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Unparticle dark matter

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ABSTRACT

Once a parity is introduced in unparticle physics, under which unparticle provided in a hidden conformal sector is odd while all Standard Model particles are even, unparticle can be a suitable candidate for the cold dark matter (CDM) in the present universe through its coupling to the Standard Model Higgs doublet. We find that for Higgs boson mass in the range, 114.4 GeV $\lesssim m_h \lesssim$ 250 GeV, the relic abundance of unparticle with mass 50 GeV $\lesssim m_{\mathcal{U}} \lesssim$ 80 GeV can be consistent with the currently observed CDM density. In this scenario, Higgs boson with mass $m_h \lesssim$ 160 GeV dominantly decays into a pair of unparticles and such an invisible Higgs boson may be discovered in future collider experiments.

Existence of the dark matter (DM) is now strongly supported by various observations of the present universe, in particular, the Wilkinson Microwave Anisotropy Probe (WMAP) satellite [1] have determined the various cosmological parameters with greater accuracy. The relic abundance of cold dark matter (CDM) is estimated to be (in 2σ range)

$$0.096 \leqslant \Omega_{\rm CDM} h^2 \leqslant 0.122. \qquad (1)$$

To clarify the identity of a particle as cold dark matter is still a prime open problem both in particle theory and cosmology.

Absence of any suitable candidate of cold dark matter in the Standard Model (SM) suggests the existence of new physics beyond the SM in which a dark matter candidate is implemented. The most promising candidate of CDM is the so-called weakly interacting massive particle (WIMP). Once the stability of WIMP is ensured by some symmetry (parity), its relic abundance can naturally be consistent with the WMAP data for WIMP mass and its typical interaction scales around the electroweak scale. This scale is accessible to future collider experiments such as the Large Hadron Collider (LHC) at CERN which will be in store for its operation next year. A large missing energy associated with WIMP DM production is one of the important keys to discover new physics at collider experiments. There have been proposed the WIMP DM candidates in several new physics models, such as neutralino as the lightest sparticle in supersymmetric model with R-parity, the neutral heavy vector boson in the littlest Higgs model with T-parity [2], the lightest Kaluza–Klein particle in the universal extra dimension model [3] and so on.

In this Letter, we propose a new candidate for CDM in the context of a new physics model recently proposed by Georgi [4], "unparticle". We introduce a $\mathbb{Z}_2$ parity under which unparticle is odd while all Standard Model particles are even. The unparticle, which is provided by a hidden conformal sector and is originally massless, obtains masses associated with the electroweak symmetry breaking through its coupling to the SM Higgs doublet. We find that the unparticle can be a suitable candidate for CDM through the coupling. In addition, in our scenario the SM Higgs boson can invisibly decay into a pair of unparticles with a large branching ratio.

Unparticle provided in a hidden conformal sector could posses strange properties, especially in its energy distributions. A concrete example which can proved unparticle was discussed by Banks–Zaks [5] (BZ) many years ago, where introducing a suitable number of massless fermions, theory reaches a non-trivial infrared fixed point and a conformal theory can be realized at low energy.[1] After the Georgi's proposal, it has been paid a lot of interests in the unparticle physics and various studies on the unparticle physics in scope of the LHC, cosmology, etc., have been developed in the literature.

Now we begin with a very brief review of the basic structure of the unparticle physics. First, we introduce a coupling between the

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[1] Our present analysis does not depend on the model behind unparticle. We suppose a more general theory than the BZ theory for the model behind the unparticle, where the unparticle provided as a composite state in low energy effective theory, like baryons in QCD. In such a theory, we may expect that a low energy effective theory includes a global symmetry like the baryon number in QCD and a composite state has a non-trivial charge under it like the baryon number of proton and neutron. We assume such situation for the unparticle and introduce a $\mathbb{Z}_2$ symmetry under which the unparticle is odd.

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new physics operator ($\mathcal{O}_{\rm UV}$) with dimension $d_{\rm UV}$ and the Standard Model one ($\mathcal{O}_{\rm SM}$) with dimension n,

$$\mathcal{L} = \frac{c_n}{M^{d_{\rm UV}+n-4}} \mathcal{O}_{\rm UV} \mathcal{O}_{\rm SM}, \tag{2}$$

where c_n is a dimension-less constant, and M is the energy scale characterizing the new physics. This new physics sector is assumed to become conformal at a scale $\Lambda_{\mathcal{U}}$, and the operator $\mathcal{O}_{\rm UV}$ flows to the unparticle operator $\mathcal{U}$ with dimension $d_{\mathcal{U}}$. In low energy effective theory, we have the operator of the form (here we consider scalar unparticle, for simplicity),

$$\mathcal{L} = c_n \frac{\Lambda_{\mathcal{U}}^{d_{\rm UV}-d_{\mathcal{U}}}}{M^{d_{\rm UV}+n-4}} \mathcal{U} \mathcal{O}_{\rm SM} \equiv \frac{1}{\Lambda^{d_{\mathcal{U}}+n-4}} \mathcal{U} \mathcal{O}_{\rm SM}, \tag{3}$$

where the scaling dimension of the unparticle ($d_{\mathcal{U}}$) have been matched by $\Lambda_{\mathcal{U}}$ which is induced the dimensional transmutation, and Λ is the (effective) cutoff scale of low energy effective theory. Interestingly, $d_{\mathcal{U}}$ is not necessarily to be integer, but can be any real number or even complex number. In this Letter we consider the scaling dimension in the range, $1 \leqslant d_{\mathcal{U}} < 2$, for simplicity. It was found in Ref. [4] that, by exploiting scale invariance of the unparticle, the phase space for an unparticle operator with the scale dimension $d_{\mathcal{U}}$ and momentum p is the same as the phase space for $d_{\mathcal{U}}$ invisible massless particles,

$$d\Phi_{\mathcal{U}}(p) = A_{d_{\mathcal{U}}} \theta\big(p^0\big)\theta\big(p^2\big)\big(p^2\big)^{d_{\mathcal{U}}-2} \frac{d^4 p}{(2\pi)^4}, \tag{4}$$

where

$$A_{d_{\mathcal{U}}} = \frac{16\pi^{\frac{5}{2}}}{(2\pi)^{2d_{\mathcal{U}}}} \frac{\Gamma(d_{\mathcal{U}}+\frac{1}{2})}{\Gamma(d_{\mathcal{U}}-1)\Gamma(2d_{\mathcal{U}})}. \tag{5}$$

Also, based on the argument on the scale invariance, the (scalar) propagator for the unparticle was suggested to be [6,7]

$$\frac{A_{d_{\mathcal{U}}}}{2\sin(\pi d_{\mathcal{U}})} \frac{i}{(p^2)^{2-d_{\mathcal{U}}}} e^{-i(d_{\mathcal{U}}-2)\pi}. \tag{6}$$

Because of its unusual mass dimension, unparticle wave function behaves as $\sim (p^2)^{(d_{\mathcal{U}}-1)/2}$ (in the case of scalar unparticle).

Now let us impose a $\mathbb{Z}_2$ parity under which unparticle is odd while all SM particles are even, so that unparticle should appear in a pair in interaction terms. Among many possibilities, we focus on the interaction term between unparticles and the Standard Model Higgs doublet (H) such as

$$\mathcal{L}_{\rm int} = -\frac{\lambda}{\Lambda^{2d_{\mathcal{U}}-2}} \mathcal{U}^2 \big(H^\dagger H\big), \tag{7}$$

where λ is a real and positive dimensionless coefficient. Note that this is the lowest dimensional operator among all possible operators between a pair of unparticles and the SM particles. Thus, this operator would be the most important one in unparticle phenomenology at low energies, at least, it is so in our discussion on unparticle dark matter for $\Lambda \gtrsim 1$ TeV, for example. Although unparticle is originally provided by a hidden conformal sector and is massless, it obtains mass through this interaction once the Higgs doublet develops the vacuum expectation value (VEV), $\langle H\rangle = v/\sqrt{2}$ ($v = 246$ GeV), breaking the electroweak symmetry. After the symmetry breaking, we have

$$\mathcal{L}_{\rm int} = -\frac{1}{2} m_{\mathcal{U}}^{4-2d_{\mathcal{U}}} \mathcal{U}^2 \left(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\right), \tag{8}$$

where $m_{\mathcal{U}} = (\sqrt{\lambda} v/\Lambda^{d_{\mathcal{U}}-1})^{1/(2-d_{\mathcal{U}})}$ is the unparticle mass, and h is the physical Standard Model Higgs boson. For $d_{\mathcal{U}} \sim 1$ unparticle has mass around the electroweak scale and interactions with Higgs boson characterized also by the electroweak scale. The parity we have introduced ensures the stability of unparticle. These are ideal situations for unparticle to be the WIMP dark matter.

Our scenario shares similar structures with some simple modes for dark matter [8], where the gauge singlet scalar is introduced into the SM and can be a suitable candidate for dark mater through couplings to Higgs boson. The crucial difference of unparticle from such a singlet scalar is that unparticle is originally massless because of the conformal invariance of a hidden sector. The absence of mass term reduces the number of free parameters involved in dark matter physics and as a result, we can analyze the relic density of unparticle dark matter as a function of only unparticle mass ($m_{\mathcal{U}}$) and Higgs boson mass (m_h), as we will see later.

Now let us evaluate the relic density of unparticle dark matter. In our analysis, we consider the case $d_{\mathcal{U}} \sim 1$, for simplicity, where unparticle is almost identical to a gauge singlet scalar. We can expect that even for a general $d_{\mathcal{U}}$ in the range, $1 \leqslant d_{\mathcal{U}} < 2$, our results will remain almost the same in the following reasons. First, the phase space factor $A_{d_{\mathcal{U}}}$ is a slowly varying function of $d_{\mathcal{U}}$. Second, the unparticle dark matter decouples from thermal bath in non-relativistic regime, where the most important factor to fix the decoupling temperature is the Boltzmann factor $e^{-m_{\mathcal{U}}/T}$ independent of $d_{\mathcal{U}}$.[2] Moreover, in non-relativistic regime, the unparticle wave function behaves as $m_{\mathcal{U}}^{d_{\mathcal{U}}-1}$ and the interaction terms in Eq. (8) becomes independent of $d_{\mathcal{U}}$ in momentum space.

The relic abundance of the dark matter is obtained by solving the following Boltzmann equation [10],

$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle}{Hx} s\big(Y^2 - Y_{\rm eq}^2\big), \tag{9}$$

where $Y = n/s$ is the yield of the dark matter defined by the ratio of the dark matter density (n) to the entropy density of the universe ($s = 0.439 g_* m_{\mathcal{U}}^3/x^3$), $g_* = 86.25$, and $x \equiv m_{\mathcal{U}}/T$ (T is the temperature of the universe). The Hubble parameter is given by $H = 1.66 g_*^{1/2} m_{\mathcal{U}}^2 m_{\rm Pl}/x^2$, where $m_{\rm Pl} = 1.22 \times 10^{19}$ GeV is the Planck mass, and the yield in the equilibrium $Y_{\rm eq}$ is written as $Y_{\rm eq} = (0.434/g_*) x^{3/2} e^{-x}$. After solving the Boltzmann equation with the thermal averaged annihilation cross section $\langle\sigma v\rangle$, we obtain the present abundance of dark matter (Y_∞). With a good accuracy, the solution of Eq. (9) is approximately given as [10]

$$\Omega h^2 = \frac{1.07 \times 10^9 x_f\ {\rm GeV}^{-1}}{\sqrt{g_*} m_{\rm PL} \langle\sigma v\rangle}, \tag{10}$$

where $x_f = m_{\mathcal{U}}/T_f$ is the freeze-out temperature for the dark matter and given as $x_f = \ln(X) - 0.5\ln(\ln(X))$ with $X = 0.038 \cdot (1/g_*^{1/2}) m_{\rm PL} m_{\mathcal{U}} \langle\sigma v\rangle$.

The unparticle dark matter annihilates into the SM particles through its interaction to Higgs boson in Eq. (8). Since this annihilation occurs in the s-wave, the thermal averaged annihilation cross section $\langle\sigma v\rangle$ is simply given by

$$\langle\sigma v\rangle = \sum_{IJ} \sigma v|_{IJ}, \tag{11}$$

where I, J stand for SM particles in each possible annihilation process $\mathcal{U}\mathcal{U} \to IJ$. When $m_{\mathcal{U}} \leqslant m_h$, possible annihilation processes of unparticle dark matters are $\mathcal{U}\mathcal{U} \to h \to IJ$, where $IJ = f\bar{f}$, W^+W^-, ZZ, etc. In our analysis, off-shell states for $IJ = W^+W^-$ and ZZ are also taken into account. When $m_{\mathcal{U}} > m_h$, the process $IJ = hh$ should be added into the annihilation processes. However,

[2] In precise, the thermal history of the unparticle is still an issue under discussion. In this Letter, since we consider a massive unparticle and its decoupling nature in non-relativistic regime, we implicitly assume that the thermal distribution of unparticle is almost the same as usual WIMP dark matter with the Boltzmann suppression factor. One the other hand, in relativistic regime, it has been demonstrated in [9]. that thermal distribution of the unparticle is quite different from usual relativistic particle. It is an interesting issue to find a correct formula which smoothly connects relativistic regime with non-relativistic one (that we expect). We leave this issue for future study.

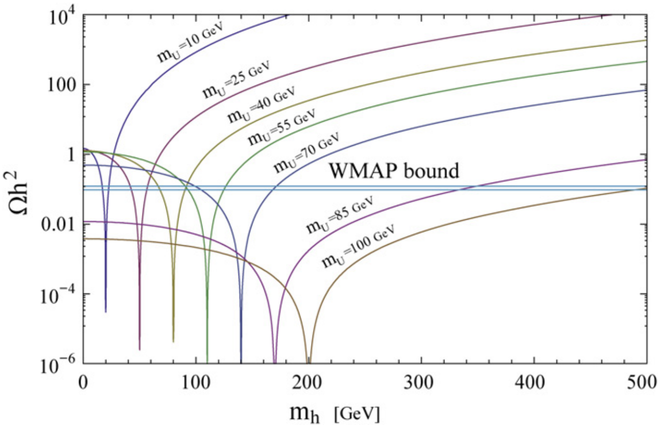

Fig. 1. The relic abundance of the unparticle dark matter as a function of the Higgs boson mass for fixed unparticle masses, together with the WMAP measurements, $0.096 \leqslant \Omega_{\rm CDM}h^2 \leqslant 0.122$. Each curve corresponds to the unparticle mass, $m_{\mathcal{U}} = 10, 25, 40, 55, 70, 85, 100$ GeV.

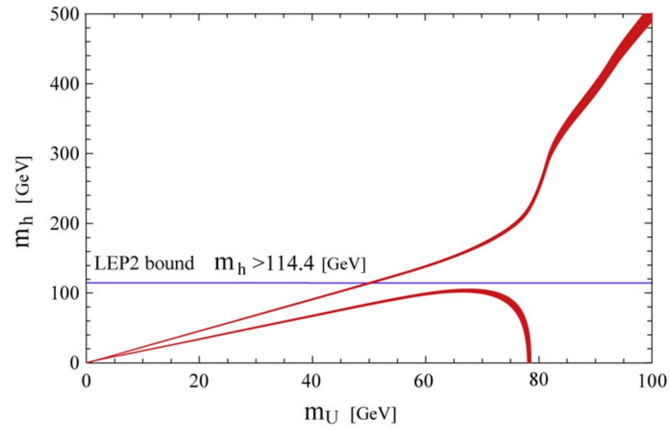

Fig. 2. The contour plot of the relic abundance of the unparticle dark matter Ωh^2 in $(m_{\mathcal{U}}, m_h)$-plane. The shaded thin area is the allowed region for the WMAP measurements, $0.096 \leqslant \Omega_{\mathcal{U}}h^2 \leqslant 0.122$, at 2σ confidence level.

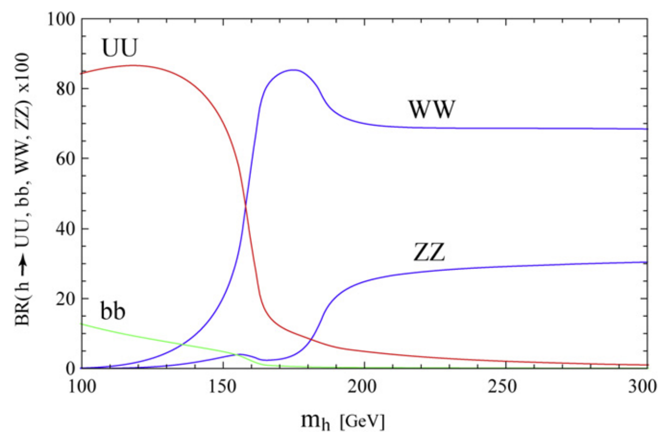

Fig. 3. Branching ratios of the Higgs boson decays as a function of the Higgs mass, along the WMAP allowed region for $m_h > 2m_{\mathcal{U}}$ in Fig. 2.

we find that the WMAP allowed region appears most for $m_{\mathcal{U}} < m_h$, and it is sufficient to consider only the processes mediated by Higgs boson in the s-channel. In this case, the annihilation cross section can be simply described as

$$\sigma v|_{IJ} = 4\frac{m_{\mathcal{U}}^3}{v^2}\frac{\Gamma(h \to IJ)|_{m_h=2m_{\mathcal{U}}}}{(4m_{\mathcal{U}}^2 - m_h^2)^2 + m_h^2\Gamma_h^2}, \tag{12}$$

where $\Gamma(h \to IJ)$ is the SM Higgs boson partial decay width into IJ, and the subscript $m_h = 2m_{\mathcal{U}}$ means to replace m_h into $2m_{\mathcal{U}}$ in the formula of the Higgs boson partial decay width. When $m_h > 2m_{\mathcal{U}}$, the partial decay width,

$$\Gamma(h \to \mathcal{U}\mathcal{U}) = \frac{1}{8\pi m_h}\frac{m_{\mathcal{U}}^4}{v^2}\sqrt{1 - 4\frac{m_{\mathcal{U}}^2}{m_h^2}}, \tag{13}$$

should be added in the Higgs boson total decay width Γ_h. Note that the relic density of the unparticle dark matter can be determined by only two free parameters, $m_{\mathcal{U}}$ and m_h.

In Fig. 1, the relic abundance of the unparticle dark matter are depicted as a function of the Higgs boson mass for fixed unparticle masses, together with the WMAP result. The relic abundance sharply falls down at Higgs boson pole, $m_h = 2m_{\mathcal{U}}$, because of the resonance, as can be easily understood from Eq. (12). Therefore, the WMAP consistent region appears in both sides of the Higgs pole. The cross section becomes larger as $m_{\mathcal{U}}$ is raised for fixed m_h, so that the WMAP allowed region for $m_h < 2m_{\mathcal{U}}$ eventually disappears. This growth of the annihilation cross section is related to the unitarity violation, since the original interaction in Eq. (7) is higher dimensional and the cross section becomes larger as energy, in other word, $m_{\mathcal{U}}$ becomes large. For $d_{\mathcal{U}} = 1$, this corresponds to razing a coupling λ. The allowed region always exists for $m_h > 2m_{\mathcal{U}}$, because the annihilation cross section is suppressed for a large m_h.

The WMAP allowed region on $(m_{\mathcal{U}}, m_h)$-plane is shown in Fig. 2. The lower bound on the Higgs boson mass by LEP2 [11] excludes the WMAP allowed region for $m_h < m_{\mathcal{U}}$ and the region $m_{\mathcal{U}} \lesssim 50$ GeV. From $m_{\mathcal{U}} \simeq 80$ GeV, the Higgs boson mass starts growing quickly since the annihilation process into a real W-boson pair in the final state opens up and the annihilation cross section becomes large from the threshold. Light Higgs boson mass $m_h \lesssim 250$ GeV is favored from the electroweak precision measurements [12], so that the unparticle mass is constrained to be in the range, 50 GeV $\lesssim m_{\mathcal{U}} \lesssim$ 80 GeV.

As shown in Fig. 2, the region consistent with both the WMAP data and the Higgs boson mass bound by LEP2 appears only for $m_h > 2m_{\mathcal{U}}$, so that Higgs boson can decay into a pair of unparticles. The branching ratio is depicted in Fig. 3. In fact, for $m_h \lesssim 160$ GeV, Higgs boson dominantly decays into unparticle dark matters. Even for $m_h = 200$ GeV, the branching ratio of invisible Higgs boson decay is sizable, BR$(h \to \mathcal{U}\mathcal{U}) \simeq 8.5\%$. Besides our scenario and simply extended SM models [8], the invisible Higgs boson decay has been discussed in Majoron models [13], extra-dimension models [14] and the little Higgs model with T-parity [15]. When Higgs boson dominantly decays into the invisible mode, the Higgs boson search at LHC would be more challenging. However, there are several ideas to search the invisibly decaying Higgs boson through its associated productions with weak bosons [16] or top quarks [17] and its production through weak boson fusion [18]. On the other hand, at International Linear Collider (ILC), the search for such an invisible Higgs boson and the measurement of its invisible decay width are easier through the final state fermions from recoiled Z-boson decay.

In summary, we have investigated the possibility of unparticle dark matter. Imposing the $\mathbb{Z}_2$ parity for unparticle and hence ensuring the stability of unparticle, we have introduced the coupling between unparticles and the SM Higgs doublets. Associating with the electroweak symmetry breaking, unparticle obtains mass and becomes the WIMP dark matter candidate. We have evaluated the relic abundance of unparticle dark matter and found the WMAP allowed region with the unparticle mass around the electroweak scale. Interestingly, in this allowed region, Higgs boson can decay into a pair of unparticle dark matters with a sizable branching ratio, even this invisible decay mode can be dominant. Such an invisible Higgs boson may be observed in future collider experiments. It would be worth investigating indirect detections of unparticle dark matter through cosmic rays originating from unparticle pair annihilation in the halo associated with our galaxy. Since this annihilation occurs in the s-wave, the annihilation cross section does not suffer from the suppression by low relative velocity of colliding unparticles, as a result, we can expect a sizable cosmic ray flux. Cosmic positron flux has been analyzed in Ref. [19] for the dark matter in the littlest Higgs model with T-parity. The annihilation processes of unparticles we have considered are basically the same as those in the Letter, and we can apply the same arguments for the cosmic ray from unparticle annihilation in the halo. In this Letter, we have assumed scalar unparticle, for simplicity. It is easy to consider fermionic or vector unparticle as the dark matter. We will arrive at the same conclusions except different numerical factors related with the representations under Lorentz group.

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