the cosmic electron energy spectrum. If the DM halo has a Navarro–Frenk–White (NFW) distribution [28] [29], then the energy density of DM is:

$$\rho(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}. \quad (3.1)$$

The following parameters were adopted for the sub-halo:  $\gamma = 0.5$ ,  $\rho_s = 100 \text{ GeV/cm}^3$ , and  $r_s = 0.1 \text{ kpc}$ . It was assumed that the distance between the sub-halo centre and the solar system was  $d_s = 0.3 \text{ kpc}$ . The following parameters were adopted for the Milky Way halo:  $\gamma = 1$ ,  $\rho_s = 0.184 \text{ GeV/cm}^3$ , and  $r_s = 24.42 \text{ kpc}$ . It was further assumed that the distance between the Milky Way halo centre and the solar system is  $r_\odot = 8.33 \text{ kpc}$ .

The mass of the scalar DM was fixed as  $m_\phi = 1513.6 \text{ GeV}$ , the mass of the scalar mediator as  $m_\eta = 3027.19 \text{ GeV}$ , and the mass of particles from  $\Psi$  as  $m_0 = 600 \text{ GeV}$ . Note that three dimensionless coefficients,  $\xi_\phi$ ,  $\xi_\eta$ , and  $\xi_e$ , together determine  $\langle\sigma v\rangle_{\text{direct}}$ , whereas another set of three dimensionless coefficients,  $\xi_\phi$ ,  $\xi_\eta$ , and  $\xi_0$ , determines  $\langle\sigma v\rangle_{\text{indirect}}$ .

The total cosmic electron flux includes three major contributions:

$$F^{\text{total}} = F^{\text{BG}} + F^{\text{SH}} + F^{\text{MW}} \quad (3.2)$$

where  $F^{\text{BG}}$  is the cosmic ray background,  $F^{\text{SH}}$  is the contribution of the DM sub-halo, and  $F^{\text{MW}}$  is the contribution of the Milky Way DM halo. It is assumed that the cosmic ray background follows a single power-law  $F^{\text{BG}} = CE^{-\alpha}$ . Using the first eight points and the last eight points of the DAMPE data, one can obtain the following best-fitting parameters:  $C = 458 (\text{GeV m}^2 \text{ s sr})^{-1}$  and  $\alpha = 3.25$ , where  $E$  represents the energy of the electrons [21]. Green's function method [21] [30], was used to calculate the contribution of the DM sub-halo to the cosmic electron flux  $F^{\text{SH}}$  and the contribution of the DM Milky Way halo to the cosmic electron flux  $F^{\text{MW}}$ :

$$F^{\text{SH}}(\vec{x}, E) + F^{\text{MW}}(\vec{x}, E) = \frac{v_e}{4\pi} \int d^3x_s \int dE_s G(\vec{x}, E; \vec{x}_s, E_s) Q(\vec{x}_s, E_s) \quad (3.3a)$$

$$Q(\vec{x}_s, E_s) = \frac{1}{4} \frac{\rho_\phi^2(\vec{x}_s)}{m_\phi^2} \langle\sigma v\rangle \frac{dN}{dE_s}(E_s) \quad (3.3b)$$

$$G(\vec{x}, E; \vec{x}_s, E_s) = \frac{1}{b(E)} (\pi\lambda^2)^{-3/2} e^{-\frac{(\vec{x}-\vec{x}_s)^2}{\lambda^2}} \quad (3.3c)$$



$$\lambda^2 = 4 \int_E^{E_s} dE' D(E')/b(E') \quad (3.3d)$$

where the subscript  $s$  indicates the quantities associated with the DM source and  $b(E) = b_0(E/\text{GeV})^2$  is the energy loss coefficient. The main energy losses are from synchrotron radiation and inverse Compton scattering at energies  $E > 10$  GeV,  $b_0 = 10^{-16}$  GeV/s,  $D(E) = D_0(E/\text{GeV})^\delta$  is the diffusion coefficient,  $D_0 = 11$  pc<sup>2</sup>/kyr and  $\delta = 0.7$ ,  $v_e$  is the velocity of the electrons,  $\rho_\phi(\vec{x}_s)$  is the DM mass density, and  $dN/dE_s$  is the energy spectrum of electrons per DM annihilation. The results show that the contribution of the Milky Way halo to the cosmic electron flux between 500 GeV and 1500 GeV is two orders of magnitude smaller than the contribution of the DM sub-halo.

The specific calculation of these three major contributions must obtain the electron spectrum per DM annihilation at initial production. The challenge is extracting the electron spectrum per DM annihilation from the Higgs, muon, tau, and primary electron spectra per DM annihilation. Let us use the Higgs boson to illustrate; it is similar for the muon, tau, and the primary electron spectrum. Marco Cirelli et al. [31] used PYTHIA to generate the spectrum of electrons induced by a Higgs boson with given energy  $E_h$ :  $dN/dE(E_h)$ , where  $E$  represents the energy of an electron. The effect of quantum electrodynamics and electroweak Bremsstrahlung are included when they use PYTHIA to generate  $dN/dE(E_h)$  [31]. Using their results, the energy spectrum of electrons contributed by Higgs bosons per DM annihilation in indirect channels can be numerically calculated as:

$$(\frac{dN}{dE})_h = \int \frac{dN}{dE}(E_h) \frac{dN_h}{dE_h} dE_h \quad (3.4)$$

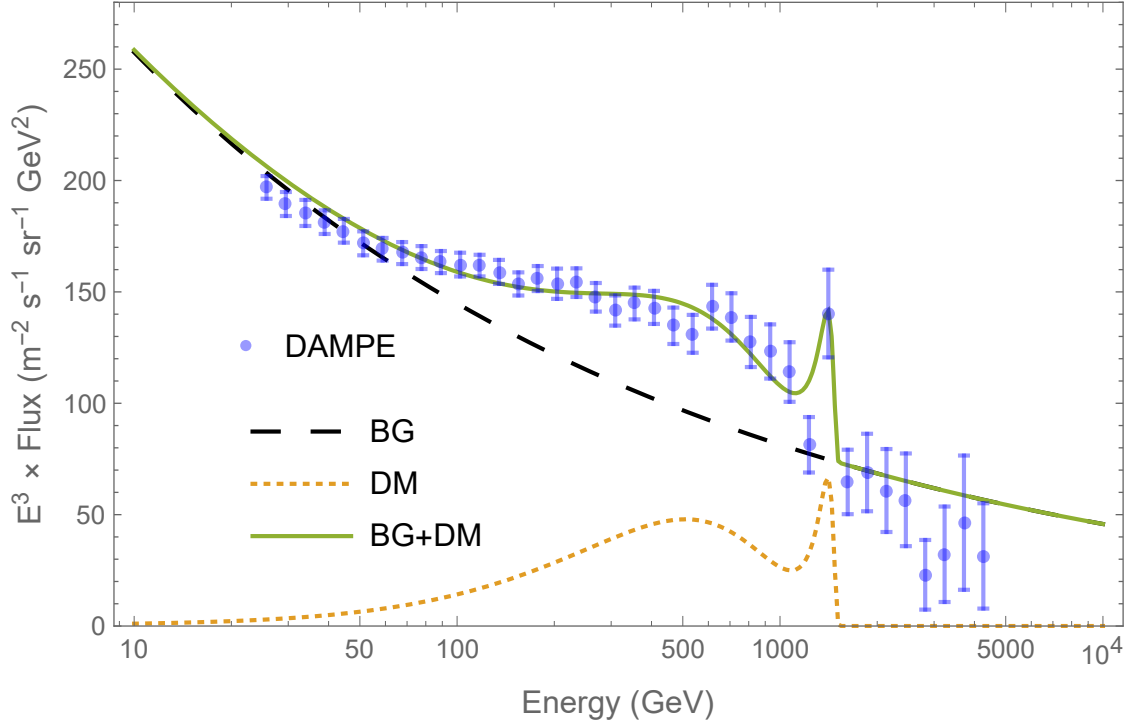
where  $dN_h/dE_h$  is the primary energy spectrum of the Higgs bosons per DM annihilation.

A  $\chi^2$  analysis was carried out as follows:

$$\chi^2 = \sum_i \frac{[F_i^{\text{total}}(\langle E \rangle_i^{\text{exp}}) - F_i^{\text{exp}}]^2}{\delta_i^2} \quad (3.5)$$

where  $F_i^{\text{exp}}(\delta_i)$  is the electron flux (uncertainty) of the  $i$ -th bin as reported by DAMPE and  $\langle E \rangle_i^{\text{exp}}$  is the representative value of the energy in the  $i$ -th bin.

The  $\chi^2$  test was used to determine certain parameters. The decay property of  $\Psi$  is characterized by  $\xi_\mu$  and  $\xi_\tau$ .  $\xi_\mu \neq 0$  means that  $\Psi$  can decay into the second generation of leptons, whereas  $\xi_\tau \neq 0$  means that  $\Psi$  can decay into the third generation of leptons. The  $\chi^2$  test was used to find the ratio of decay between the second and third generations of leptons, characterized by  $\xi_\mu/\xi_\tau$ . The result was  $\xi_\mu/\xi_\tau = 0.84$ , which means that 41% of  $\Psi$  decays into the second generation of leptons. The  $\chi^2$  test was also used to determine  $\xi_\phi \xi_\eta \xi_0 \zeta^2$  and  $\xi_\phi \xi_\eta \xi_e \zeta^2$ . The result was  $\xi_\phi \xi_\eta \xi_0 \zeta^2 = 2.34 \times 10^{26}$  (e.g.,  $\xi_0 = 2.34 \times 10^{-2}$ ,  $\xi_\phi = 10^{14}$ ,  $\xi_\eta = 10^{14}$ ), and  $\xi_\phi \xi_\eta \xi_e \zeta^2 = 4.38 \times 10^{24}$  (e.g.,  $\xi_e = 4.38 \times 10^{-4}$ ,  $\xi_\phi = 10^{14}$ ,  $\xi_\eta = 10^{14}$ ). Consequently, the  $\langle \sigma v \rangle_{\text{direct}}$  ( $\phi, \phi \rightarrow e^+, e^-$  channel) was  $5 \times 10^{-26}$  cm<sup>3</sup>/s, and the  $\langle \sigma v \rangle_{\text{indirect}}$  of all channels was  $2.2 \times 10^{-24}$  cm<sup>3</sup>/s. Among the channels of  $\langle \sigma v \rangle_{\text{indirect}}$ , 79.5% were two-body final states, and 20.5% were three-body final states. The broad excess was mainly contributed by  $\langle \sigma v \rangle_{\text{indirect}}$ , and the resonance was mainly contributed by  $\langle \sigma v \rangle_{\text{direct}}$ . The fitting result is shown in Figure 5.



**Figure 5:** Cosmic ray electron spectrum (multiplied by  $E^3$ ). The blue points with error bars are the flux measured by DAMPE. The dashed line shows the cosmic electron background (BG). The dotted line shows the flux contributed by DM. The solid line represents total cosmic electron flux. In the figure, it is assumed that  $d_s = 0.3$  kpc,  $\xi_\eta \xi_\phi \xi_e \zeta^2 = 4.38 \times 10^{24}$ ,  $\xi_\eta \xi_\phi \xi_0 \zeta^2 = 2.34 \times 10^{26}$ ,  $m_\phi = 1513.6$  GeV,  $m_\eta = 3027.19$  GeV,  $m_0 = 600$  GeV,  $\xi_\mu/\xi_\tau = 0.84$ . (The resulting velocity averaged cross section are  $\langle\sigma v\rangle_{\text{direct}} = 5 \times 10^{-26}$  cm<sup>3</sup>/s, and  $\langle\sigma v\rangle_{\text{indirect}} = 2.2 \times 10^{-24}$  cm<sup>3</sup>/s.)

### 3.2 Constraints from the isotropic diffuse $\gamma$ -ray background

The IGRB is measured by Fermi-LAT [32]. The  $\gamma$ -ray flux produced by DM was then compared with IGRB. The analysis of IGRB by Fermi-LAT included only high latitudes ( $|b| > 20^\circ$ ) [32].

The  $\gamma$ -ray flux that can be detected by Fermi-LAT as originating from DM is:

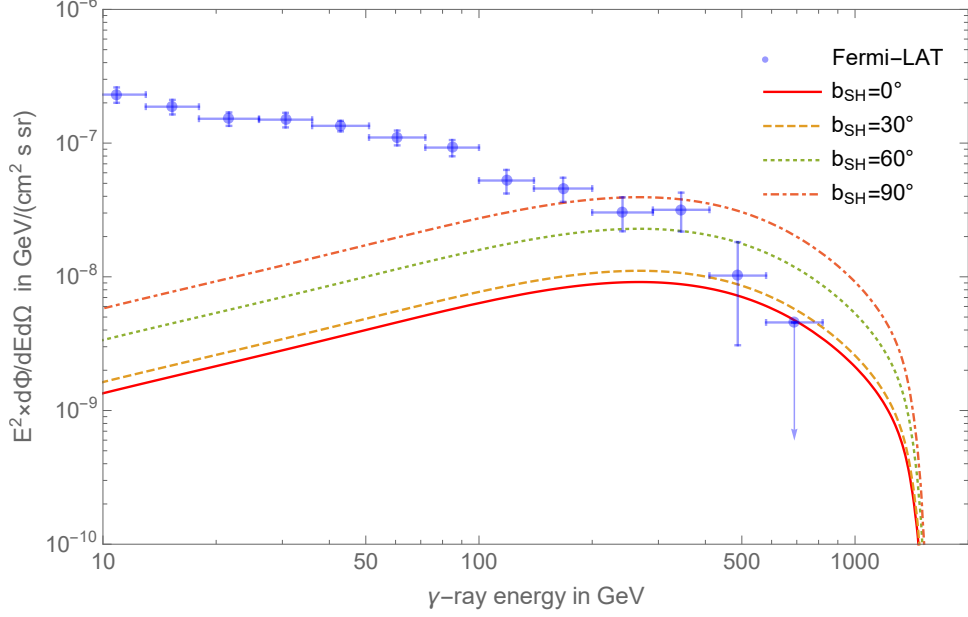
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\phi^2} \left(\frac{dN_\gamma}{dE_\gamma}\right) \bar{J} \quad (3.6)$$

where  $dN_\gamma/dE_\gamma$  is the energy spectrum of photons per DM annihilation,  $\bar{J} = J(\Delta\Omega)/\Delta\Omega$  is the averaged J-factor over the region of analysis, and  $\Delta\Omega$  is the solid angle.

The averaged J-factor was then calculated over the analyzed region ( $|b| > 20^\circ$ ):

$$\bar{J} = \frac{\int ds \int_{|b|>20^\circ} db dl \cos b \rho_\phi^2}{\int_{|b|>20^\circ} db dl \cos b} \quad (3.7)$$

where  $b$  is the galactic latitude,  $l$  is the galactic longitude,  $s$  is the distance away from the solar system, and  $\rho_\phi$  is the DM density. The J-factor of the sub-halo is  $6 \times 10^{21}$  GeV<sup>2</sup>/cm<sup>5</sup>



**Figure 6:** IGRB (multiplied by  $E^2$ ). The blue points with error bars are the flux measured by Fermi-LAT. The sub-halo is  $d_s = 0.3$  kpc away from the Sun. The galactic latitude varies:  $b_{\text{SH}} = \{0^\circ, 30^\circ, 60^\circ, 90^\circ\}$ .

when  $b_{\text{SH}} = 0^\circ$ , where  $b_{\text{SH}}$  denotes the galactic latitude of the centre of the sub-halo. The J-factor of the sub-halo is  $8 \times 10^{21} \text{ GeV}^2/\text{cm}^5$  when  $b_{\text{SH}} = 30^\circ$ . The J-factor of the sub-halo is  $2 \times 10^{22} \text{ GeV}^2/\text{cm}^5$  when  $b_{\text{SH}} = 60^\circ$ . The J-factor of the sub-halo is  $3.74 \times 10^{22} \text{ GeV}^2/\text{cm}^5$  when  $b_{\text{SH}} = 90^\circ$ . The J-factor of the Milky Way halo is  $3.48 \times 10^{21} \text{ GeV}^2/\text{cm}^5$ .

When calculating the photon spectrum per DM annihilation at production,  $dN_\gamma/dE_\gamma$ , the challenge is to extract the photon spectrum per DM annihilation from the Higgs, muon, tau, and primary electron spectra per DM annihilation. Let us take the Higgs boson to illustrate; it is similar for the muon, tau, and the primary electron spectrum. Marco Cirelli et al. [31] used PYTHIA to generate the spectrum of photons induced by a Higgs boson with given energy  $E_h$ :  $dN_\gamma/dE_\gamma(E_h)$ , where  $E_\gamma$  represents the energy of a photon. When calculating the induced  $\gamma$ -ray fluxes, only all photons in final-state showers or hadron decays as given by PYTHIA were included, as well as those from quantum electrodynamics and electroweak Bremsstrahlung, whereas radiation from inverse Compton processes or synchrotron radiation from  $e^\pm$  was not included [31]. Using their results, the photon spectrum contributed by Higgs bosons per DM annihilation can be numerically calculated as:

$$\left(\frac{dN_\gamma}{dE_\gamma}\right)_h = \int \left(\frac{dN_\gamma}{dE_\gamma}\right)(E_h) \frac{dN_h}{dE_h} dE_h \quad (3.8)$$

where  $dN_h/dE_h$  is the primary energy spectrum of Higgs bosons per DM annihilation.

As shown in Figure 6, the  $\gamma$ -ray flux produced by DM satisfies the IGRB (observed by Fermi-LAT) constraint when the center of the DM sub-halo is on the galactic plane ( $b_{\text{SH}} = 0^\circ$ ).

## 4 Conclusions

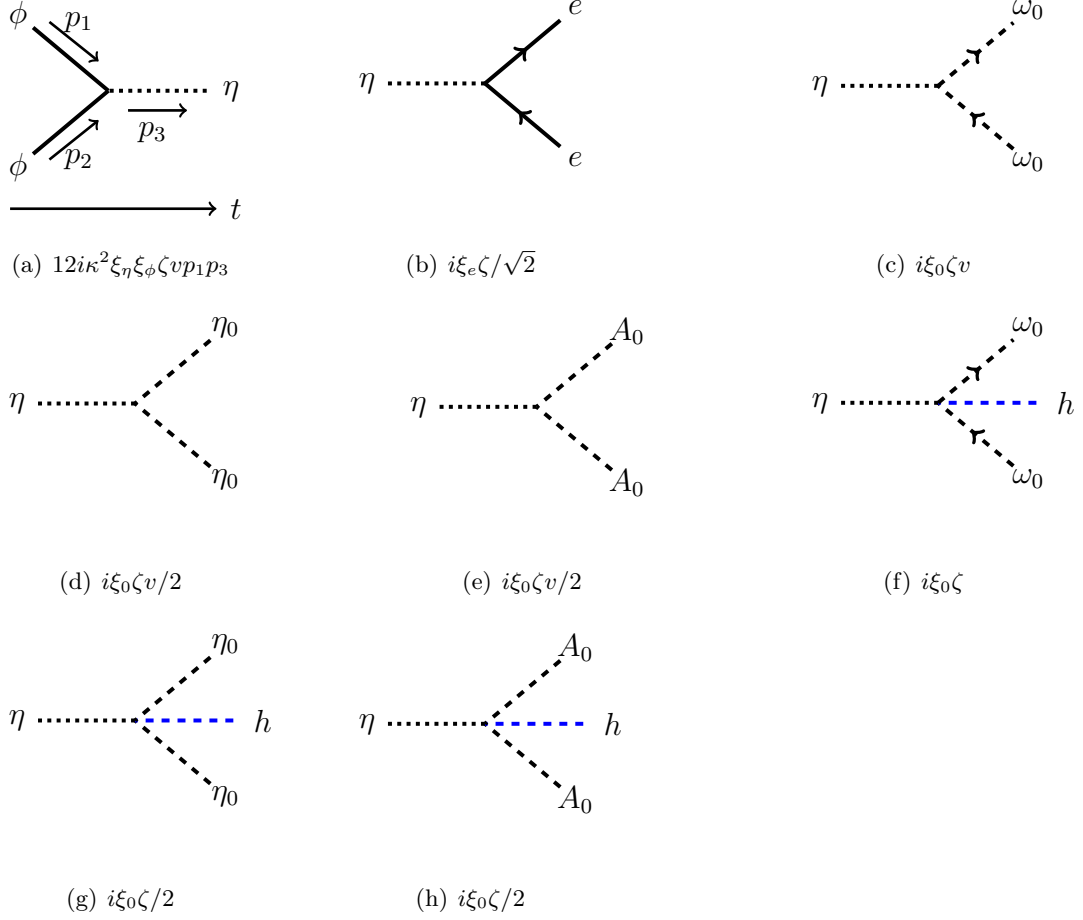
The fact that all evidence for the existence of DM comes from gravitational interaction inspired us to study DM from the perspective of gravity. General relativity has been of great success in describing gravitational interaction, but it is not renormalizable. Because general relativity is not the correct theory at the quantum level, an effective quantum theory of gravity is needed at energies below the reduced Planck scale. The existence of scalar fields, including scalar DM, the Higgs boson, and the newly introduced leptonphilic SU(2) scalar doublet  $\Phi$ , could lead to possible nonminimal coupling dimension-four operators in the effective theory.

This paper has considered the behaviour of scalar DM under these nonminimal coupling operators. It was determined that the operators  $\mathcal{L} \supset -\xi_\eta(H^\dagger\Phi + \Phi^\dagger H)R$  and  $\mathcal{L} \supset -\xi_\phi\phi^2 R$  act together, which can lead to efficient  $s$ -channel DM annihilation:  $\phi\phi \rightarrow \eta \rightarrow \text{final-state particles}$ . The final-state particles of all these channels depend on the properties of the scalar mediator,  $\eta$ . It is assumed that  $\eta$  can decay into the first generation of leptons directly. The annihilation channel related to this property is called the direct channel. It is also assumed that  $\eta$  can decay into the second and third generation of leptons through coupling to another leptonphilic SU(2) scalar doublet  $\Psi$ . The annihilation channels related to this property are called indirect channels.

After electroweak symmetry breaking, the DM thermal average annihilation cross-section is greatly improved when the mass of DM is about half the electrophilic scalar  $\eta$  due to Breit–Wigner resonance. Breit–Wigner resonance explains why the thermal average annihilation cross-section needed to obtain the correct excess in the cosmic electron/positron energy spectrum reported by DAMPE is many orders of magnitude larger than that needed to obtain the correct DM relic abundance.

By assuming a nearby DM sub-halo and choosing suitable parameters for the model and the DM sub-halo, the predicted cosmic electron/positron energy spectrum fits the spectrum reported by DAMPE quite well. The broad excess in the cosmic electron/positron energy spectrum up to TeV energy is mainly contributed by indirect channels. The line structure at about 1.4 TeV is mainly contributed by direct channels. The  $\gamma$ -ray flux produced by DM cannot exceed the IGRB as reported by Fermi-LAT. It was found that when the center of the DM sub-halo is on the galactic plane, that constraint can be satisfied.

## A Vertex rules in the Einstein Frame



**Figure 7:** Vertex rules in Einstein Frame

## References

- [1] M. A. DuVernois et al., *Cosmic-Ray Electrons and Positrons from 1 to 100 GeV: Measurements with HEAT and Their Interpretation*, [\*ApJ\* \*\*559\*\* \(2001\) 296](#).
- [2] J. Chang et al., *An excess of cosmic ray electrons at energies of 300-800 GeV*, [\*Nature\* \*\*456\*\* \(2008\) 362-365](#).
- [3] O. Adriani et al., *Cosmic-Ray Electron Flux Measured by the PAMELA Experiment between 1 and 625 GeV*, [\*Phys. Rev. Lett.\* \*\*106\*\* \(2011\) 201101](#). [arxiv:1103.2880](#)
- [4] **Fermi LAT** Collaboration, *Measurement of the Cosmic Ray  $e^+ + e^-$  Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope*, [\*Phys. Rev. Lett.\* \*\*102\*\* \(2009\) 181101](#). [arxiv:0905.0025](#)
- [5] The **Fermi-LAT** Collaboration, *Cosmic-ray electron-positron spectrum from 7 GeV to 2 TeV with the Fermi Large Area Telescope*, [\*Phys. Rev. D\* \*\*95\*\* \(2017\) 082007](#). [arxiv:1704.07195](#)

- [6] **AMS** Collaboration, *Precision Measurement of the  $(e^+ + e^-)$  Flux in Primary Cosmic Rays from 0.5 GeV to 1 TeV with the Alpha Magnetic Spectrometer on the International Space Station*, *Phys. Rev. Lett.* **113** (2014) 221102.
- [7] **DAMPE** Collaboration, *Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons*, *Nature* **552** (2017) 63-66. [arxiv:1711.10981](#)
- [8] Hong-Bo Jin, Bin Yue, Xin Zhang and Xuelei Chen, *Dark matter explanation of the cosmic ray  $e^+e^-$  spectrum excess and peak feature observed by the DAMPE experiment*, *Phys. Rev. D* **98** (2018) 123008. [arxiv:1712.00362v3](#)
- [9] Maxim Khlopov, *Cosmoparticle physics of dark matter*, *EPJ Web Conf.* **222** (2019) 01006. [arxiv:1910.12910v1](#)
- [10] Michael Atkins and Xavier Calmet, *Bounds on the Nonminimal Coupling of the Higgs Boson to Gravity*, *Phys. Rev. Lett.* **110** (2013) 051301. [arxiv:1211.0281](#).
- [11] J. F. Donoghue, *General relativity as an effective field theory: The leading quantum corrections*, *Phys. Rev. D* **50** (1994) 3874-3888. [arxiv:gr-qc/9405057](#).
- [12] J. F. Donoghue, *The effective field theory treatment of quantum gravity*, *AIP Conf. Proc.* **1483** (2012) 73. [arxiv:1209.3511](#).
- [13] O. Catà, A. Ibarra, and S. Inghenütt, *Dark Matter Decays from Nonminimal Coupling to Gravity*, *Phys. Rev. Lett.* **117** (2016) 021302. [arxiv:1603.03696](#).
- [14] O. Catà, A. Ibarra, and S. Inghenütt, *Dark matter decay through gravity portals*, *Phys. Rev. D* **95** (2017) 035011. [arxiv:1611.00725v2](#)
- [15] Gonzalo, Alonso-Álvarez and Joerg Jaeckel, *Lightish but clumpy: scalar dark matter from inflationary fluctuations*, *JCAP* **10** (2018) 022. [arxiv:1807.09785](#)
- [16] Catarina Cosme, João G. Rosa and O. Bertolami, *Scale-invariant scalar field dark matter through the Higgs portal*, *JHEP* **05** (2018) 129. [arxiv:1802.09434](#)
- [17] Wei Cheng and Ligong Bian, *From inflation to cosmological electroweak phase transition with a complex scalar singlet*, *Phys. Rev. D* **98** (2018) 023524. [arxiv:1801.00662](#)
- [18] Wei Cheng, Ligong Bian, *From inflation to cosmological electroweak phase transition with a complex scalar singlet*, *Phys. Rev. D* **99** (2019) 035038. [arxiv:1805.00199](#)
- [19] Jing Ren, Zhong-Zhi Xianyu and Hong-Jian He, *Higgs gravitational interaction, weak boson scattering, and Higgs inflation in Jordan and Einstein frames*, *JHEP* **06** (2014) 032. [arxiv:1404.4627](#)
- [20] Zhong-Zhi Xianyu and Jing Ren and Hong-Jian He, *Gravitational interaction of Higgs boson and weak boson scattering*, *Phys. Rev. D* **88** (2013) 096013. [arxiv:1305.0251](#).
- [21] Xuwen Liu, Zuowei Liu and Yushan Su, *Two-mediator dark matter models and cosmic electron excess*, *JHEP* **06** (2019) 109. [arxiv:1902.04916v1](#)
- [22] Daniel Feldman, Zuowei Liu, and Pran Nath, *PAMELA positron excess as a signal from the hidden sector*, *Phys. Rev. D* **79** (2009) 063509. [arxiv:0810.5762](#).
- [23] K. Ghorbani and P. H. Ghorbani, *DAMPE electron-positron excess in leptophilic  $Z'$  model*, *JHEP* **05** (2018) 125. [arxiv:1712.01239v4](#)
- [24] J. Cao et al., *Explaining the DAMPE data with scalar dark matter and gauged  $U(1)_{L_e-L_\mu}$  interaction*, *Eur. Phys. J. C* **78** (2018) 198. [arxiv:1712.01244v4](#)

- [25] J. Cao et al., *Scalar dark matter interpretation of the DAMPE data with  $U(1)$  gauge interactions*, *Phys. Rev. D* **97** (2018) 095011. [arxiv:1711.11452](#)
- [26] N. Okada and O. Seto, *DAMPE excess from decaying right-handed neutrino dark matter*, *Mod. Phys. Lett. A* **33** (2018) 1850157. [arxiv:1712.03652](#)
- [27] T. Li, N. Okada and Q. Shafi, *Scalar dark matter, type II seesaw and the DAMPE cosmic ray  $e^+ + e^-$  excess*, *Phys. Lett. B* **779** (2018) 130-135. [arxiv:1712.00869](#)
- [28] Julio F. Navarro, Carlos S. Frenk and Simon D.M. White, *The Structure of cold dark matter halos*, *Astrophys. J.* **462** (1996) 563–575. [arxiv:astro-ph/9508025](#)
- [29] Julio F. Navarro, Carlos S. Frenk and Simon D.M. White, *A Universal Density Profile from Hierarchical Clustering*, *Astrophys. J.* **490** (1997) 493–508. [arxiv:astro-ph/9611107](#)
- [30] M. Kuhlen and D. Malyshev, *ATIC, PAMELA, HESS, and Fermi data and nearby dark matter subhalos*, *Phys. Rev. D* **79** (2009) 123517. [arxiv:0904.3378](#)
- [31] M. Cirelli, G. Corcella, A. Hektor, G. Hütsi, M. Kadastik, P. Panci, M. Raidal, F. Sala and A. Strumia, *PPPC 4 DM ID: a poor particle physicist cookbook for dark matter indirect detection*, *JCAP* **03** (2011) 051. [arxiv:1012.4515](#)
- [32] M. Ackermann et al., *The spectrum of isotropic diffuse gamma-ray emission between 100 MeV and 820 GeV*, *Astrophys. J.* **799(1)** (2015) 86. [arxiv:1410.3696](#).