A Democratic Gauge Model for Dark/Visible Matter Symmetry

O. Oliveira*,†, C. A. Bertulani‡, M. S. Hussein∥, W. de Paula* and T. Frederico*

†Departamento de Física, Universidade de Coimbra, 3004-516 Coimbra, Portugal
‡ Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce TX 75429, USA
∥ Instituto de Física, Universidade de São Paulo, Caixa Postal 66318, 05314-970 São Paulo, SP, Brazil
*Departamento de Física, Instituto Tecnológico de Aeronáutica, DCTA 12.228-900, São José dos Campos, SP, Brazil

Abstract

We develop a model for visible matter-dark matter interaction based on the exchange of a weakly interacting massive gauge boson called herein the WIMG. Our model hinges on the assumption that all known particles in the visible matter have their counterparts in the dark matter. We postulate six families of particles five of which are dark. This leads to the unavoidable postulation of six parallel worlds, the visible one and five invisible worlds. We give arguments on particle decays and lifetimes that set a limit on the mass of the WIMG, the gray boson responsible for the very meager communication among these worlds. The 5:1 ratio of dark to visible matter is taken for granted.

Key words: Dark Matter, Weakly Interacting Massive Particles, Parallel Universes

It is widely accepted that our Universe is composed of 70% Dark Energy (DE), 25% Dark Matter (DM) and only about 5% Visible Matter (VM). The existence of the DM and the DE is inferred to through observation made on the VM (galaxies, black holes) or, in the latter case, to cosmological consequences of having a negative pressure in the equation of state (the cosmological constant problem). The interaction between DM and DE, and DM and VM have received a great deal of attention over the last decades (see e.g. [1,2,3] and references therein). In particular the latter interaction has evoked new scenarios that go beyond the Standard Model, such as the existence of Weakly Interacting Massive Particles (WIMPs), Sterile Neutrinos, Axions, etc. The
discovery of any of these will constitute a most important input to our under-
standing of the nature of DM. Experimental limits on the interaction and
masses of WIMPs inferred through recoil measurement of nuclear targets
are now available [4,5,6,7,8,9,10]. More work is required though, to bett-
er our understanding of how the VM particles interact with the DM counter-
parts [11,12].

The ratio of DM to VM inspired us to pursue a new venue which lead to the
present work. We develop a model which assumes that for each charge family
of particles in the VM there are a corresponding 5 charge families of Dark
particles in the 5 parallel universes of the DM. Namely, one of them is our
visible universe which is composed of two charge families of quarks, u, c, and
t of charge 2e/3; d, s and b, of charge -e/3; the leptons and their correspond-
ing neutrinos. The other five universes contain only DM in similar two charge
families of dark quarks, u_d, d_d, c_d, d_d, t_d of charge 2e/3, d_d, s_d, b_d, of charge -e/3; lep-
tons, e_d, μ_d and τ_d, and dark neutrinos. Dark photons can only interact with
the Dark charges. The weakly interacting massive gauge boson responsible for
the new force between these parallel universes is baptized as the WIMG. The
current Letter describes the above six-parallel-universe picture of the inter-
action between DM and VM. Several consequences of the possible existence
of the WIMG boson are looked at through calculation of the lepton anomalous
magnetic moments (which sets a bound on the WIMG mass of several
hundreds GeVs), lepton flavor violation processes, μ, and β decays of D and
B mesons, and the SM tree level forbidden process e^+ + p → μ^+ + Λ, or Λ_c,
allowed through a WIMG exchange in our model. In the following we give a
detailed account of our DM-VM 6 parallel Universes model.

The gauge theory includes the spin-1 WIMG field M_μ, the matter fields Q_f,
where f is a flavor index, and a scalar field φ_a belonging to the adjoint repre-
sentation of SU(3) color group. As in the Standard Model, the scalar field is
required to provide a mass to M_μ to ensure that the WIMG interaction is of
short distance. In this way, new contributions to the long distance nature of
the gravitational force are avoided.

In what concerns the matter fields, the visible multiplets are

\[
Q_1 = \begin{pmatrix}
  u \\
  c \\
  t 
\end{pmatrix}, \quad Q_2 = \begin{pmatrix}
  d \\
  s \\
  b 
\end{pmatrix}, \quad Q_3 = \begin{pmatrix}
  e \\
  \mu \\
  \tau 
\end{pmatrix}, \quad Q_4 = \begin{pmatrix}
  \nu_e \\
  \nu_\mu \\
  \nu_\tau 
\end{pmatrix}.
\]  

It will be assumed that the Q_f’s belong to the fundamental representation of
SU(3), with all members of each multiplet having the same electrical charge.
Further, in the following we will consider two different types of multiplets:
(i) the matter fields in Q_f do not include a chiral projector, called non-chiral
theory below; (ii) the fields in $Q_f$ are all left-handed, called chiral theory below, and a $\gamma_L = (1 - \gamma_5)/2$ should be attached to each field in (1).

In order to comply with the relative abundance between dark and visible matter, we postulate that for each visible multiplet $Q_f, f = 1, \ldots, 4$, there are five dark matter multiplets. The dark matter multiplets are built just as the visible multiplets. However, given that the dark matter does not seem to couple with the electromagnetic field, it will be assumed that the dark multiplets all have zero electrical charge. As discussed below, within each multiplet the interaction is invariant with respect to a U(1) transformation. Therefore, we can define a dark-photon which couples only with the dark multiplets. The matter multiplets have different U(1) charges, an electric charge, which vanishes for the dark multiplets, and a dark electric charge, which vanishes for the visible matter. Then, from the point of view of the theory, visible and dark matter are treated democratically, i.e. apart from the relative abundance of the two different types of matter, they are distinguished only by their electric and dark electric charge. Further, it will be assumed that dark and visible matter can only interact via WIMG exchange. In order to explain the non-observation of such type interactions, the WIMG field must be a massive field with a mass much larger than the electroweak mass scale.

The Lagrangian for the gauge theory reads

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \sum_f \overline{Q}_f \{ i\gamma^\mu D_\mu - m_f \} Q_f +$$

$$+ \frac{1}{2} (D^\mu \phi^a) (D_\mu \phi^a) - V_{\text{oct}}(\phi^a \phi^a) + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{gh}}$$

where $D_\mu = \partial_\mu + ig_M T^a M^\mu_a$ is the covariant derivative, $T^a$ stands for the generators of $SU(3)$ color group, $m_f$ the current quark mass matrix and $V_{\text{oct}}$ is the potential energy associated with $\phi^a$. A sum over the six species of matter, VM and DM, is implicit in our notation. $\mathcal{L}_{\text{GF}}$ is the gauge fixing part of the Lagrangian and $\mathcal{L}_{\text{gh}}$ contains the ghost terms. The various terms in $\mathcal{L}$ are gauge invariant, with the exception of $\mathcal{L}_{\text{GF}}$ and $\mathcal{L}_{\text{gh}}$. However, for example in the Landau gauge, $\mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{gh}}$ is BRST invariant. The Lagrangian density (2) fixes unambiguously the interactions between visible and dark matter.

The Lagrangian density $\mathcal{L}$ has several symmetries besides the local SU(3) gauge invariance. It is invariant under U(1) gauge transformations within each multiplet. This allows the introduction of multiple photon-like fields. Apart from the mass matrices in $\mathcal{L}$, the Lagrangian is invariant under flavor transformations. Further, setting $g_M = 0$, the Lagrangian is invariant under global SU(3) transformations within each multiplet $Q_f$. This freedom, allows for the introduction of unitary matrices associated with each multiplet to diagonalize the mass matrices that, although of different origin, play a similar role as the
CKM-matrix in the Standard Model Lagrangian. In this way, the model can accommodate neutrino mixing. Further, if one takes the democratic principle seriously, one can build a standard model like Lagrangian for the dark sector. Despite its rich structure, in the present work we will not explore the features just mentioned in this paragraph. Here, we are mainly concerned with the mass scales and phenomenological implications of the theory summarized in [2]. The implications of all the symmetries of $\mathcal{L}$ will be the subject of a future publication.

The WIMG should not change the long distance properties of the gravitational interaction. The only way this can be achieved is if the WIMG is a massive particle. In order to generate a mass to $M^a_\mu$, keeping gauge invariance, one has to rely on scalar fields. According to the Goldstone theorem [13], the Higgs mechanism leaves a number of components of $M^a_\mu$ massless and, to keep the long distance forces unchanged, the Higgs mechanism must be excluded as a way to give mass to the gauge fields. In [14], the authors propose a mechanism for mass generation via the introduction of a scalar condensate which complies with gauge invariance. Further, the mass generation mechanism provides the same mass for all the components of the gauge field. In the following, we will assume that the WIMG acquires mass through this mechanism, which we are about to describe.

The kinetic term associated with the scalar field accommodates a mass term for the WIMG field. The gauge field mass term is associated with the operator

$$\frac{1}{2} g_M^2 \phi^c (T^a T^b)_{cd} \phi^d M^a M^b \phi^\mu. \quad (3)$$

The scalar field cannot acquire a vacuum expectation value without breaking gauge invariance. However, to generate a mass for the WIMG, it is sufficient to assume a non-vanishing boson condensate $\langle \phi^a \phi^b \rangle$. The origin of this condensate can be associated with local fluctuations of the scalar field. From now on, we assume that the dynamics of the scalar field is such that

$$\langle \phi^a \rangle = 0 \quad \text{and} \quad \langle \phi^a \phi^b \rangle = v^2 \delta^{ab}. \quad (4)$$

Given that for the adjoint representation $\text{tr} (T^a T^b) = 3 \delta^{ab}$, the square of the WIMG mass reads

$$M^2 = 3 g_M^2 v^2. \quad (5)$$

Note that the condensate $\langle \phi^a \phi^b \rangle$, i.e. $v^2$, and therefore the WIMG mass is gauge invariant. The proof of gauge invariance follows directly from the transformations properties of $\phi^a$. We have assumed that the real scalar field $\phi$ belongs to the adjoint representation of SU(3). However, the same mechanism can be applied if $\phi$ belongs to the fundamental representation of the gauge group. The main difference being that for the adjoint representation $\phi$ is real and, therefore, has zero charge, while for the fundamental representation $\phi$ is
complex field and, in this way, couples to the photon or dark-photon fields.

We now aim to discuss the phenomenology associated with the new interaction. For the first hadronic visible family, the \( WIMG \) - quark interaction part of the Lagrangian is

\[
\mathcal{L}_{Mq} = \frac{g_M}{2} \left[ \pi \gamma^\mu c \right] \left( M_\mu^1 - iM_\mu^2 \right) + \frac{g_M}{2} \left[ \pi \gamma^\mu t \right] \left( M_\mu^4 - iM_\mu^5 \right) + \frac{g_M}{2} \left[ \pi \gamma^\mu u \right] \left( M_\mu^3 + \frac{1}{\sqrt{3}} M_\mu^8 \right) + \frac{g_M}{2} \left[ \pi \gamma^\mu c \right] \left( -M_\mu^3 + \frac{1}{\sqrt{3}} M_\mu^8 \right) + \frac{g_M}{2} \left[ \pi \gamma^\mu c \right] \left( -M_\mu^3 + \frac{1}{\sqrt{3}} M_\mu^8 \right) + h.c.
\] (6)

The remaining families having similar types of interactions. The new vertices can give rise to flavor changing type of processes but only if the flavor changing occurs only within the same family. Given that the \( WIMG \) has no electrical charge, it seems that it can give rise to flavor changing neutral processes which are, at most, suppressed by \( \sim g_2^2 M^2 / M^2 \). However, the flavor structure of (6) and given that the \( WIMG \) propagator is flavor diagonal, the \( S \)-matrix element for these processes vanishes. For example, as discussed below, the \( WIMG \) vertices give no contributions to the lepton flavor violation processes reported at the particle data book [15]. In this sense, the \( WIMG \) interaction is compatible with the GIM (Glashow-Iliopoulos-Maiani) mechanism of the standard model and the flavor changing neutral currents should remain suppressed at high energies. However, the interaction Lagrangian (6) allows lepton family number violation, as we will discuss (see e.g. figures 3 and 4).

![Fig. 1. Lepton-photon vertex correction by WIMG exchange.](image)

The new gauge boson interactions provide corrections to the lepton-photon vertex which contribute to the lepton anomalous magnetic moment as depicted in fig[11]. The new contributions to \( (g - 2)/2 \) coming from the \( WIMG \) are UV-finite, reading

\[
a_{e,\mu} = \frac{g_M^2}{16\pi^2} \left( \frac{m_{e,\mu}}{M} \right)^2 \left( \frac{5}{3} - \frac{3}{4} \frac{m_\tau}{m_{e,\mu}} \right) \quad \text{and} \quad a_\tau = \frac{7 g_M^2}{96\pi^2} \left( \frac{m_\tau}{M} \right)^2,
\] (7)
for the non-chiral theory and
\[ a_l = \frac{5 g^2 \mathcal{M}^2}{96\pi^2} \left( \frac{m_l}{M} \right)^2, \tag{8} \]
where \( l = (e, \mu, \tau) \), if the particle in the multiplets are left-handed. In (7) and (8) only the leading contributions in \( m^2_l/M^2 \), where \( m_l \) is the lepton mass and \( M \) the WIMG mass, are taken into account.

The particle data group \([15]\) quotes the following values for the anomalous magnetic moment

\[ a_l = \left( \frac{g - 2}{2} \right)_l = \begin{cases} 
(1159.65218073 \pm 0.00000028) \times 10^{-6} & \text{for } l = e, \\
(11659208.9 \pm 5.4 \pm 3.3) \times 10^{-10} & \text{for } l = \mu, \\
> -0.052 \text{ and } < 0.013 & \text{for } l = \tau.
\end{cases} \]

Further, for the muon there is a 3.2\( \sigma \) difference between the experimental value \( a^{\text{exp}}_\mu \) and the standard model prediction \( a^{\text{SM}}_\mu \) which is of
\[ \Delta a_\mu = a^{\text{exp}}_\mu - a^{\text{SM}}_\mu = 255(63)(49) \times 10^{-11}. \]

For the non-chiral theory the WIMG contribution to the lepton anomalous magnetic moment is, for the electron and for the \( \mu \), negative due to the \( \tau \) loop correction to the vertex. Therefore, in the non-chiral theory, the WIMG cannot explain \( \Delta a_\mu \) and \( a_{e,\mu} \) should be, at most, of the order of the experimental error. This provides the constraints
\[ \frac{g^2 \mathcal{M}}{M^2} \leq 6.50 \times 10^{-14} \text{ MeV}^{-2} \quad \text{or} \quad \frac{g^2 \mathcal{M}}{M^2} \leq 8.14 \times 10^{-13} \text{ MeV}^{-2} \quad \tag{9} \]
if one uses \( a_e \) or \( a_\mu \); for \( a_\mu \) the errors reported in \([15]\) were added in quadrature. In the above calculation we used \( m_e = 0.511 \text{ MeV} \) and \( m_\mu = 105.658 \text{ MeV} \).

This bounds can be rewritten in terms of the WIMG mass as
\[ M \geq g_M \times 3.9 \text{ TeV} \quad \text{and} \quad M \geq g_M \times 1.1 \text{ TeV}, \quad \tag{10} \]
respectively. The WIMG contribution to the \( \tau \) anomalous magnetic momenta should be \( \sim 1.5 \times 10^{-9} \) or smaller.

For the chiral, the WIMG contribution to \((g - 2)/2\) should comply with the above results and can be, at most, of the order of the muon anomaly \( \Delta a_\mu \), i.e.
\[ a_\mu \leq 255(63)(49) \times 10^{-11}, \text{ therefore} \]

\[ \frac{g_M^2}{M^2} \leq 4.33 \times 10^{-11} \text{ MeV}^{-2} \tag{11} \]

and the \textit{WIMG} mass should

\[ M \geq g_M \times 0.152 \text{ TeV}. \tag{12} \]

For the non-chiral theory, the choice of \( \Delta a_\mu \) to define the \textit{WIMG} mass complies with the experimental error for the electron and tau. Indeed, from (8) it follows that the contribution of the new gauge bosons to the electron/tau magnetic moment is

\[ a_l = \frac{m_l^2}{m_\mu^2} a_\mu. \tag{13} \]

These scaling laws give an \( a_e = 6.0 \times 10^{-14} \) and \( a_\tau = 7.2 \times 10^{-7} \) which are smaller than the experimental error.

We call the reader attention that we are assuming a perturbative solution for the theory, i.e. that \( g_M \ll 1 \), and the bounds derived from the magnetic moment for the \textit{WIMG} mass can be of the same order of magnitude as the electroweak scale.

The Lagrangian (6) allows for flavor changing processes within the same family. The \textit{WIMG} propagator is flavor diagonal, therefore only those processes where the propagator links the same type of vertices at both ends can have a non-vanishing \( S \)–matrix. The following lepton family number violating decays

\begin{align*}
\mu^- &\rightarrow e^- \nu_e \bar{\nu}_\mu, \quad \mu^- \rightarrow e^- e^+ e^-, \quad \tau^- \rightarrow e^- e^+ e^-, \\
\tau^- &\rightarrow e^- \mu^+ \mu^-, \quad \tau^- \rightarrow \mu^- e^+ e^-, \quad \tau^- \rightarrow \mu^+ e^+ e^-,
\end{align*}

can only occur if the vertices connected by the \textit{WIMG} propagator are different and, therefore, they are forbidden within the model. On the other hand, the quark - \textit{WIMG} vertex structure gives a vanishing \( S \)–matrix for \( \mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu \).

Processes with photons, such as, \( \mu^- \rightarrow e^- \gamma \) or \( \mu^- \rightarrow e^- \gamma \gamma \) can only occur via loops and are highly suppressed at low energies. The same arguments apply to process \( B_d \rightarrow e^- \tau^+ \) and \( B_s^0 \rightarrow \mu^+ \tau^- \) which are forbidden in the model. It turns out that the gauge theory described here complies with the lepton flavor violation bounds reported in the particle data book.

The \textit{WIMG} can also contribute to the leptonic decays of the \( \mu \), the \( D \)'s and the \( B \)'s mesons. Let us now discuss the bounds coming from this processes. We start by computing the main muonic decay channel \( \mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu \) as shown in fig. 2. The \( S \)–matrix gets a contribution from \( W \) exchange and \textit{WIMG}
exchange. To leading order in $M_W$ and $M$, for the chiral theory the matrix element for the transition reads

$$\langle i | M | f \rangle = 64 G_F^4 \left[ 1 - \frac{1}{2\sqrt{2}} \frac{g_M^2/M^2}{G_F^2} \right] (p_\mu \cdot p_\nu) (p_e \cdot p_{\nu_e}).$$

For the chiral theory an extra factor of $1/2$ should multiply the $g_M^2/M^2$. The WIMG contribution can be viewed as a modification to the Fermi coupling constant, i.e.

$$G_F \rightarrow G_F \left[ 1 - \frac{1}{2\sqrt{2}} \frac{g_M^2/M^2}{G_F^2} \right]^{1/4} \approx G_F \left[ 1 - \frac{1}{8\sqrt{2}} \frac{g_M^2/M^2}{G_F^2} \right],$$

with $G_F = 1.16637(1) \times 10^{-5}$ GeV$^{-2}$. Requiring that the WIMG contribution to be of order of the error on $G_F$ or smaller, gives the following bound

$$\frac{1}{8\sqrt{2}} \frac{g_M^2}{M^2} \leq 1.0 \times 10^{-10} \text{ GeV}^{-2} \quad \text{or} \quad \frac{g_M^2}{M^2} \leq 1.13 \times 10^{-9} \text{ GeV}^{-2}.$$ (16)

If instead of the Fermi coupling constant, one uses the relative error on the muon width $\Gamma_\mu = 4.799980(46) \times 10^{-17}$ MeV, the bound becomes

$$\frac{1}{8\sqrt{2}} \frac{g_M^2}{G_F^2 M^2} \leq 9.58 \times 10^{-6} \quad \text{or} \quad \frac{g_M^2}{M^2} \leq 1.26 \times 10^{-9} \text{ GeV}^{-2}.$$ (17)

The corresponding mass bounds are, respectively,

$$M \geq g_M \times 30 \text{ TeV} \quad \text{and} \quad g_M \times 28 \text{ TeV}.$$ (18)

Assuming that $g_M \approx e = \sqrt{4\pi\alpha} = 0.30$, we have a lower bound the WIMG mass of $\approx 9$ TeV to comply with both the $\beta$-decay, i.e. the error on the Fermi coupling constant, and the muon decay. These mass bounds are more restrictive than the bounds coming from the anomalous magnetic moment.

The WIMG vertices can give rise to the following leptonic decays

$$D^0(c\bar{u}) \rightarrow \mu^- e^+, \quad B^0(b\bar{d}) \rightarrow \tau^- e^+, \quad B^0_s(s\bar{b}) \rightarrow \tau^- \mu^+.$$
Fig. 3. \( D^0 \) decay to \((\mu^+, e^-)\) by WIMG exchange process.

an its complex conjugate decays. The processes width can be computed using the relation

\[
\langle 0 | \bar{q} \gamma^\mu \gamma_5 q' \rangle (q\bar{q}') = i f P^\mu,
\]

where \(|(q\bar{q}')\rangle\) stands for the meson state composed of quarks \( q\bar{q} \), \( f \) is the meson decay constant and \( P \) the four-momentum of the meson. Note that the above decays are possible only within the chiral theory. The heavy meson leptonic decay width is calculated by evaluating the amplitude shown in fig. 3 exemplified for \( D^0 \to \mu^- e^+ \), which in the general case is given by:

\[
\Gamma = \frac{1}{256 \pi} \frac{q_M^4}{M^4} f^2 m^2 \left(1 - \frac{m_f^2}{m_m^2}\right)^2,
\]

where we have assumed that the lightest lepton is massless, \( m_l \) is the mass of the heavier lepton and \( m_m \) the mass of the meson state.

For the decay \( D^0 \to \mu^- e^+ \), using a \( m_{D^0} = 1.864 \text{ GeV} \) and \( f_{D^0} = 0.206 \text{ GeV} \), from the bound (16) it follows that the corresponding branching ratio should satisfy

\[
Br(D^0 \to \mu^- e^+) < 8.7 \times 10^{-13}
\]

to be compared with the experimental limit [15] of

\[
Br(D^0 \to \mu^- e^+) < 2.6 \times 10^{-7}.
\]

For the decay \( B^0 \to \tau^- e^+ \), using a \( m_{B^0} = 5.279 \text{ GeV} \) [15] and \( f_{B^0} = 0.22 \text{ GeV} \) [16], the bound (16) gives a

\[
Br(B^0 \to \tau^- e^+) < 2.3 \times 10^{-9}
\]

to be compared with the experimental limit [15] of

\[
Br(B^0 \to \tau^- e^+) < 2.8 \times 10^{-5}.
\]

Finally, for the decay \( B^0_s \to \tau^- \mu^+ \), using a \( m_{B^0_s} = 5.366 \text{ GeV} \) [15] and \( f_{B^0_s} = 0.24 \text{ GeV} \) [16], the bound (16) gives a

\[
Br(B^0_s \to \tau^- \mu^+) < 2.7 \times 10^{-9}.
\]
To the best knowledge of the authors, for this decay there is no experimental information.

The $D^0$ and $B^0$ branching ratios are at least two orders of magnitude smaller than the experimental upper bounds. According to our estimates, there branching ratios should be quite smaller. For $B_s^0$, the experimental bounds coming from $g-2$ and muon decay predicts a branching ratio of the same order of magnitude as for $B^0$. Note that, in the standard model, the decays discussed are not allowed at tree level but they are allowed if one consider one-loops diagrams.

The same type of processes can give rise to the production of dark matter. For example, the bounds (21), (23), (25) also apply to the decays where the leptons are replaced by their dark counter parts. These bounds suggests that the branching rates for production of dark matter from $D$, $B^0$ and $B_s^0$ decays are, at most, of the order of $10^{-9}$. Note that the width are proportional to the lepton mass squared and vanish for massless particles in the final state.

Our estimates for the WIMG mass suggest a $M \geq 9$ TeV. Then, from the point of view of the WIMG all the particles in the multiplets $\mathbf{1}$ are massless. This simplifies considerably the computation of the WIMG width. It follows that,

$$\Gamma = \frac{g^2 M}{24 \pi} N_F,$$  \hspace{1cm} (26)

where $N_F$ is the number of multiplets. For the chiral theory (26) should be multiplied by 1/2. The bound (16) gives

$$\Gamma \leq 1.5 \times 10^{-5} M^3 N_F,$$  \hspace{1cm} (27)

respectively. $\Gamma$ and $M$ are given in TeV. It follows that $\Gamma \approx 0.8$ TeV or smaller and, therefore, the WIMG should have a very short lifetime $\tau = 1/\Gamma \approx 8 \times 10^{-28}$ s. This means that in the cosmic rays either the WIMG is produced via an high energy process or it is absent from the cosmic rays spectrum.

![Fig. 4. Lepton-quark scattering with violation of the lepton family number and flavor exchange by WIMG mediated processes. Positron conversion to antimuon and flavor exchange $u \rightarrow c$ (a) and $d \rightarrow s$ (b).](image)

The WIMG interaction can give rise to processes which are forbidden in the
Standard Model. In particular for the collision $e^+ + p \rightarrow \mu^+ + X$ where $X = \Lambda$ or $\Lambda_c$ can occur via $t$-channel WIMG exchange but is forbidden at tree level in the Standard Model. At the parton level, the tree-level amplitude for lepton-quark scattering with violation of the lepton family number and flavor exchange is shown in fig. 4 (a) and (b), for charm and strangeness production, respectively. Note that processes $e^- + p \rightarrow \mu^- + X$ is forbidden at tree-level within our model.

The differential cross section at the parton level is

$$
\frac{d\sigma}{d\Omega} = \frac{1}{1024 \pi^2} \frac{g_M^4}{M^4} s \left( 1 - \frac{m^2}{s} \right)^2 (1 + \cos \theta) \left[ 2 - \left( 1 - \frac{m^2}{s} \right) (1 - \cos \theta) \right] \quad (28)
$$

where $s$ is the c.m energy, $m$ the mass of the quark in the final state and $\theta$ the angle between the $\mu^+$ and $e^+$ momentum. The total cross section reads

$$
\sigma(s) = \frac{1}{384 \pi} \frac{g_M^4}{M^4} s \left( 1 - \frac{m^2}{s} \right)^2 \left( 2 + \frac{m^2}{s} \right) . \quad (29)
$$

From the bound (16), it follows that

$$
\sigma(s) \leq 8.2 \times 10^{-13} \left( \frac{s}{1 \text{ GeV}^2} \right) \text{pbarn} . \quad (30)
$$

So far, we have investigated the visible sector to constrain the parameters of the model through comparison with well established experimental results. The data clearly provide acceptable bounds for $g_M/M$ and set a scale for the WIMG lifetime. Experimental limits for the WIMP-nucleon interaction cross section, from precision recoil measurements on different nuclear targets, have been reported recently \[4,5,6,7,8,9,10\]. Our WIMG model allows to compute this type of process involving dark and nuclear particles by constructing the expected Fermi-like point interaction from our basic lagrangean \[2\]. This work is in progress and will be reported elsewhere \[17\].

In summary, we have developed a detailed model for the particle interactions between Dark Matter and Visible Matter. We go beyond the Standard Model by postulating the existence of six parallel universes, one of which is our visible universe which is composed of two charge families of quarks, u, c, and t of charge $2e/3$; d, s and b, of charge $-e/3$; the leptons and their corresponding neutrinos. The other five universes contain only DM in similar two charge families of dark quarks, $u_d, c_d, t_d$ of charge $2e/3$, $d_d, s_d, b_d$, of charge $-e/3$; leptons, $\nu_d$, $\mu_d$ and $\tau_d$, and dark neutrinos. The boson responsible for the interactions between the DM particles and the VM ones, the WIMG, is estimated to have a mass much larger than the electroweak mass scale. We stress that the model is economic in the number of parameters and the phenomenological implications for fermionic processes at tree-level require only the new gauge coupling
and WIMG mass. Several decay modes and other processes are calculated and upper bounds are established for them.

The existence of the interaction associated with a new gauge boson, the WIMG with a mass of the order of TeV or higher, implies that a new phase transition should happen in early Universe before the electroweak one. The new phase transition corresponds to the scale where the visible and dark matter decouple. Then, for lower temperatures, dark and visible matter see each other mainly through gravity. The implications and signatures of this new phase transition remain to be investigated.

Acknowledgements

The authors acknowledge financial support from the Brazilian agencies FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and the US Department of Energy Grants DE-FG02-08ER41533, [de-sc0004971], DE-FC02-07ER41457 (UNEDF, SciDAC-2) and the Research Corporation. OO acknowledges financial support from FCT under contract PTDC/FIS/100968/2008.

References

[1] G. Bertone, D. Hopper, and J. Silk, Phys. Reports 405 (2005) 279.
[2] G. Bertone, Nature 468 (2010) 389.
[3] J-H. He, B. Wang, E. Abdalla, Phys. Rev. D83 (2011) 063515.
[4] Z. Ahmed et al. (CDMS Collaboration), Phys. Rev. Lett. 106 (2011) 131302.
[5] E. Aprile et al. (XENON100 Collaboration), Phys. Rev. Lett. 105 (2010) 131302.
[6] E. Aprile et al. (XENON100 Collaboration), arXiv:1104.2549.
[7] R. Bernabei et al. (DAMA/LIBRA Collaboration), Nucl. Phys. B 212-213 (Proc. Suppl.) (2011) 307.
[8] R. Bernabei et al. (DAMA/LIBRA Collaboration), Eur. Phys. J. C56 (2008) 333.
[9] R. Bernabei et al. (DAMA/LIBRA Collaboration), Eur. Phys. J. C67 (2010) 39.
[10] C. E. Aalseth et al. (CoGeNT Collaboration), Phys. Rev. Lett. 106 (2011) 131301.
[11] Y. Cui, L. Randall and B. Shuve, arXiv:1106.4834.

[12] N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, N. Weiner, Phys. Rev D79 (2009) 015014.

[13] K. Huang, “Quark, Leptons & Gauge Fields”, World Scientific Publishing Co. Pte. Ltd., 1992.

[14] O. Oliveira, W. de Paula, T. Frederico, arXiv:1105.4899.

[15] K. Nakamura et al. (Particle Data Group), J. Phys. G37 (2010) 075021.

[16] R. Mohanta, arXiv:1011.4184.

[17] O. Oliveira, C. A. Bertulani, M. S. Hussein, W. de Paula, T. Frederico, in preparation.